

# Polarization of asteroid (387) Aquitania: the newest member of a class of large inversion angle asteroids

Joseph Masiero<sup>1</sup>, Alberto Cellino<sup>2</sup>

## ABSTRACT

We present new imaging polarimetric observations of two Main Belt asteroids, (234) Barbara and (387) Aquitania, taken in the first half of 2008 using the Dual-Beam Imaging Polarimeter on the University of Hawaii 2.2 meter telescope, located on Mauna Kea, Hawaii. Barbara had been previously shown to exhibit a very unusual polarization-phase curve by Cellino et al. (2006). Our observations confirm this result and add Aquitania to the growing class of large inversion angle objects. Interestingly, these asteroids show spinel features in their IR spectra suggesting a mineralogical origin to the phase angle-dependent polarimetric features. As spinel is associated with calcium-aluminum-rich inclusions and carbonaceous chondrites, these large inversion angle asteroids may represent some of the oldest surfaces in the solar system. Circular as well as linear polarization measurements were obtained but circular polarization was not detected.

## 1. Introduction

The radiation we receive from asteroids at visible wavelengths is sunlight scattered by the solid surfaces of the objects. The scattering process polarizes the emerging photon flux, with the most general state of polarization being partial elliptical polarization. In the case of asteroid scattering, linear polarization dominates over circular and is modulated by the properties of the surface (e.g. albedo, texture, composition, regolith size) and the illumination conditions. Measuring the degree of linear polarization can diagnose physical

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<sup>1</sup>Institute for Astronomy, University of Hawaii, 2680 Woodlawn Dr, Honolulu, HI 96822, [masiero@ifa.hawaii.edu](mailto:masiero@ifa.hawaii.edu)

<sup>2</sup>INAF - Osservatorio Astronomico di Torino, strada Osservatorio 20, I-10025 Pino Torinese (TO), Italy, [cellino@oato.inaf.it](mailto:cellino@oato.inaf.it)

conditions of the scattering surface and is complementary to photometry and spectroscopy for the remote analysis of small solar system objects.

A common way to quantify the polarization of light is by using the Stokes vectors  $I$ ,  $Q$ ,  $U$ , &  $V$ , where  $I$  is the total intensity,  $Q$  the amount of light polarized in the  $0^\circ$  or  $90^\circ$  planes,  $U$  the light in the  $45^\circ$  or  $-45^\circ$  planes, and  $V$  the light polarized circularly with left- or right-handedness. In particular, Stokes  $Q$  and  $U$  fully describe the state of linear polarization. For cases of linear polarization,  $Q$  and  $U$  can be converted into a measure of the total degree of polarization ( $P$ ) and the position angle of polarization ( $\theta$ ) using:  $P = \frac{\sqrt{Q^2+U^2}}{I}$  and  $\theta = \frac{1}{2} \arctan U/Q$ .

The reference for the position angle of polarization is typically celestial north, though definitions in the instrument frame or the galactic frame can also be used if convenient. In asteroid polarimetry it is found that with few exceptions the orientation of the plane of linear polarization is perpendicular or parallel to the scattering plane: the plane encompassing the Sun, the target, and the observer. Since most scattering cases result in light polarized perpendicular to the scattering plane we define that direction as the reference for polarization position angle. The new degree of polarization is then defined as

$$P_r = \frac{(I_\perp - I_\parallel)}{(I_\perp + I_\parallel)}$$

where  $I_\perp$  and  $I_\parallel$  are the intensities of light perpendicular and parallel to the scattering plane, respectively. For this definition,  $P_r$  will be positive for the “normal” scattering case, or negative if the scattered light is polarized in the plane of scattering. This allows us to refer to polarization of an asteroid as either “positive” or “negative” and still be completely descriptive.

The primary observable in asteroid polarimetric studies is the change in percent polarization  $P_r$  as a function of phase angle (the angle between the Sun and the Earth as seen from the asteroid). Close to zero phase angle  $P_r$  tends to zero, but as the phase angle increases  $P_r$  becomes increasingly negative. This is the so-called branch of negative polarization. After reaching a maximum negative value usually between  $8^\circ$  and  $10^\circ$  phase angle,  $P_r$  decreases in absolute value (that is, becomes depolarized) and reaches zero at the so-called inversion angle ( $\alpha_0$ ) usually between  $15^\circ$  and  $20^\circ$  phase. The maximum value of negative polarization is an important parameter, usually indicated as  $P_{min}$ , and varies mostly between  $-0.5\%$  and  $-2.0\%$ . Measurements of  $P_{min}$  can be used to calculate albedo (Zellner & Gradie 1976), and can be used along with inversion angle as an indication of surface texture (Dollfus & Zellner 1979).

