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Icarus 203 (2009) 124-133

Contents lists available at ScienceDirect

Icarus



journal homepage: www.elsevier.com/locate/icarus

Measurements of the Gegenschein brightness from the Solar Mass Ejection Imager (SMEI)

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ARTICLE INFO

Article history: Received 14 January 2009 Revised 22 April 2009 Accepted 28 April 2009 Available online 9 May 2009

Keywords: Zodiacal light Photometry Interplanetary dust

ABSTRACT

The Gegenschein is viewed by the Solar Mass Ejection Imager (SMEI), which has provided near-full-sky broadband visible-light photometric maps for over 5 years. These have an angular resolution of about 0.5° and differential photometric stability of about 1% throughout this time. When individual bright stars are removed from the maps and an empirical sidereal background subtracted, the residue is dominated by the zodiacal light. The unprecedented sky coverage and duration of these measurements enables a definitive characterization of the Gegenschein. This article describes the analysis method for these data, presents a movie with time of the Gegenschein brightness distribution, determines empirical formulae describing its average shape, and discusses its variation with time. These measurements unambiguously confirm previous reports that the Gegenschein surface-brightness distribution has a decided peak in the antisolar point, which rises above a broader background.

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1. Introduction

The visible-light Gegenschein is a diffuse glow in the night sky centered upon Earth's antisolar point. It is caused by Sunlight backscattering from the zodiacal dust particles. Qualitative descriptions date back more than a century (e.g., see Minnaert (1954) and the historical sketch and references provided by Roosen (1970)). More recent measurements and discussion have focused on the nature of the reflecting material, its scattering phase function and its distribution in the Solar System, with particular focus on its distance from Earth (Roosen, 1970; Weinberg et al., 1973; Muinonen, 1993). A dependable characterization of the Gegenschein when combined with a proper scattering phase function would enable a detailed characterization of the distribution of this material. This article presents a series of new Gegenschein measurements from the Solar Mass Ejection Imager (SMEI) in Earth orbit on board the Air Force Coriolis satellite (Eyles et al., 2003; Jackson et al., 2004). Its location above the atmosphere and 24-h sky coverage produced a long time series of Gegenschein measurements since February 2003, only occasionally interrupted by periodic calibrations and data outages.

2. SMEI observations and data analyses

The Coriolis satellite is in a Sun-synchronous circular polar 840km altitude orbit with an inclination of 98°. SMEI was designed to detect Coronal Mass Ejections (CMEs, e.g., Jackson et al., 2004; Tappin et al., 2004; Webb et al., 2006) early enough to forecast their arrival at the Earth. SMEI consists of three CCD cameras that collectively view a $\sim 160^{\circ} \log \times 3^{\circ}$ wide strip of sky oriented such that the long axis spans solar elongation. Thus, nominally, 85% of the sky is swept out each 102-min orbit. Individual SMEI data frames are read out every 4 s for each camera; these data frames obtained from one orbit are combined into a photometric sky map of nearly the entire sky. The observations and analysis reported herein are taken from "camera 1" only, which covers about half of the antisolar hemisphere at large elongation angles from the Sun. The field of view (FOV) of this camera is slightly tilted with respect to the orbital axis, which is at -8.8° declination and right ascension (RA) opposite to that of the Sun (solar RA plus 12^h). This tilt produces a hole in the camera 1 sky coverage. Fig. 1a illustrates how the SMEI data frames combine to yield sky coverage with outer and inner diameters of 130° and 10°, respectively. This area moves about 1° per day in RA during the course of a year, thus covering a 130°-wide band of sky along the equator. The antisolar location moves relative to the orbital axis, its annual path tracing out an analemma.

