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Zodiacal light observed by Helios throughout solar cycle No. 21: stable dust and varying plasma

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Summary. The zodiacal light observations performed by the Helios space probes covered a period of more than 11 years, from December 1974 through February 1986. During this time no variation in zodiacal light brightness was detected, with limits of ±2% for secular variations. However, the density of solar wind at high heliographic latitudes showed a strong enhancement during the maximum of solar cycle.

Key words: Zodiacal light – interplanetary dust – solar wind – Helios space probes

1. Introduction

Variations in zodiacal light brightness normally would result from changes in the number, orientation or surface properties of interplanetary dust particles, and therefore are related to physical processes and dynamical forces acting on interplanetary dust. The frequent claims of variability in earlier observations (e.g. Robley, 1980; review in Leinert, 1975) may reflect the difficulty to perform precise zodiacal light observations from the ground. The Helios spacecraft, launched in 1974 and 1976, offered an excellent opportunity to monitor the brightness of zodiacal light free from atmospheric disturbances. The data show a remarkable stability of both brightness and polarization of zodiacal light (Richter et al., 1982; Leinert et al., 1982a, b). The present paper strengthens and extends this conclusion by using the complete time interval, for which data available, from December 1974 through February 1986, when the signals of Helios 1 no longer reached the earth. With a minor shift this corresponds to the total extent of solar cycle No. 21.

2. Instrument and data

The description of the zodiacal light experiment on Helios (Leinert et al., 1975, 1981b) and the data reduction (Leinert et al., 1981a) will not be repeated here. Of the total of six photometers on the two space probes we present data obtained with Helios 1 at an ecliptic latitude of −16°, because none of the other photometers covered the whole time interval: with Helios 2, giving measurements at positive ecliptic latitudes, the spacecraft failed in its fourth year; the measurements at the south ecliptic pole were corrupted by the large Magellanic cloud; the photometer looking at ecliptic latitude of −30° had its photomultiplier broken by thermal stresses when the aging spacecraft no longer could provide the necessary heating in the cold parts of the orbit. The data presented below were taken in $B(\lambda_{\mathrm{eff}} = 429\,\mathrm{nm})$ and refer to polarization parallel to the ecliptic. This choice was dictated by the positions, in which the filter wheels got stuck after a few years.

To emphasize the reliability of the data shown below let us note that the zodiacal light photometer on Helios was a simple, well calibrated, repeatable instrument, which had good straylight suppression.

Simple: The imaging was done with a minimum of optical elements, one objective lens and one field lens, both quite thin. The field of view of $1° \times 1°$ (for the photometer under consideration) was unvignetted and precisely known, as was the slight nonlinearity of the photon counting photomultiplier and its temperature dependence.

Well calibrated: Absolute preflight calibration allowed to predict the counts due to bright stars, and the in flight observations agreed to this prediction within ±5%. Actually, a small systematic discrepancy was evident which could be made disappear by assuming that the *U–B* and *B–V* colours of the sun were redder by 5% than assumed (Leinert et al., 1981b). Indeed, this assumption was shown to be true soon after by Tüg and Schmidt-Kaler (1982). This demonstrates good consistency between preflight and in-flight measurements.

Repeatable: Repeated preflight testing showed that repeatability after switch off/on would be a particular strength of this instrument, since the contractor Dornier System exceeded the 1% specification by a factor of about ten. Long-term stability is best shown by the data below. In particular the repeated measurements on the bright star α CMi (Fig. 2) suggest that the sensitivity of the corresponding photometer did not change by more than 1% over a decade of measurements.

Stray light suppression: Laboratory tests showed that in flight the stray light contribution due to scattered sunlight should be less than a few percent even in the most unfavorable geometric

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Send offprint requests to: Ch. Leinert conditions (Leinert and Klüppelberg, 1974). Attitude maneuvers during the first weeks of the mission showed that the instrument performed even better (Leinert et al., 1981b).

We therefore expect the instrument to be largely free of spurious disturbances and to be well suited to look for variations in zodiacal light.

