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Stability and Symmetry of Zodiacal Light Polarization in the Antisolar Hemisphere

C. Leinert and B. Planck

Max-Planck-Institut für Astronomie, Königstuhl, D-6900 Heidelberg, Federal Republic of Germany

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Summary. Observations of zodiacal light polarization in the antisolar hemisphere performed by the Helios 1 and 2 spaceprobes were searched for variations and anomalies reported earlier from ground-based photometry. No change in polarized intensity or direction of polarization was found, the upper limit of a few S 10 or a few degrees simply decreasing with improving signal-to-noise ratio, with no obvious lower bound. The polarization pattern was found symmetric to the antisolar point. The angle of polarization is perpendicular to the scattering plane except for the viewing directions closest to the antisolar point ($\beta = \pm 16°$, $\varepsilon = 161°$) where there is a tendency for negative polarization. This impressively regular behaviour of zodiacal light polarization leaves no basis for exciting peculiarities and sheds some doubt on the reliability of those observations, which led to such claims.

Key words: zodiacal light photometry – zodiacal light polarization

1. Introduction

Observations of zodiacal light polarization in the antisolar hemisphere are difficult for ground-based observers because there the polarization is small and the disturbing atmospheric foreground and stellar background radiation are not much less than the zodiacal light. On the other hand, it is tempting to search for irregularities like night-to-night changes in polarized intensity or direction of polarization, or like non-zero polarization at the antisolar point and asymmetry of average zodiacal light polarization with respect to it. Such findings would have the far-reaching consequence that the interplanetary dust particles would have to be elongated and aligned, the latter property changing in degree and direction. The zodiacal light experiment on Helios 1 and 2 provided new data on zodiacal light polarization at large elongations over the period 1974–1979, which we searched for the effects mentioned above. As a space probe experiment it has the advantage to be completely free of airglow and disturbing atmospheric effects, while the continuous operation with a repetition cycle of 5 h allows to check and improve on the statistics of the experiment. Thus both reliable and precise data are obtained to which earlier reports on irregularities in zodiacal light polarization have to be confronted (Wolstencroft and Bandermann, 1973; Bandermann and Wolstencroft, 1974, 1976). As a by-product of the Helios observations we then are able to take position in the controversy (Sparrow and Weinberg, 1975; Bandermann and Wolstencroft, 1977) regarding those reports.

Send offprint requests to: C. Leinert

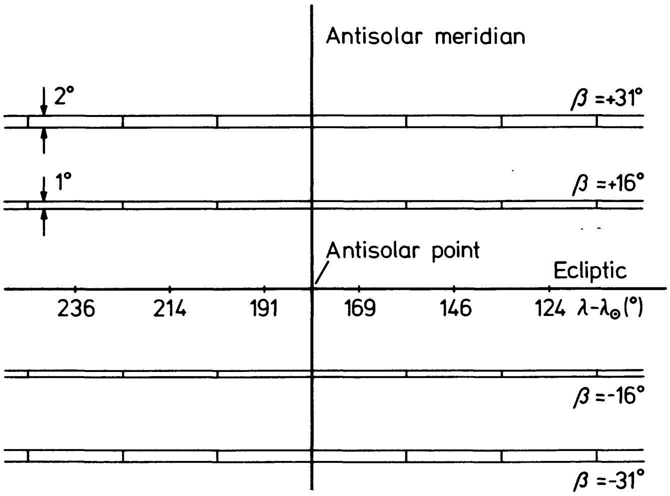

Fig. 1. Fields-of-view of the Helios experiment in the antisolar hemisphere. The length of the sectors is 22.°5. Note that the measurements at positive (Helios 2) and negative (Helios 1) latitudes are performed from different orbits and therefore different positions in space

2. Experiment and Data Reduction

Helios 1 was launched on December 10, 1974, Helios 2 on January 15, 1976. Their aphelia are at 0.98 A.U., their perihelia near 0.30 A.U. The experiment, its calibration and data reduction already have been described (Leinert et al., 1975, 1978, 1981a, b). On Helios 1 it scans the sky at constant ecliptic latitudes of $\beta = -16°$ and $\beta = -31°$, while Helios 2 surveys the same bands at positive latitude (see Fig. 1). The general brightness increase of the zodiacal light with decreasing heliocentric distance R is proportional to $R^{-2.3}$. This factor essentially was used to reduce the observations to 1 A.U. for comparison with earthbound observations.