Beyond the inversion angle  $P_r$  becomes re-polarized in the positive sense, increasing

nearly linearly with phase. The slope ( $h$ ) of the branch of positive polarization for phase angles greater than the inversion angle is another important parameter, since it is known to be diagnostic of the albedo of the surface (see, e.g. Cellino et al. 1999, and references therein). The maximum value of positive polarization is reached at values of phase which are well beyond the maximum values attainable by main belt asteroids observed from Earth. Only near-Earth objects are occasionally visible over very large intervals of phase angle, and the maximum value of positive polarization is observed in some cases to occur at phase angles of the order of 80 - 100 degrees.

Shkuratov et al. (1994) review the many possible physical models that have been used to try to explain the negative polarization seen in asteroid phase curves. The most promising are the coherent backscattering models, described in e.g. Muinonen (1989), which can explain both the photometric opposition surge observed for atmosphereless bodies as well as the negative polarization seen for asteroids at small phase angles. The polarimetric effect in this theory has a strong dependence on the size and spacing of the scattering particles meaning that surface chemistry and mineralogy should play a large role in determining the polarization as a function of phase. According to Muinonen et al. (2002), coherent backscattering is the key physical process generating both these effects.

As part of an extensive campaign to characterize the polarization-phase curves of over 100 asteroids Cellino et al. (2005, 2006) found an interesting case in the asteroid (234) Barbara, which was found to exhibit an unusual polarimetric behavior. Whereas most asteroids have an inversion angle of around  $20^\circ$  Barbara shows strong negative polarization ( $\sim -1\%$ ) for phase angles larger than  $25^\circ$ . The authors proposed that this strange behavior was due to unusual surface properties, likely the surface mineralogy driving the rare Ld-type classification. Gil-Hutton et al. (2008) performed a follow-up investigation of other L/Ld-type asteroids, finding four that show these unusual polarization properties. While not all L-type asteroids show this effect (e.g. (12) Victoria, see Cellino et al. (2005)), both Barbara and (980) Anacostia from Gil-Hutton et al. (2008)'s survey show strong spinel features in their IR spectra (Sunshine et al. 2007). Burbine et al. (1992) identified strong spinel features in the IR spectra of both (387) Aquitania and Anacostia, so we investigated Aquitania to look for the same strange polarization signatures seen in other spinel-rich L-types.

## 2. Observations

Observations of the asteroids (387) Aquitania and (234) Barbara were conducted on four nights spread from January to June 2008 on the University of Hawaii 2.2 m telescope located on Mauna Kea, Hawaii. Polarizations were measured with the Dual-Beam Imaging

Polarimeter (DBIP, Masiero et al. (2007)), a broad-band CCD imaging system sensitive to both linear and circular polarizations simultaneously. DBIP has very low instrumental systematics and can reach polarization precisions of better than 0.1%. DBIP uses an IR-blocked clear filter which transmits from 400 – 700 nm, a close approximation to a Sloan  $g' + r'$  filter. Although there is some evidence for color dependence of polarization (Cellino et al. 2005), the difference in measured polarization between  $P_V$  and  $P_R$  is usually within error. V and R band polarizations of Barbara showing this consistency can be seen in Fig 1. Using a broader filter does not impair our measurements of the bulk polarization properties.

Stokes parameters were measured for our targets using a beam-swapping pattern of waveplate alignments. Each image measured complimentary values of a single Stokes vector (i.e.  $I + Q$  in the north beam and  $I - Q$  in the south beam;  $I + U$  north and  $I - U$  south; or  $I + V$  north and  $I - V$  south) which were then swapped in a second image. By combining both images we were able to completely remove time-dependent and flat-field effects on the measured polarization values. Individual exposure times were adjusted so that each image of our target had a peak count value on the CCD between 20,000 and 40,000 counts per pixel to provide enough photons for good statistics while avoiding non-linear issues near saturation. Image reduction was completed as described in Masiero et al. (2007).