3. Results

Figure 1 shows the about 7000 individual measurements at $\varepsilon = 63°$, $\beta = -16°$, $\lambda - \lambda_{\odot} = -62°$. These represent the full data set, with no points rejected and no averaging or smoothing applied. The data have been corrected to a position of the observer at 1 AU in the symmetry plane of the dust, taken to have inclination $i = 87°$ and node $\Omega = 87°$ in the inner solar system. This correction has been used earlier (Leinert et al., 1982) and given in tedious detail in the description of data tapes delivered to the World Science Data Center at Goddard. If the corrections were perfect and if the zodiacal light was constant, the dots would all fall on the reference line at 150 S 10 [1] or have the same distance from it. This is approximately the case. Almost every deviation has an identifiable reason, enumerated in the figure caption, mostly the excess count rate due to solar flare protons. For one event the reason is unknown. In a similar, smaller data set for Helios 2 (Richter et al., 1982) also one event was classified unknown. This has now been shown to have been due to comet West (Jackson, private communication).

In Fig. 1, points at different heliocentric longitude of Helios were measured at different heliocentric distances, against a different stellar background and in different positions relative to the symmetry plane of dust. This may explain a large part of the remaining low frequency variations. However, points lying on the same vertical line through the diagram all do refer to the same heliocentric longitude and therefore have these circumstances in common and are truly comparable. Intercomparing such measurements we almost entirely get rid of any possible flaws in the above-mentioned corrections. We use such groups of data to look into the longterm variation of zodiacal light.

The result is given in Fig. 2. The different symbols refer to different lonitudes of Helios, to the just mentioned groups of comparable data. The upper part of the diagram gives the measurements over the south pole of the sun at ecliptic latitude $-16°$. The middle section derives from Fig. 1. As a test on instrument sensitivity we present stellar calibrations in the lower panel. Each group of zodiacal light measurements was normalized to the average during the first three years. The measurements of α CMi were not normalized; also a correction for the heliocentric position of Helios is not necessary in this case. The predicted signal was 0.78 mag. The lines shown in Fig. 2 are fits through all available data points, excluding only the plasma events marked by "*e*". For the quantitative discussion below, which only includes "comparable" data groups before and after solar maximum, therefore slightly different slopes apply.

The results of the other photometers (except for that looking to the south ecliptic pole, where the data were not fully reduced) are essentially the same. Indeed they are also suited to study the changes due to interplanetary plasma. But, because of their shorter time basis, and because the end of their measurements falls into the period of solar maximum, these data do not give measurements of zodiacal light stability of the same quality as those data presented above.

4. Discussion

Two effects are evident in Fig. 2: a good stability of the stellar measurements and of the zodiacal light at large elongations and a brightness increase close to the sun during the years of solar maximum (1979–1981). This increase is due to Thompson scattering by electrons of the interplanetary plasma. This could be shown by colour and polarization of the excess light. It confirms our earlier finding (Richter et al., 1982) that during solar maximum the interplanetary plasma densities at high heliographic latitudes nearly double. But only now we can show that densities return to normal at the following minimum again. A similar effect, but only of the order of 2% may also occur at elongation $\varepsilon = 63°$. It would be interesting to see how the mass flux and energy flux of solar wind change over the poles with solar cycle and compare with the few similar attempts available (Lallement et al., 1985; Schwenn, 1983). To this end we will combine our data with velocity measurements derived from interplanetary scintillations (Jackson and Schwenn, 1988).

The stability of the underlying zodiacal light brightness over the interval of more than 11 years is evident. Comparing the measurements 1984–1986 with those obtained 1975–1977 in the same viewing directions, the resulting changes at $\varepsilon = 16°$, $\varepsilon = 63°$ and for the star α CMi are $+0.3 \pm 1.0\%$, $0.0 \pm 0.7\%$, and $+0.8 \pm 1.0\%$, respectively, where 3σ errors are given. The maximum difference between fit lines, for $\varepsilon = 63°$ against α CMi, amounts to 0.8% per 11 years, the average scatter of the data points around the fits being $\pm 0.7\%$. We conclude that we detected no long-term changes of zodiacal light within the accuracy of our measurement. An upper limit for secular variability of $\pm 1.5\%$ results from the numbers given above. A secular change of more than $\pm 2\%$ safely can be excluded. As expected, space observations allowed to improve on the limit of 10% given by Dumont and Levasseur-Regourd (1978) as the result of well-reduced ground-based observations over one solar cycle.