The cameras' wavelength-dependent response is roughly triangular with a maximum at 0.7 μ m linearly tapering to zero at 0.4 μ m and

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^{0019-1035/\$ -} see front matter © 2009 Elsevier Inc. All rights reserved. doi:10.1016/j.icarus.2009.04.007

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Fig. 1. Skymaps for 21 April 2003. Individual bright stars, a residual sidereal background, and part of the zodiacal light *Z* (Eqs. (1)–(4) in the text) are all subtracted. The 0.97 factor which matches to camera 2 is not included. (a) A sampling of data to illustrate how the SMEI FOV sweeps over this portion of sky. (b) Same orbit as (a), but including all data. At this time the Moon is just off to the left of the image, and rejection of stray light from it creates a slice in the map. (c) Two orbits earlier, *Coriolis* is passing through the South Atlantic Anomaly (SAA) whose contamination removes another slice of the map above that of the Moon. (d) Median-filtered skymap for this day, 15 maps contributing. In these maps, West is to the left: this is the reverse of the more familiar Sun-centered case. Note in the median map that the gap due to the Moon has closed, auroral contamination has become barely visible, and there is no residue of the SAA.

at 1.1 μ m. The solar-spectrum-weighted mean wavelength is 0.70 μ m and the full-width-at-half maximum is 0.35 μ m. The point-spread function is complex (see Fig. 8 in Eyles et al. (2003)), but has about a 0.5° diameter extent. The short-term differential photometric precision is 0.1% over most of the sky, but degrades near bright stars or the Moon, during periods of bright aurora (Mizuno et al., 2005) or when auroral electrons or South Atlantic Anomaly (SAA) protons impact the CCD (Buffington et al., 2006a).

The SMEI data are originally recorded in the form of per-pixel electron counts from the CCD detector that are labeled analog-todigital units (ADUs) in the various SMEI publications. Buffington et al. (2007) have calibrated the SMEI camera responses using 17 bright stars having a range of spectral types, in order to relate the SMEI photometric brightness scale to that of the Large Angle and Spectrometric COronagraph (LASCO) C3 instrument (Morrill et al., 2006). From this they also derive a surface brightness of one S10s (the equivalent brightness of one 10th visual-magnitude G-type star spread over one square degree, see Leinert et al., 1998; Cox, 2000) in a SMEI sky map corresponds to 0.46 ± 0.02 ADUs.¹

¹ It is emphasized that the conversion to S10s surface-brightness units in the context of other instruments may require a significant adjustment to account for differing band passes (Buffington et al., 2007). Moreover, the wide SMEI bandpass averages over any structures that may have strong spectral features.

At the beginning of the mission the multiplicative normalization factor ("gain factor") to match camera 1 to camera 2 was found to be 0.97. Tracking the apparent brightness versus time, of portions of sky along the Galactic disk, the responsivity of both cameras 1 and 2 diminished on average by about 1% per year. On the other hand, the bright center of the galaxy diminished by only 0.6% per year, while darker sky diminished by 1.6% per year. The latter value was used for the Buffington et al. (2007) calibration. A 1% per year value is the best compromise for the present work. When combining cameras or (as here) reporting surface-brightness measurements we use "normalized camera 2 units", referring to camera 2 at "mission start time" (taken at the start of year 2003). This takes into account the gain differences between the cameras at mission start, and the decrease in responsivity with time.

The first step in using these skymaps for seeing faint heliospheric features consists of separately fitting and subtracting several thousand bright stars and a fainter-star background from individual $0.1^{\circ} \times 0.1^{\circ}$ bins in equatorial coordinates (Hick et al., 2005, 2007). For the present analysis, we also subtract a model (described below) for the zodiacal-light contribution that does not include the "Gegenschein enhancement". The residual sky maps are then presented in Sun-centered ecliptic coordinates, which are binned to an angular image pixel of $0.5^{\circ} \times 0.5^{\circ}$. The zodiacal surfacebrightness model, *Z*, is somewhat arbitrarily parameterized to match and thus, when subtracted, remove the observed zodiacallight contribution all around the edge of camera 1's FOV (where it joins camera 2) to within a few ADUs, throughout the year.