DBIP’s native polarization measurement is of the fractional values  $Q/I = q$  and  $U/I = u$ , which can be converted to  $P$  and  $\theta$ , as well as  $V/I = v$ . Table 1 presents the asteroid name, UT date of observation, apparent V magnitude, total exposure time, phase angle ( $\alpha$ ), measured linear polarization ( $P_r$ ), angle of polarization ( $\theta$ ) and measured circular polarization. Total listed exposure time includes all six waveplate positions needed to develop a full measurement of  $q$ ,  $u$ , and  $v$ . The linear polarization measurements and angles of polarization have been rotated into the frame of the asteroid scattering plane. The circular polarization values in all cases are consistent with a zero signal to within  $2.5\sigma$ , and thus we do not detect any circular polarization of the light scattered from these asteroids. Circular polarization is predicted to appear on asteroids that have surfaces containing powdered metals, especially those with highly irregular shapes (Degtjarev & Kolokolova 1992), however circular polarization as of yet has not been detected from an asteroid (e.g., Muinonen et al. 2002).

Polarized and unpolarized standard star measurements were taken each night in addition to the asteroid observations. Standards were drawn from Fossati et al. (2007) as well as the standard list published for Keck/LRIS<sup>1</sup> which includes the *Hubble* standards (Schmidt et al. 1992). Standard measurements showed that induced instrumental polarization, systematic depolarization and instrumental crosstalk were all below the 0.1% level, and so are not

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<sup>1</sup><http://www2.keck.hawaii.edu/inst/lris/polarimeter/polarimeter.html>

included in the data tables. See § 3 for further discussion on systematic error determination.

Our linear polarization data are shown in Figure 1 along with the Barbara data presented in Cellino et al. (2006), Cellino et al. (2007) (these data also published in Gil-Hutton et al. (2008) as the Torino observations), and the CASPROF data from Gil-Hutton et al. (2008). In addition, two comparison phase curves are also plotted. The first is the fit by Muinonen et al. (2002) to polarization data from (24) Themis, a member of the B taxonomic class. B-type and C-type asteroids typically show the deepest negative polarization branches. The other curve is a fit by Gil-Hutton et al. (2008) of data for (12) Victoria, a typical L-class object. Although different fitting models were used in these two cases, both models are qualitatively the same at the phase angles of interest. Note that Aquitania was classified as an L-class and Barbara as an Ld-class by Bus & Binzel (2002) whereas both are now L-class under the classification system of Demeo (2007) but show very different polarization features from other L-class objects.

### 3. Instrumental Polarization Calibration

Following the calibrations reported in Masiero et al. (2007) a quarterwave retarder was added in series with the halfwave retarder affecting the instrumental systematics, especially crosstalk between linear and circular polarization. To quantify these instrumental errors, extensive lab bench crosstalk calibrations were performed. Details of the calibration procedure can be found in Masiero et al. (2008), and are briefly summarized here.

Figure 2 shows the measured polarization state for an input of pure linear polarization stepped through 360 degrees both without and with a fixed quarterwave plate in the light path (Figs 2a and 2b, respectively). Ideally the former test should show pure  $Q$  and  $U$  polarization as offset sinusoids peaking at 100% with zero  $V$  polarization, while the latter test should show offset  $Q$  and  $V$  (in this case, the  $U$  that is in the same phase as  $Q$  indicates a slight misalignment of the quarterwave plate at the input, while the out of phase  $U$  indicates crosstalk). A chi-squared minimizer was used to fit the measured variations in the Stokes vectors to determine crosstalk and depolarization. In all cases, the crosstalk and depolarization were found to be a few percent of the input polarization, so that for sources with “typical” polarizations (i.e. 5–10%) the errors are comparable to the desired statistical errors of  $\sim 0.1\%$  polarization, as has been measured for polarized and unpolarized standards.

#### 4. Discussion

The new measurements of (234) Barbara presented here agree with those from Cellino et al. (2006) and Cellino et al. (2007). Despite very different optical designs, data acquisition methods, observing circumstances, and physical locations, the consistency between our results and those from previous work (e.g. Cellino et al. (2006)) indicate that comparisons and combinations of results from these instruments are legitimate.