Polarization is being measured by consecutive measurements through three polarizing foils oriented at 0°, 90°, and 45° with respect to the ecliptic. For a polarization at an angle θ to the ecliptic the polarized intensity $p \cdot I$ is obtained with an accuracy of

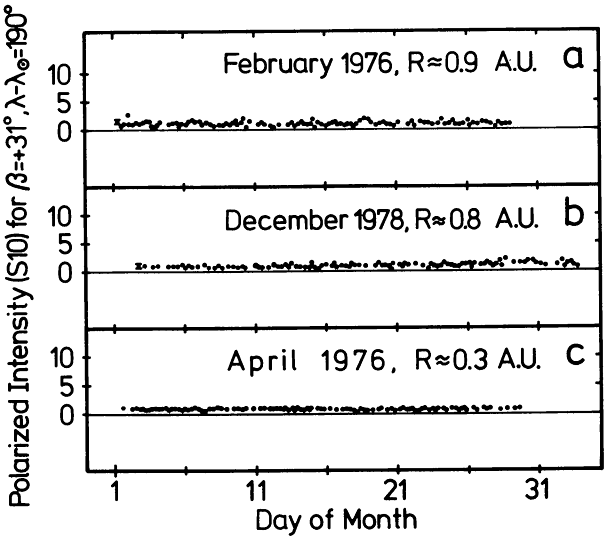

Fig. 2a–c. Three examples for the constancy of the polarized component of zodiacal light in the antisolar hemisphere. The error bars show the expected scatter due to photon statistics and dark current fluctuations while the actual scatter is ± 0.26, ± 0.23, and ± 0.07 S 10 for **a–c**, respectively. Zürich sunspot numbers are 13 for **a**, **c** and 118 for **b**. Intensities have been normalized to 1 A.U. by a factor $R^{2.3}$

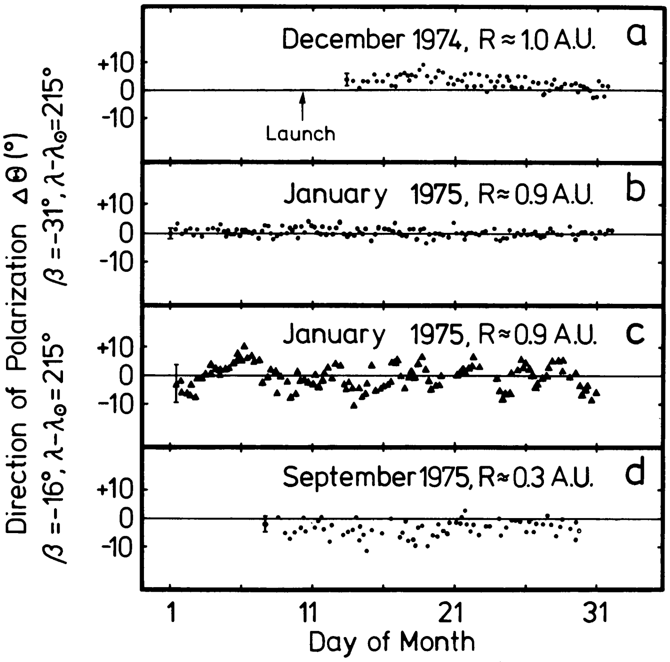

Fig. 3a–d. Four examples for the stability of the direction of zodiacal light polarization in the antisolar hemisphere. $\Delta\theta$ is measured counterclockwise from the expected direction perpendicular to the scattering plane. Error bars as in Fig. 1, the scatter of the data in **a–d** being $\pm 2\overset{\circ}{.}0$, $\pm 1\overset{\circ}{.}5$, $\pm 4\overset{\circ}{.}5$, and $\pm 2\overset{\circ}{.}6$