The subtracted zodiacal brightness model, in units of the above "normalized" SMEI ADUs, here takes the form

$$Z = (R/R_0)^{-2.3} \times (Z_1 + Z_2 + Z_3).$$
(1)

Here *R* is the Sun–Earth distance, and $R_0 = 1$ AU. We use the dependence on Earth–Sun distance from Cox (2000). For an ecliptic longitude and latitude $[\lambda, \beta]$ (all angles are in degrees):

$$Z_1 = 7 + 8(1 - \cos b) + \{65 + 120c + 154c^2 + 88c^3\} \\ \times 10^{-\sin b/(0.009 \times (\varepsilon + 40))}.$$
(2)

Here ε is the solar elongation, $c = \cos \varepsilon = \cos(\lambda - \lambda_{Sun}) \times \cos \beta$, $b = 1.5 \times \left(\sqrt{1 + (\beta/1.5)^2} - 1\right)$, and λ_{Sun} is the solar ecliptic longitude relative to the vernal equinox. The hyperbolic expression *b* is

used to avoid a cusp and its attendant discontinuity in the derivative at $\beta = 0$ inherent using an exponential term. The values for most parameters were derived from a preliminary analysis of the whitelight components observed primarily in the antisolar hemisphere using data from all SMEI cameras (Buffington et al., 2006b). The second contribution is a Gaussian band Z_2 centered on the ecliptic plane:

$$Z_2 = 6e^{-\beta^2/512}.$$
 (3)

Finally, an enhancement, Z_3 , accounts for the small inclination of the plane of symmetry of the zodiacal dust with the ecliptic plane:

$$Z_3 = 6|\sin(\lambda_{\text{Sun}} - \Omega)|\sin(180 - \varepsilon). \tag{4}$$

The symmetry plane's ascending node is at an ecliptic longitude Ω = 78.25° (Leinert et al., 1998; Cox, 2000). For 0° $\leq \lambda_{Sun} - \Omega \leq 180°$ (during summer and spring) the Earth is above the plane of symmetry; at these times the zodiacal brightness in the antisolar hemisphere is biased to the South, and hence the Z_3 contribution is added just to the southern hemisphere. For $180° \leq \lambda_{Sun} - \Omega \leq 360°$ (during winter and autumn), the Earth is below the plane of symmetry; the zodiacal brightness is biased to the North, and hence Z_3 is only applied to the northern hemisphere. The $|\sin(\lambda_{Sun} - \Omega)|$ term in Eq. (4) term guarantees that the contribution be always

positive. To avoid an abrupt transition, the edge of the enhancement is "feathered" over $\pm 5^{\circ}$ centered at the ecliptic plane. In most of the sky, the contribution from Z_1 dominates that of Z_2 and Z_3 . Finally, total Z (Eq. (1)) is subtracted from the measured surface brightness at the given location: this produces a measured residual that is taken here as the Gegenschein contribution.

This parameterization of the zodiacal light (Buffington et al., 2006b) given by Eqs. (2)–(4) is currently being developed further as the analysis is extended to all the SMEI data including the sunward hemisphere. The antisolar hemisphere parameterization presented here is not expected to change significantly. Moreover, the large characteristic angular scale of this zodiacal-light removal has little effect on the detailed Gegenschein structure presented here. Annual variation in background is affected by Eq. (1)'s correction for distance from the Sun, and subtracting Z_3 removes some apparent Gegenschein motion.

Although we have done our best to reduce contamination from particle hits and auroral light while creating individual SMEI sky maps, inevitably some contamination remains. Fig. 1b and c illustrate this for a couple of orbits with minimal but non-zero contamination from the Moon. These contamination residuals must be further reduced in order to isolate and best analyze heliospheric features such as the Gegenschein. This reduction is accomplished by median filtering and selectively combining a day's worth of sky maps in which at least five good maps for a day are required out of a possible 14 or 15. Anomalous large responses in each of the maps are deleted in determining the median response for each map bin. The value in a bin is the average of all the responses below this median; this somewhat unusual procedure takes advantage of the fact that almost all contaminated sky bins have a larger (rather than smaller) apparent brightness. Fig. 1d shows the result of this filtering for this day. Similar processing yields 1722 daily maps between 6 February 2003 and 17 September 2008. These maps have been assembled into a 5.6-year movie, scaled to S10s units, and are provided as supplemental material with this article. The movies are presented with both a black-towhite scale and a false-color scale. These can also be found on the SMEI website at http://smei.ucsd.edu/gegenschein.html.