The similarity between the Barbara and (387) Aquitania polarization values clearly point toward Aquitania being a member of the new class of large inversion angle (LIA, or “Barbarian”) asteroids that includes Barbara, (172) Baucis, (236) Honoria, (679) Pax and (980) Anacostia (Gil-Hutton et al. 2008). Barbara, Aquitania, and Anacostia all show strong  $2\mu$  spinel features in their IR spectra (Sunshine et al. 2007; Burbine et al. 1992) implying a mineralogical origin to the unusual polarization properties of these asteroids. The other three LIA objects do not currently have published IR spectral coverage at  $2\mu$ , but we predict that they too will show the same spinel feature. Sunshine et al. (2007) explain that a spinel-rich spectrum can be used as a tracer of Calcium-Aluminum-Rich Inclusions (CAIs), one of the oldest known materials in the Solar System, as determined from meteorite chemical analysis (e.g. Sunshine et al. (2008)).

Gil-Hutton et al. (2008) propose that the surfaces of these bodies may be coarse regoliths of a dark matrix mixed with smaller white inclusions. This mixing of two components with different albedos can alter the behavior of bulk polarization as a function of phase and explain the large inversion angle seen in these objects. The authors point out that their sample of LIA asteroids covers a wide range of semimajor axis-space (2.38 – 2.80 AU) and thus cannot be fragments from a single parent body.

Table 2 shows that Aquitania has orbital and physical properties fairly similar to those of Anacostia (Gil-Hutton et al. 2008). This similarity was also pointed out by Burbine et al. (1992) when they were both identified as spinel-bearing asteroids. However, it is very unlikely that these two objects originate from the same parent body, based on the velocity spread between their orbits compared to those seen for other disrupted bodies and dynamical families (Willman 2008; Zappala et al. 1995). In other words, if both Aquitania and Anacostia were fragments from the collisional disruption of a common parent body, the difference in orbital elements would imply unrealistic ejection velocities of the order of many km/sec. Moreover, given the non-negligible sizes of Aquitania and Anacostia, such a collisional event should also be expected to have generated an important dynamical family that should be possible to identify even after a very long time. Such a family, however, is simply not found.

It is worth noting that of the six asteroids now identified as LIA objects four have periods longer than 20 hours when the average for these sizes is  $\sim 10 - 15$  hours. Though still a victim of small number statistics, if this trend of long rotation periods holds for other LIA asteroids it may indicate that they are characterized by rotation periods significantly longer than the typical values found for most large Main Belt asteroids (Pravec et al. 2002). This would imply a highly porous, “fluffy” internal structure that is very efficient at absorbing energy from impacts without transferring it into an increase in rotation rate. This kind of structure is similar to what was observed for the Tagish Lake meteorite (Zolensky et al. 2002) and what is expected for carbonaceous chondrites in which all CAIs found thus far have been observed (Burbine et al. 2002). This would support the theory proposed by Sunshine et al. (2008) that spinel-bearing asteroids, and thus probably all LIAs, are composed of pristine material from the beginning of the solar system. We note also that long spin periods might also be diagnostic of binarity, although any physical reason for a correlation between binarity and anomalous polarimetric properties remains unknown.

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Table 1. Asteroid Polarization Measurements

Target	UT Obs Date	V mag	$T_{exp}$ (sec)	$\alpha$	Linear % Pol <sup>a</sup>	$\theta_p$	Circ % Pol <sup>a</sup>
387 Aquitania	2008-01-17	12.7	360	21.2°	$-0.97 \pm 0.06$	$91.36 \pm 2.57$	$0.03 \pm 0.02$
	2008-03-12	11.7	72	15.6°	$-1.42 \pm 0.06$	$88.95 \pm 1.84$	$-0.07 \pm 0.04$
	2008-05-14	11.3	72	17.1°	$-1.31 \pm 0.06$	$89.58 \pm 1.35$	$0.00 \pm 0.03$
	2008-06-11	11.7	60	23.3°	$-0.82 \pm 0.07$	$90.16 \pm 2.54$	$-0.03 \pm 0.04$
234 Barbara	2008-01-17	14.3	1620	19.9°	$-1.24 \pm 0.06$	$92.11 \pm 2.80$	$0.06 \pm 0.03$
	2008-03-12	13.6	720	23.6°	$-0.93 \pm 0.04$	$89.33 \pm 1.61$	$0.08 \pm 0.03$
	2008-05-14	12.2	270	13.7°	$-1.53 \pm 0.09$	$87.98 \pm 2.70$	$-0.01 \pm 0.03$
	2008-06-11	12.0	108	13.3°	$-1.67 \pm 0.13$	$89.07 \pm 2.45$	$0.06 \pm 0.03$

<sup>a</sup> quoted errors are  $1\sigma$  statistical errors; systematic errors are  $\approx 0.05\%$ .