$$\Delta(pI) = \frac{\Delta M}{\sqrt{2}} \cdot [1 + 2\sin^2(2\theta)]^{1/2}, \tag{1}$$

where ΔM is the scatter of an individual measurement M. From this we have for $p \ll 1$

$$\Delta p = \frac{\Delta M}{\sqrt{2}\,M} \cdot [1 + 2\sin^2(2\theta)]^{1/2} \tag{2}$$

and, as well known,

$$\Delta\theta = \frac{1}{2}\,\frac{\Delta p}{p}. \tag{3}$$

Equations (1)–(3) were used to predict the scatter of the polarization data.

The absolute accuracy of the polarization measurements is more difficult to assess. Although the calibration was mainly done in the laboratory before launch, a correction had to be applied in order to have nominal direction of polarization for the viewing directions closest to the Sun. The justification for this correction, which was performed individually for each latitude band and each colour, is given in detail by Leinert et al. (1981b). A possible small error in this correction would have no effect on the time dependence of observed polarization, but could change the absolute values of polarized intensity or degree of polarization by ≤ 1 S 10 and $\leq 1\%$, respectively. However, the close symmetry between independent latitude bands at $\beta = \pm 16°$ and $\pm 30°$ suggests that the actual systematic accuracy of polarization measurements is considerably better than this.

Polarization of the zodiacal light was measured in U, B, and V. Since Bandermann and Wolstencroft measured at wavelengths of 508 nm and 530 nm, here we use only our visual observations ($\lambda_{\text{eff}} = 529$ nm). In blue and ultraviolet we have the same trends with slightly increased scatter.

3. Results

The zodiacal light experiment on Helios does not perform observations along the ecliptic. Therefore no contribution is possible concerning the alleged polarization at the antisolar point. However, the three other reported peculiarities can be confronted with the Helios observations.

3.1. *Variations in Polarized Intensity?*

Considerable changes in polarized intensity of the zodiacal light were reported by Wolstencroft and Bandermann (1973) from a comparison between the nights 14./15. June and 16./17. June, 19./20. June and 20./21. June 1969. For the Helios field-of-view at $\beta = +31°$, $\lambda - \lambda_\odot = 180°$–$202\overset{\circ}{.}5$ these changes happened to be particularly pronounced, exceeding 5 S 10 (equivalent number of *solar type* stars with $V = 10.0$ per square degree). Although one would not expect that possible changes be concentrated in one viewing direction, we choose to study the polarized intensity for this field-of-view in more detail. Figure 2 gives, for three months, all available individual measurements without averaging or smoothing. Two of the months were selected at heliocentric distances of Helios close to 1 A.U. in such a way that one of the corresponding Zürich Sunspot Numbers is larger than the value 106 for June 1969. The small variations appear to be due to the scatter expected because of dark current fluctuations. The values of the third