3. Surface-brightness distribution of the Gegenschein enhancement

Fig. 2 shows the result of averaging 1722 median-filtered individual-day maps. These are simply stacked together in antisolar coordinates, and then each bin averaged separately. Fig. 3 presents orthogonal profiles through this distribution along the antisolar ecliptic longitude ($\tilde{\lambda} = \lambda - \lambda_{\text{Sun}} - 180^{\circ}$) and ecliptic latitude (β) axes. Also shown are the empirically-determined fits, given in Eqs. (5) and (6), of the sum of two exponentials to these profiles. Taking $\tilde{\varepsilon} = 180 - \varepsilon$ as the antisolar elongation of a given map location, then:

$$G_{\ell} = 7.5e^{-\tilde{\epsilon}/4} + 39.5e^{-\tilde{\epsilon}/25},\tag{5}$$

$$G_{\tilde{\lambda}} = 7.5e^{-\tilde{\epsilon}/4} + 39.5e^{-\tilde{\epsilon}/35}.$$
 (6)

For these two profiles, $\tilde{\epsilon}$ is, respectively, the absolute value of the appropriate ecliptic latitude β (for Eq. (5)) or the antisolar ecliptic longitude $\tilde{\lambda}$ (for Eq. (6)). To extend these formulae to all locations covered by Fig. 2, we define $G_{\text{tot}}(\tilde{\lambda}, \beta)$:

$$G_{\text{tot}}(\tilde{\lambda},\beta) = (1 - 0.02(\beta\tilde{\lambda})^2/\tilde{\varepsilon}^3) \times (\beta^2 G_\beta + \tilde{\lambda}^2 G_{\tilde{\lambda}})/\tilde{\varepsilon}^2.$$
(7)

Here $\cos \tilde{e} = \cos \beta \times \cos \tilde{\lambda}$. This distribution is shown in Fig. 4. These equations provide an excellent match to the measured distribution in Fig. 2. As noted in Section 2, to convert the ADUs of these figures and equations to S10s surface-brightness units consists simply of

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Fig. 2. Contour plot of stacked antisolar median-filtered average maps for 1722 days from 6 February 2003 to 17 September 2008. The distribution peaks at 46 ADUs. Conversion of ADUs to S10s units consists simply of dividing by 0.46 (see text).



Fig. 3. Distribution of responses along the major axes of Fig. 2, together with empirical formulae (Eqs. (5) and (6), respectively) which fit these two distributions. The right-hand scale shows ADU brightness scaled to S10s.

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Fig. 4. Contour plot of the Gegenschein enhancement model from Eqs. (5)-(7).

dividing them by 0.46. The supplemental material also includes an enhanced-contrast movie with Eqs. (5)–(7) subtracted.