Grün et al. (1985) have argued that collisions in interplanetary space do produce an excess of interplanetary dust, leading at 1 AU to 10% increase of dust density in 3000 yr, while at 0.1 AU in the ecliptic the time scale reduces to 30 yr. The Helios measurements at elongation $\varepsilon = 16°$ approach the sun to 0.08 AU in perihelion. Much of the observed brightness comes from the regions closest to the sun. The data points shown in Fig. 2 refer to Helios positions somewhat farther away, but the line of sight still goes to 0.12 AU. The upper limit of zodiacal light changes of 2% therefore may be compared to the predicted increase in dust.

The two values more or less are compatible, but the zodiacal light observations indicate that the predicted dust production by collisions should be considered an upper limit.

Essentially the Helios experiment detected no zodiacal light variations at all. This does not exclude the possiblitiy of changes at other times and in other places in particular at higher than our $1° \times 5.6°$ effective spatial resolution. But it sets the standards that an experiment reporting on zodiacal light variations and the associated physical processes first should prove that it is able to recognize a constant brightness as such.

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[1] 1 S 10 (solar type star of 10 mag per square degree): except for slightly different assumptions on solar colour it is identical with the unit S_{10} (V) (Weinberg and Sparrow, 1978)

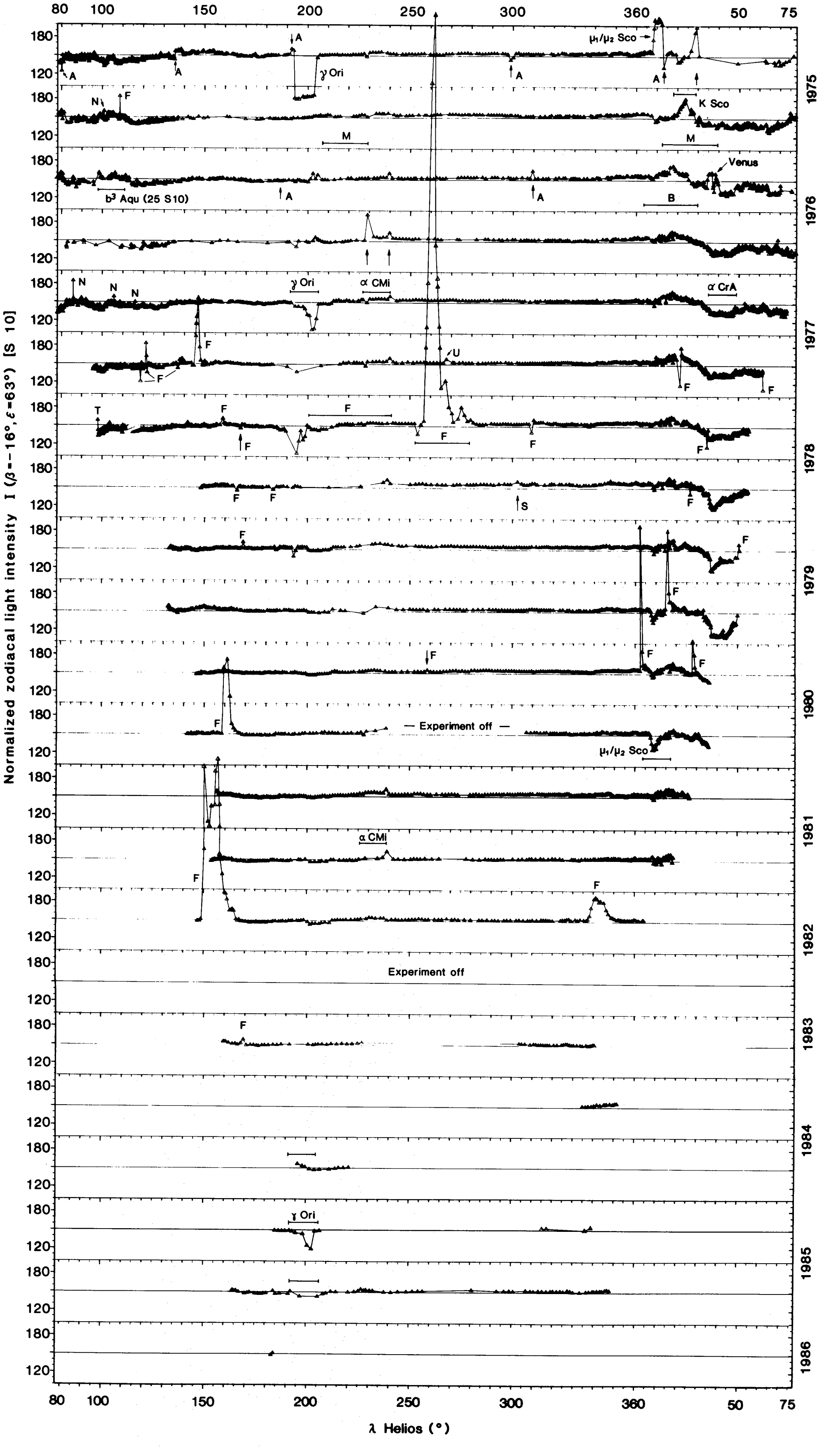