Table 2. Orbital and Physical Parameters

Asteroid	a (AU) <sup>a</sup>	e <sup>a</sup>	i (deg) <sup>a</sup>	H (mag) <sup>b</sup>	Diameter (km) <sup>b</sup>	Rot. Period (h) <sup>c</sup>
387 Aquitania	2.739	0.237	18.14	7.41	100.51	24.144
980 Anacostia	2.743	0.200	15.90	7.85	86.19	20.117

<sup>a</sup> from MPCORB: <http://www.cfa.harvard.edu/iau/MPCORB.html>. <sup>b</sup> from Tedesco et al. (2002). <sup>c</sup> from <http://cfa-www.harvard.edu/iau/lists/LightcurveDat.html>.

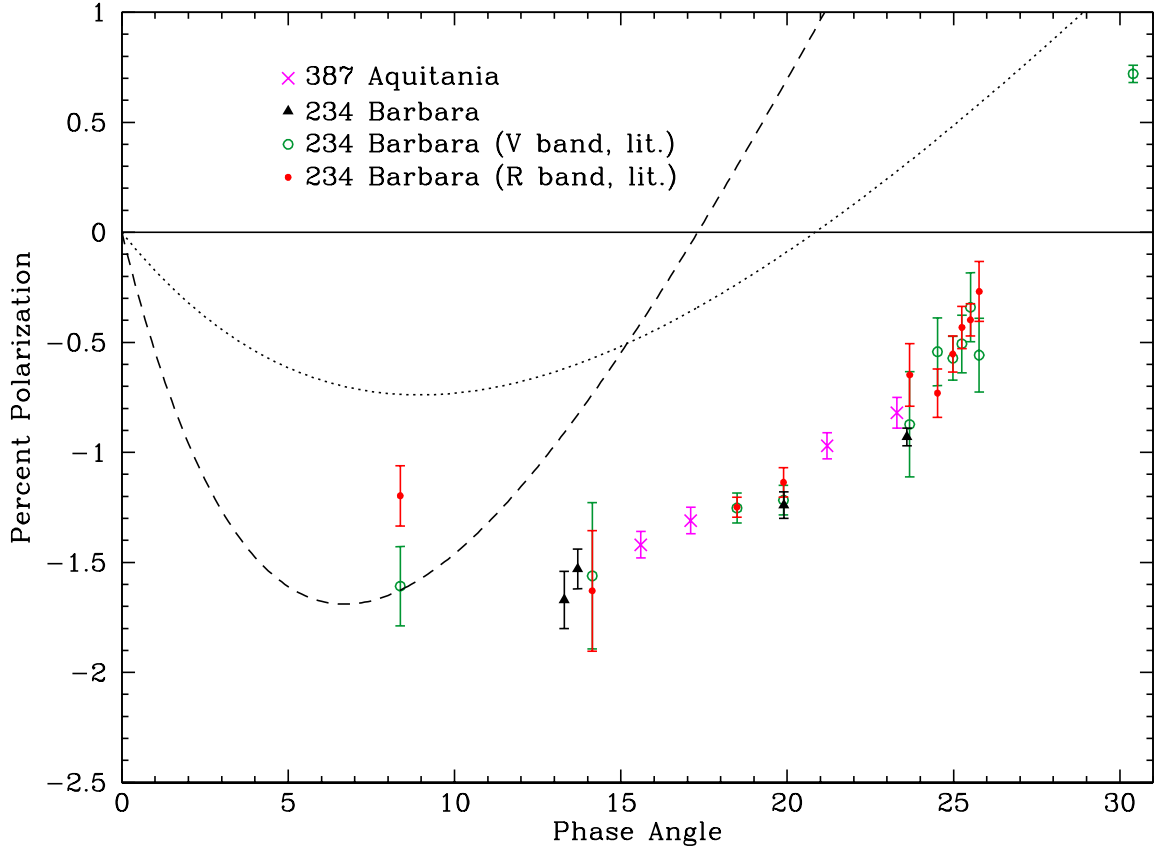


Fig. 1.— Polarization measurements of (387) Aquitania and (234) Barbara from this work (crosses and filled triangles, respectively) compared to the V and R band Barbara measurements (open and filled circles) from Cellino et al. (2006), Cellino et al. (2007) and Gil-Hutton et al. (2008). The dashed and dotted lines show typical polarization-phase curves for B-type (e.g. (24) Themis) and L-type (e.g. (12) Victoria) asteroids, respectively (Muinonen et al. 2002; Gil-Hutton et al. 2008).