Noah and Noah (2001) describe a zodiacal model that we compare to the SMEI observations. This model, called "CBZodi", assumes that zodiacal-dust density is proportional to the inverse of the heliocentric distance (1/R) and employs a Lorentz function for the out-of-the-plane distribution (Clark et al., 1993). The center of the cloud is offset from the Sun (Dermott et al., 1992; Kelsall et al., 1998) and a 4 AU cutoff boundary is assumed for the cloud (van Dijk et al., 1988; Hovenier and Bosma, 1991). The cloud is assumed to have both an inner and outer plane of symmetry, each of which has a separate inclination and longitude of the ascending node. The inner plane extends from the Sun to 1.02 AU. Within this volume the zodiacal dust cloud is placed centered upon this plane instead of upon the ecliptic plane. Analogously, the second plane extends from 1.02 AU to 4 AU, and governs the dust cloud placement over this range of distances. Since the two planes do not smoothly join at 1.02 AU, the densities of the two planes are averaged together near 1.02 AU to produce a smooth transition at the joint. This smoothing over the density normalizations produces a circumsolar ring at 1.02 AU, just outside the orbit of the Earth (Jackson and Zook, 1989; Dermott et al., 1994; Reach et al., 1995). The model also includes small density enhancements in this ring leading and trailing the Earth to match the East-West asymmetry observed in the infrared observations (e.g., Reach, 1991). The model also includes the Reach et al. (1995) migrating dust bands. The model uses the three-term Henyey-Greenstein scattering function of Hong (1985), who fit this function's predicted integrated zodiacal brightness to the observations at Tenerife (Dumont and Sánchez, 1975) to derive its parameters. The scattering function has been modified as specified by van Dijk et al. (1988) to account for the finite dust cloud assumed by the model. Results of a comparison of the CBZodi calculation with the above SMEI measurements are presented in Section 5.

4. Variation of the Gegenschein brightness with time

Eq. (7) describes the Gegenschein enhancement of the zodiacal light shown in Fig. 4 for an average spanning 5.6 years of SMEI data. Maps analogous to Figs. 2 and 3, but averaged over separate two-month intervals, were examined to search for seasonal changes in the Gegenschein shape, but no significant changes appeared. Also, no residual annual motion of the Gegenschein central bright spot was seen once the seasonal variation due to the inclination of the plane of symmetry of the zodiacal dust with the ecliptic plane was removed (Z_3 , Eq. (4)). In the absence of such motion, averaging the response within a $3^\circ \times 3^\circ$ square centered on the antisolar point and folding time by day-of-year (DOY) provides a quick and simple means of observing potential annual changes in the Gegenschein. The result is shown in Fig. 5.

The $3^{\circ} \times 3^{\circ}$ square method (Fig. 5) is quite noisy, and of course also contains whatever large-angular-scale variable background, including an overall change in background, may be present. A better method consists of least-squares fitting Eq. (7) to the data within an entire $45^{\circ} \times 45^{\circ}$ map, with two free parameters: for each map, a scale factor *M* for Eq. (7) and a constant offset *N*. These two parameters were here varied to minimize the formula shown by Eq. (8):

$$\chi^{2} = \sum_{\tilde{\lambda},\beta} \left[\left(\text{Observed response at } \tilde{\lambda}, \beta \right) - MG_{\text{tot}} \left(\tilde{\lambda}, \beta \right) - N \right]^{2}.$$
(8)

This summation over all bins increases the systematic noise in N and especially M when the Moon is within the map or nearby.

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Fig. 5. Surface-brightness average over a $3^{\circ} \times 3^{\circ}$ square centered on the antisolar point, versus day of year (DOY). Subsequent years are shown in different colors. Passage of the Galactic Center (around DOY 170) marks increased systematic noise from the sidereal subtraction. Twice per year as shown, the hole in the FOV passes over this particular square, resulting in a reduced average response. The "running average" is smoothed over one week. The right-hand scale shows brightness scaled to \$10\$ suits.

However, the program making the sky maps sets to zero most of those portions of the sky affected by the Moon. Thus the majority of these maps are easily flagged and removed by requiring that the number of contributing non-zero pixels be close to that expected. Time-series results for the minimized χ^2 and associated *N* and *M* $G_{tot}(0,0)$, are shown in Figs. 6–8, with elapsed time folded to DOY as in Fig. 5.