Fig. 1. Summary of all individual zodiacal light observations obtained by Helios 1 at $\beta = -16°$, $\varepsilon = 63°$, $\lambda - \lambda_{\odot} = -62°$. Each box corresponds to one orbit. Known disturbances are indicated. A = altitude maneuver, B = star brighter than 150 S 10 in field-of-view, F = increased dark current due to solar flare, M = Milky Way background brighter than 150 S 10, N = single noise spike, S = switch on of cold experiment, T = wrong temperature adopted, U = unknown reason. Astronomical sources repeat from orbit to orbit. For several brighter stars we indicated. A = attitude maneuver, the field of view. 1 S 10 corresponds to $1.02\ 10^{-9}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}\,\AA^{-1}}$ for our bandpass ($\lambda_{\mathrm{eff}} = 429$ nm)

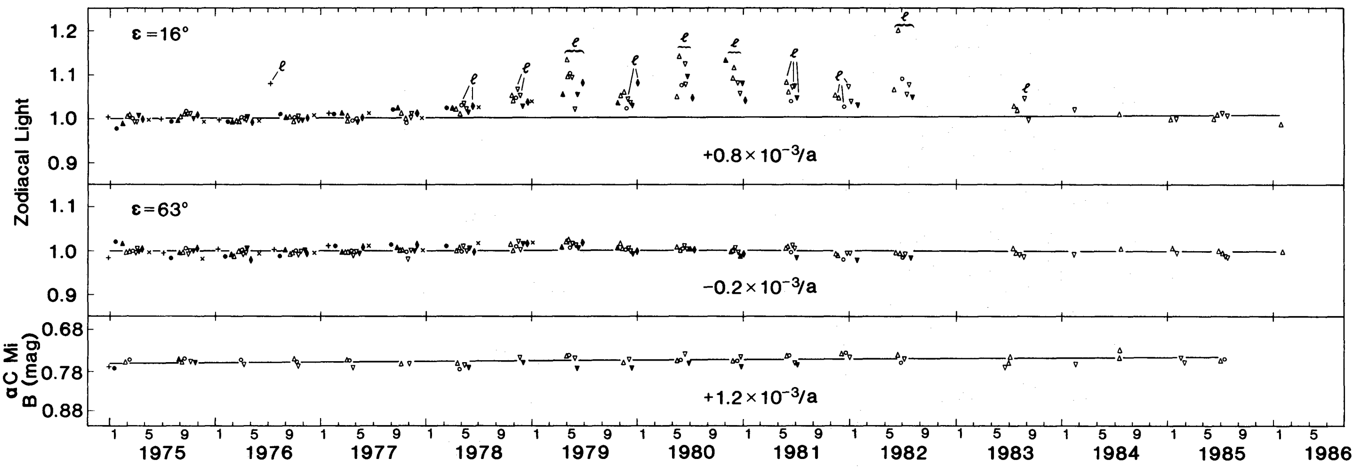

Fig. 2. Relative brightness of zodiacal light observed with Helios 1 at $\beta = -16°$ from December 1974 through February 1986. "*e*" designates disturbances induced by interplanetary plasma clouds. As a measure of instrument stability the observations of the star α CMi are shown to the same scale

5. Conclusion

1. The zodiacal light is remarkably stable. No definite temporal variation could be found.

2. Long term zodiacal light observations like those on Helios have reached an accuracy where they start to constrain collisional models for interplanetary dust.

3. Zodiacal light observations can be used to detect solar cycle changes of average solar wind densities out of the ecliptic.

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