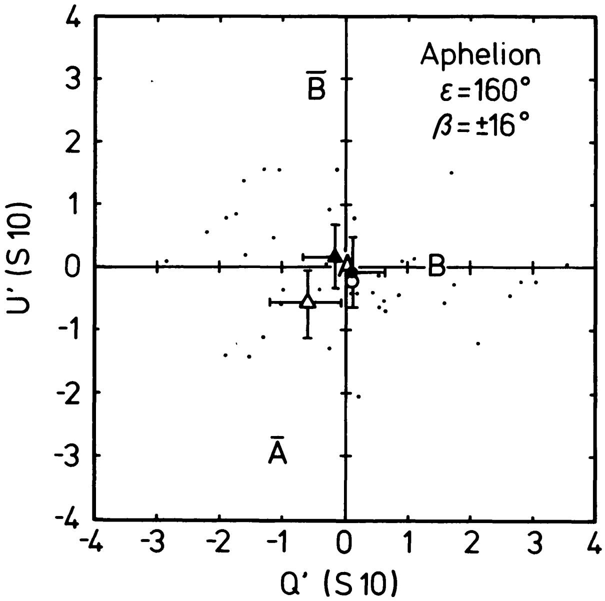

Fig. 4. Evidence for the symmetry of zodiacal light polarization with respect to the antisolar point. U', Q' refer to the deviation $\Delta\theta$ from the expected direction of polarization. The results of Bandermann and Wolstencroft (1976) are indicated for $\beta=+16°$ as $A(\lambda-\lambda_\odot=160°)$ and $B(\lambda-\lambda_\odot=191°)$, while $\bar{A}$ and $\bar{B}$ refer to the corresponding symmetric points. The averages of Helios measurements for these viewing directions are given in the same order by ●, ▲, ○, △. Error bars give the 3σ uncertainty of the mean. For the first of the Helios results, where the scatter was worst, we also show the daily values on which the result is based

month, centered around the first perihelion, support this judgement. Here the signal-to-noise ratio is better and the variations naturally get greatly reduced. A search through the four years of Helios 2 data for this field-of-view also showed no signs of real variations. This is typical for other fields-of-view, too. The data would look still smoother, if like Bandermann and Wolstencroft we decided to show daily averages.

3.2. Variations in Direction of Polarization?

Large ($\approx 30°$) changes in the direction of polarization from night to night were reported by Bandermann and Wolstencroft (1976), e. g. for the period September 25–October 4, 1974. The pattern was very extended but particularly clear in the direction of our fields-of-view at $\lambda-\lambda_\odot=202°.5$–$225°$, $\beta=-16°$ and $-31°$. We choose to present in Fig. 3 data for these two viewing directions. For the months shown here there appear to be no systematic variations in the polarization angle. The fluctuations of dark current, which are about ten times the expected value (see Leinert et al., 1981), are a problem for the photometer at $\beta=-16°$ with its small $1°\times 1°$ instantaneous field-of-view. Therefore for the month of January 1975 running averages over five individual measurements were plotted. Again with improving signal-to-noise ratio the scatter in the data is largely decreased, as shown by the individual perihelion measurements for the same viewing direction. A search through the data for $\lambda-\lambda_\odot\approx 210°$, as far as they were available on plots (one year of Helios 1, four years of Helios 2), also showed no angular variations really exceeding the scatter. It may be noted that our observation were performed only a few months after those of Bandermann and Wolstencroft and therefore refer to the same part of the solar cycle.

3.3. Asymmetry of Zodiacal Light Polarization?

The average zodiacal light polarization given by Bandermann and Wolstencroft (1976) for the period May 1973–November 1974 shows a pronounced asymmetry in the region of the antisolar point. While the polarization pattern is more or less regular north of the ecliptic, although somewhat distorted at small latitudes, there is a noticeable region with negative polarization (direction of polarization *in* the scattering plane) at negative latitudes. The largest negative polarizations of about 3 S 10 were reported for the antisolar meridian between $\beta=-10°$ and $-20°$.

Consequently we compare in Fig. 4 with the Helios observations at $\beta=\pm 16°$ the average of Bandermann and Wolstencroft's values given for $\beta=\pm 13°$ and $\beta=\pm 19°$ in the corresponding 22°.5-interval of $\lambda-\lambda_\odot$. Since polarizations are small close to the antisolar point, the Stokes Parameters Q and U were compared rather than the polarized intensities. Assuming symmetry with respect to the antisolar point, the values for $\beta=+16°$, $\lambda-\lambda_\odot=170°$ (A) and $\beta=-16°$, $\lambda-\lambda_\odot=190°$ ($\bar{A}$) and similarly B and $\bar{B}$ should coincide on this plot. Symmetry with respect to the ecliptic would require the coincidence of A with $\bar{B}$, B with $\bar{A}$. Obviously none of these symmetries is present in the Bandermann and Wolstencroft data, while the Helios monthly averages would be compatible with both.