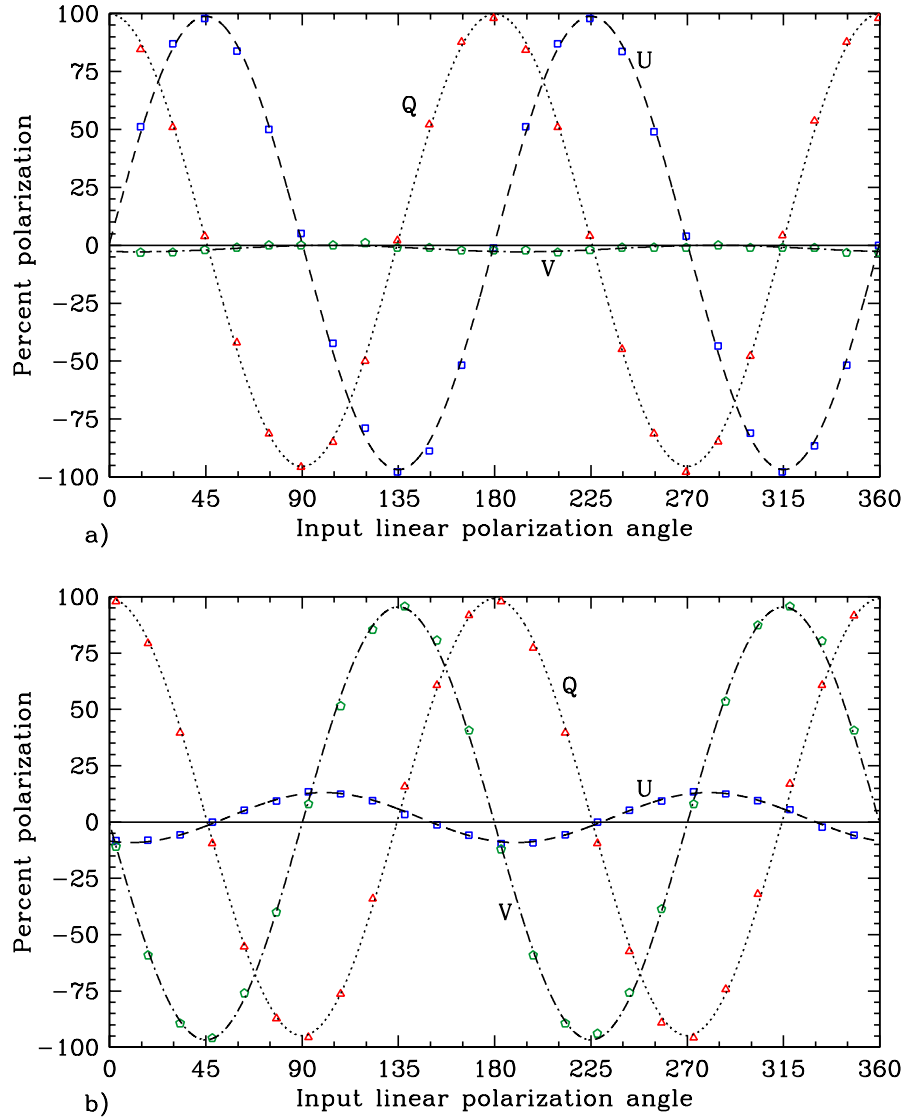


Fig. 2.— Polarization crosstalk measurements for DBIP for two cases: (a) for input of pure linear polarization rotated through 360 degrees, and (b) for input of rotated linear polarization passed through a fixed quarterwave plate. Sinusoids for both cases were fitted using a chi-squared minimizer, and are labeled with the Stokes vectors they represent. From Masiero et al. (2008)