5. Discussion and conclusions

In attempting to isolate a "Gegenschein enhancement" to the zodiacal light, ambiguity inevitably arises when assigning and then subtracting relatively-slowly-varying functions such as Eqs. (2)-(4). The subtracted portion of the zodiacal light appears to be dominated by the actual global distribution of the dust, while the enhancement, as described by Eqs. (5)-(7), is "extra" due to the scattering phase function and the geometry of the scattering. Although these two alone may dominate along the ecliptic, along lines of constant $\hat{\lambda}$ for $|\hat{\lambda}| < 45^{\circ}$, the fall off in the dust distribution with increasing latitude $|\beta|$ is an important additional factor. Thus in Fig. 3, the brightness distribution along β changes significantly with how much "background" is subtracted: subtract more and the wings of this curve drop down, subtract less and they broaden out. The equations are of course constrained not to exceed the observed brightness over any large section of sky, but a considerable range remains of acceptable parameter values, particularly the leading constant in Eq. (2). We chose the value of 7 to enable the slope set by the $e^{-\tilde{\epsilon}/25}$ in Eq. (5) for the range $15^{\circ} < |\beta| < 30^{\circ}$ to continue down unchanged for $30^{\circ} < |\beta| < 45^{\circ}$. We have no theoretical expectation that this slope should follow such an exponential, and have noted previously that the choice of this constant also leads to, or can be used to remove, a systematic offset when comparing with other measurements.

Over the years, many authors have reported peak Gegenschein brightnesses. Leinert et al. (1998) and Kwon et al. (2004) each pro-

vide a tabulated result, the former also in the widely-available "Astrophysical Quantities" (Cox, 2000). Fig. 9 compares Kwon et al. (2004) with the results of the present work, the fitted results from SMEI white-light observations. For this plot alone, 3.5 ADUs (7.6 S10s) have been added to the leading constant in Eq. (2) to match the Kwon et al. (2004) brightness value of 157 at the antisolar point, and also off this graph near the ecliptic poles. Except for a further offset of about 20 S10s, the agreement is generally quite good. Such a systematic difference is hardly surprising, considering the unavoidable ambiguity in assigning an overall brightness as being due to illuminated zodiacal dust nearby the Earth, or to a contribution everywhere from the sidereal sky. Sky coverage for SMEI camera 1 is fragmentary for $|\beta|$ or $|\tilde{\lambda}| > 45^{\circ}$ and zodiacal-light results in the remainder of sky await a more complete analysis (currently in preparation by the present authors) using data from all three cameras to supplant our preliminary results (Buffington et al., 2006b).

Both Leinert et al. (1998) and Dumont and Sánchez (1975) report a peak brightness of 180 S10s in the antisolar direction, while the average result for the present work is 157. We note also that James et al. (1997) report a brightness excess of 40 ± 5 S10s when comparing the Gegenschein peak brightness with a "background" located roughly at $(\tilde{\lambda}, \beta) = (12.5^\circ, 6^\circ)$. Our observed brightness (Fig. 2) drops by 21–22 ADUs for these angles; this, divided by the above 0.46 ± 0.02 conversion factor, yields 47 ± 2 S10s, in adequate agreement with the James et al. (1997) measurement.

Most previous measurements of the Gegenschein have taken place around October or March when the Gegenschein is farthest removed from the Galactic plane. Roosen (1970) reports no shift at these times in latitude or longitude of the center of the Gegenschein, down to a formal error of 0.03° . In contrast, Mukai et al. (2003) report a shift in position of maximum brightness from +0.1° to about -0.4° relative to the β = 0 plane in November 1997, once they had taken into account the effects of the asteroidal dust bands (Ishiguro et al., 1998, and references cited therein). This A. Buffington et al. / Icarus 203 (2009) 124-133



Fig. 6. A plot of χ^2 divided by the number of bins contributing (~30,000) versus DOY, resulting from the minimization of Eq. (8), for the daily maps from SMEI. Subsequent years are shown in different colors. Broad χ^2/f peaks near mid- and end-year are expected, since the Galactic plane transits camera 1 at these times and uncertainty in the subtraction increases systematic noise. This is particularly evident as the Milky Way galactic center passes close to the antisolar point, and χ^2/f becomes sensitive to the time-dependent uncertainty in camera 1 responsivity for this bright portion of the sky.