Unfortunately the viewing directions shown in Fig. 4 happen to be those with the worst signal-to-noise ratio. This is apparent in the considerable scatter of the Helios daily (over five individual measurements) averages, ± 1.5 S 10 in Q' and ± 0.9 S 10 in U'. On the other hand, this scatter may be predicted with the help of Eq. (1), where the orientation of the plane of scattering is such, that θ takes the values 36° and 9°, respectively, when calculating $\Delta Q'$ and $\Delta U'$. The results, $\Delta Q'=\pm 1.5$ S 10, $\Delta U'=\pm 1.0$ S 10 are so similar to the observed scatter that the observed fluctuations may be considered as statistical and the monthly averages a good approximation to reality. Further evidence for this optimistic judgement is given by the perihelion data presented in Fig. 5. The improved signal-to-noise ratio naturally leads to a much reduced scatter of ± 0.1 S 10 in the daily averages. Negative polarization is indicated in the visual data presented here, to a lesser extent also in blue, but this marginal effect could also be due to a slight error in our polarization calibration.

After this detailed look at the surroundings of the antisolar point Table 1 gives a broader comparison of polarization north and south of the ecliptic. In averaging the values east and weast of the antisolar meridian it was assumed that polarizations are equal if they are symmetric with respect to that line. In comparing the values north and south of the ecliptic again symmetric polarizations were considered equal. Differing conventions would only change unimportant details. Bandermann and Wolstencroft's data show the north-south asymmetry mentioned above, particularly at $\varepsilon=161°$. Also their polarized intensities are quite high while those of Dumont and Sanchez (1976) are comparable to the Helios values. These, on the contrary, do show a remarkable symmetry of the monthly averages with respect to the ecliptic. The perihelion data suggest that this symmetry is getting the closer the more the

Table 1. Zodiacal light polarization at large elongations

		Helios Aphelion				Helios Perihelion				Bandermann and Wolstencroft			Dumont and Sanchez	
$\varepsilon(°)$	$\beta(°)$	$p(\%)$	$p \cdot I$	$\Delta\theta$	$N\text{–}S$	$p(\%)$	$p \cdot I$	$\Delta\theta$	$N\text{–}S$	$p \cdot I$	$\Delta\theta$	$N\text{–}S$	$p(\%)$	$p \cdot I$
161	+16	0.1	0.1	−55°		0.2	0.19	−73°		0.7	1°		≈0	≈0
	−16	0.3	0.3	−74°	0.3	0.2	0.21	68°	0.04	3.0	53°	2.9		
143	+16	2.5	2.4	2°		1.9	1.76	− 1°		5.7	− 5°		3.0	3.5
	−16	2.5	2.4	− 1°	0.1	2.1	1.89	1°	0.13	7.9	14°	2.9		
122	+16	8.0	7.7	2°		5.9	5.51	0°		15.7	1°		7.0	8.2
	−16	8.7	8.0	− 1°	0.5	6.1	5.73	1°	0.23	17.2	5°	3.8		
147	+31°	1.7	1.4	− 6°		1.2	0.93	− 6°		3.6	− 4°		2.5	2.5
	−31°	2.5	2.2	− 2°	0.9	1.6	1.29	2°	0.39	2.7	36°	3.5		
135	+31°	5.1	4.3	− 2°		3.6	2.64	−3°		8.3	− 3°		5.0	4.5
	−31°	5.0	4.3	1°	0.5	3.8	2.91	1°	0.34	10.1	15°	4.1		
118	+31°	9.8	8.5	0°		7.2	5.58	− 2°		16.4	1°		8.2	7.0
	−31°	9.4	7.8	0°	0.7	7.3	5.80	1°	0.27	18.0	6°	4.4		

$p \cdot I$ is given in S 10, normalized to 1 A.U. by the factor $R^{2.3}$
$N\text{–}S$ is the difference in polarization between points symmetric to the ecliptic in S 10