Fig. 7. Offset *N* versus DOY. Like χ^2/f , the offset *N* varies systematically over the course of a year. Little or no year-to-year change in *N* can be discerned. The annual variation, typically 4 ADUs peak-to-peak, could be due either to an actual variation with DOY of the large-scale content of the zodiacal light, or to a residual in the sidereal-sky subtraction. A portion of the brightness variation with DOY, for the 3° × 3° square shown in Fig. 5, can be attributed to a contribution from *N*. As with Fig. 5, the right-hand scale here is brightness scaled to S10.

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Fig. 8. Fitted peak brightness MG_{tot}(0,0) of the Gegenschein enhancement versus DOY. Considerable structure through the course of a year is visible with features lasting typically a month. Anything shorter than this duration is not expected, as this is the time for a structure to move across the ±15° full-width-at-half-maximum of the upper curve (along longitude) in Fig. 3. Most features repeat from year to year, but $MG_{tot}(0,0)$ exhibits considerably more year-to-year variability than do either χ^2/f or N. The several-ADU increase with time near the Galactic Center (DOY 170) is likely a systematic residual error, given this bright sky, in the changing camera 1 response versus time. Again, the right-hand scale is ADU brightness scaled to S10s.





Fig. 9. Comparison of the results of Kwon et al. (2004) with the fitted $MG_{tot}(\tilde{\lambda},\beta)$ combined with Eqs. (1)–(3). Contours here are S10s. The results of Leinert et al. (1998) and those of Kwon et al. (2004) are very similar. The SMEI measured ADUs of surface brightness have been converted to \$10s by dividing by 0.46, as discussed in Section 2, and increased by 7.6 S10s as discussed in Section 5.

shift they ascribe to the Earth's location at that time of year relative to the tipped symmetry plane of the zodiacal light. Observing shifts this small is difficult here given the 0.5° sky-map bin size and the broadness of the Gegenschein distribution itself (Fig. 3). The effect of the tipped plane has been mostly removed, so no shift is expected here, nor do we see one.

A significant feature of the observations presented here is the sharp peak in the center of the Gegenschein, an "opposition effect"

described by the 7.5 $e^{-\tilde{\epsilon}/4}$ term in both Eqs. (5) and (6). The peak's small angular scale has little susceptibility to the subtractive uncertainties described above and is thus a dependable feature of the present measurements. Roosen (1970) reports no opposition effect for backscatter from zodiacal dust, but his measurements are limited to $|\beta| < 5^{\circ}$, so would include both contributing terms in Eq. (5). His average curve applied to our peak brightness of 172 S10s would predict at $\beta = \pm 5^{\circ}$ that we see the brightness drop by about 15 S10s (to about 36 ADUs). If we use his larger total brightness of 210 S10s (which includes some sidereal-sky light) the drop is 18 S10s (to about 35 ADUs). Reading from Fig. 3 or using Eq. (5), we observe 31.5 ADUs. Comparable total brightness measurements and drops are reported by Dumont and Sánchez (1975) observed at Tenerife from 1964 to 1972. These authors highlight a "concentration of the glow" toward the antisolar point in their observations, with an increase of about 20 S10s in the last 5° along the ecliptic. SMEI observations (Eq. (6)) indicate an increase of about 23 S10s over this range, a good agreement.

This sharpness of the peak might have been missed in some previous measurements because at $\tilde{\epsilon} = 0^{\circ}$ it represents only a 14% additional contribution over the much larger and broader background beneath it. Obscuration could enter also from an inevitably bumpy sidereal background and, for ground-based measurements, from changing structure in the mesospheric airglow.