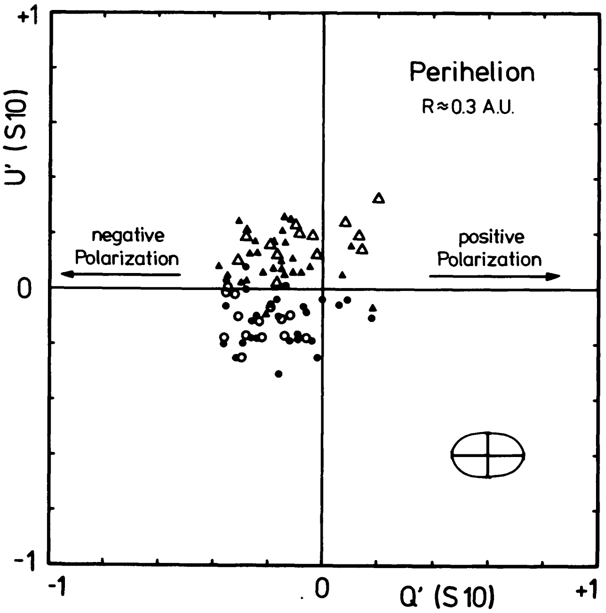

Fig. 5. Symmetry of zodiacal light polarization with respect to the antisolar point as observed for the months of perihelion April 1976 (●, ▲, $\beta = +16°$) and September 1975 (○, △, $\beta = -16°$). For each viewing direction (see Fig. 3) daily values are given, normalized to 1 A.U. by the factor $R^{2.3}$. Symmetry is present when corresponding closed and open symbols coincide. At lower right the average scatter within each data group (cross) is compared to expectation (ellipse)

signal-to-noise ratio is improving. We therefore expect this symmetry to hold also for shorter time intervals and we expect that observed deviations rather reflect the difficulty of the measurements than a lack of symmetry. – For a discussion of the decrease of polarization towards perihelion see Leinert et al. (1981b).

4. Discussion

Three difficulties inherent in our presentation should be mentioned.

First, sometimes there are considerable changes also in the Helios data. We did not mention this in the preceding section because they do not appear to be related to zodiacal light. A small number of isolated spikes of up to 50 S 10 occurred during the mission, which are considered as telemetry errors. Very bright stars in the field.of-view distort the measurements as well as the strongly enhanced dark current during solar flares. During 1978 and 1979, with the rising activity of the solar cycle, plasma clouds were detected in the viewing directions close to the Sun, recognizable by their high polarization and the simultaneous changes in intensity.

Second, the measurements north and south of the ecliptic (Helios 2 and Helios 1, respectively) were not made simultaneously and not from the same position in space. Here we rely on the cylindrical symmetry of the zodiacal cloud and on the stability of zodiacal light, which is quite striking in the Helios data. We feel that the symmetry of zodiacal light polarization obtained under these conditions from two independent spacecraft is not less convincing than if it were obtained from a single simultaneous measurement.

The third difficulty is that the Helios observations were made at a different time, and therefore are not directly comparable to Bandermann and Wolstencrofts measurements. Changes with time could be made responsible for the different results. But we find such an ad-hoc assumption unconvincing. Whatever caused the variations in their measurements, we take the position that the Helios observations reflect the true steady character of the zodiacal light and the interplanetary dust cloud.

5. Conclusion

In summary we conclude:

1. The direction of zodiacal light polarization is nominal (perpendicular to the scattering plane), except perhaps within 20° of the antisolar point.

2. Within the accuracy of a few degrees there are no changes in the direction of zodiacal light polarization.

3. Within the accuracy of less than 1 S10 the average polarization of zodiacal light at large elongations is symmetric to the antisolar point and to the ecliptic.

4. Within the accuracy of about 1 S10 there are no changes in the polarized intensity of zodiacal light at large elongations.

5. The observed symmetry and regularity of the zodiacal light gets the more pronounced the more the signal-to-noise ratio is improving. The interplanetary dust cloud appears to be a quite smooth and steady complex.

These findings leave no basis for the exciting peculiarities in zodiacal light polarization reported earlier and question the reliability of those ground-based observation which led to such claims.

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