Although the individual-day values in Fig. 5 scatter substantially more than those in Fig. 8, both of these figures have similar features. These figures agree even better if the distribution for *N* (Fig. 7) is subtracted from the $3^{\circ} \times 3^{\circ}$ square data (Fig. 5). Some of these features repeat from year to year. Except near the Galactic Center, both figures display an annual brightness distribution that repeats well for years 2003–2008 over the range 110 < DOY < 240, but has a monotonically decreasing brightness with time from outside of this range. The distribution for *N* in Fig. 7 shows a similar effect. Figs. 5 and 8 become even more similar if the *N*-distribution is subtracted from Fig. 5. This could be justified considering that *N* is a fitted flat background under the Gegenschein distribution which should thus also lie beneath the square-spot brightness shown in Fig. 5. In any case, the Gegenschein brightness reaches a local maximum near DOY 330 for both of these figures. These similar results from both analysis techniques allay a concern that the effect might instead be an annually repeating instrumental artifact, caused by a changing camera 1 response as the Gegenschein enhancement moves over the FOV. This concern is further relieved by SMEI's excellent coverage of the Gegenschein enhancement throughout this time, and its observed unchanging distribution shape. Camera 1's FOV usually includes the antisolar point, and extends in all directions to $\tilde{\epsilon}$ well beyond the 22–30° latitude and longitude 1/*e* half-widths of this feature. Figs. 5, 7 and 8 all indicate a somewhat brighter Gegenschein enhancement and sky background near the end of the year compared with mid-year. Maucherat et al. (1986) report a similar brightening in blue light at about this time of year, although with considerably fewer data than here.

Fig. 10 compares the latitude and longitude profiles from the empirical model described in Section 3 with the brightness averaged over a year as predicted by the CBZodi model. The agreement is quite good, except that the CBZodi model does not display the sharp peak in the antisolar direction, a consequence of adopting a Henyey–Greenstein expression for the scattering function. To address this deficiency, we introduce a backscatter function (Helfenstein et al., 1997) having the form $1 + B_s/(1 + (1/h_s)\tan(\alpha/2))$, where α is the phase angle (zero in the antisolar direction) and h_s is the characteristic width. The characteristic width of the backscatter function that fit the excess was found to be 0.032, corresponding to about 1.83° while the amplitude is 17 ADUs or roughly 35 S10s.

In conclusion, we note also that the supplemental movies mentioned in Sections 2 and 3 demonstrate that an original SMEI objective, namely a series of photometric sky maps good over most of the sky to about one S10s over a time period of years, has now been achieved. Here, the only empirically determined time-dependent parameter for the subtracted background is the 1% per year diminishing slope of camera 1 responsivity versus time. Summarizing the present work, this article presents:

- (1) A substantial number of SMEI photometric sky maps spanning several years, and concentrating on the antisolar portion of sky.
- (2) A subtraction procedure which removes from these, the bright stars and other sidereal background.



Fig. 10. The longitude and latitude profiles of the Gegenschein enhancement derived by SMEI (solid black) are compared to the predictions from the three-dimensional CBZodi model. By its nature, the Henyey–Greenstein scattering function used in the three-dimensional model (large dashes) does not have a peak. When the Helfenstein et al. (1997) term is included (small dashes), the peak is matched very well.

- (3) A data analysis sequence which next creates daily-average maps, and in the process removes the majority of unwanted photometric artifacts (particle contamination, aurorae, stray light from the Moon).
- (4) A further subtraction of empirically modeled zodiacal light.

The zodiacal light model explicitly does not include the Gegenschein enhancement, which is easily visible in the resultant daily maps. The combined average of these maps is then characterized and fit to simple equations. The Gegenschein has a sharp inner peak, is without seasonal variation in its location at the antisolar point, but varies by ~10% of its intensity over time, with a portion of the variation repeating seasonally.

Acknowledgments

SMEI was designed and constructed by a team of scientists and engineers from the US Air Force Research Laboratory, the University of California at San Diego, Boston College, Boston University, and the University of Birmingham, UK. The work of B.V. Jackson, A. Buffington, P.P. Hick, and UCSD student J.M. Clover was supported at the University of California at San Diego by NSF Grant ATM-0331513 and NASA Grants NAG5-134543 and NNG05GG45G. Post-doctoral fellow M.M. Bisi was supported in part by AFOSR Grant FA9550-06-1-0107. Support at AFRL for this work was provided in part from the NASA Planetary Geology & Geophysics program, Request # NNH06AE67I. The authors thank K. Grogan and K. Greist for useful discussions.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.icarus.2009.04.007.

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