Solar Oblateness, Excess Brightness, and Relativity*

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New observations show a small difference between the sun's polar and equatorial limb darkening functions. This excess equatorial brightness varies in time and can be of sufficient magnitude to account for the solar oblateness inferred by Dicke and Goldenberg from their measurements. This removes the serious consequence of their work for Einstein's general theory of relativity. The problems of a solar-edge definition and the derivation of a solar mass quadrupole moment are discussed.

Solar oblateness was first associated with relativity when Newcomb[1] suggested that an oblateness of 500 arc msec would explain the discrepancy between the prediction of Newtonian gravitational theory and the perihelion advance of Mercury observed by Leverrier.[2] But different experiments (see Poor[3] for a review) claimed that the solar oblateness $\Delta_\odot$ was less than 100, 50, and 10 arc msec, the latter value from a 22-yr period of observations. In a crucial prediction, Einstein's general theory of relativity accounted for the observed perihelion advance.

In 1967, Dicke and Goldenberg[4] published the results of their solar-oblateness observations which not only disagreed with previous work but were of sufficient magnitude to change the conclusions from the Mercury-perihelion test of gravitation theories. As pointed out by Dicke[5] in a recent review of the matter, this work led to the publication of many papers attempting to interpret the results as other than a solar mass quadrupole moment. Dicke concludes that none of these alternate interpretations of the oblateness signals can survive close experimental and/or theoretical scrutiny.

In order to measure solar oblateness, there must be, at least implicitly, a definition of the sun's edge. That definition should identify a unique point on the limb darkening curve, i.e., the intensity of the solar disk as a function of radius. However, the point defined will be influenced by solar activity, the earth's atmosphere, and the instrument. A simple difference of observed equatorial and polar diameters will yield only an apparent oblateness in which the intrinsic shape may be masked.

In order to test gravitation theories, a solar mass quadrupole moment must be inferred from the apparent solar oblateness. The logical progression to be followed is (1) apparent solar diameters are measured with some solar-edge definition, (2) an intrinsic oblateness of the visual sun is extracted from the measurement, and (3) gravitational equipotential surfaces are then derived from the intrinsic solar oblateness.

Upon examination of the three-step sequence, the second step appears to be the most fragile link. Inspection of the papers proposing alternative interpretations of the Dicke-Goldenberg data and of the responses reveals a debate over the extraction of an intrinsic visual shape from the apparent shape. The Dicke-Goldenberg edge definition makes it difficult to distinguish between an intrinsic oblateness and a small difference in the shape of the limb darkening function between equator and pole, i.e., an excess equatorial brightness. The available information is inadequate to support strong arguments rejecting the suggested brightness mechanisms.[6] Further these brightness mechanisms might complicate the third step through the introduction of stresses.

Several studies have looked for temperature differences between pole and equator.[7] For various reasons, the work to date has not clearly supported or rejected many of the proposed brightness mechanisms.

To deal with the above difficulties, the solar-oblateness program at SCLERA[8] was designed not only to yield another oblateness measurement but also to test observationally for an excess brightness. This led to the development[9] of the finite-Fourier-transform definition (FFTD) of the solar edge. The principal advantages of the FFTD are (1) high sensitivity to the shape of the limb darkening function and (2) low sensitivity to terrestrial atmospheric "seeing." The high sensitivity to limb darkening shape enables the direct observation of excess brightness and localized active regions without reliance on solar atmosphere models or other observations. Global differences between equatorial and polar limb darkening can be distinguished from local activity by a persistence longer than several days. The low sensitivity of the FFTD to "seeing" reduces the diameter variations due to seeing fluctuations by an order of magnitude from those of the Dicke-Goldenberg edge definition for the condition of the current experiment.

The solar edge in the FFTD is defined as the radial distance q from the sun's center such that the following finite Fourier transform is zero:

$$F(G; q, a) = \int_{-1/2}^{1/2} G(q + a\sin(\pi s))\cos(2\pi s)\,ds, \quad (1)$$

where s is a dummy variable, G is the observed limb darkening profile, and the parameter a determines the extent of the solar limb used in the edge definition. The FFTD is easily implemented by scanning the image of the solar limb sinusoidally across a slit, computing the Fourier transform of the slit signal, and then servoing the slit position until $F=0$. The parameter a is the scan amplitude and s equals $\omega t/2\pi$, where $\omega/2\pi$ is the scan frequency and t the time.

When $F(G; q, a)=0$, the a dependence of q can be used to look for an excess equatorial brightness. If the limb darkening function G differs from equator to pole, then $q(a)$ will vary, an oblateness will be observed, and the oblateness will depend on a. So the measure of excess brightness used is

$$E(a_1, a_2) = [D_e(a_2) - D_p(a_2)] - [D_e(a_1) - D_p(a_1)], \quad (2)$$

where D_e and D_p are the equatorial and polar diameters, respectively, and a_1 and a_2 are two different scan amplitudes. The quantity $E(a_1, a_2)$ is actually the finite Fourier transform of the excess equatorial brightness.[9]

The solar-oblateness measurements reported here were made on the SCLERA telescope. Described in detail by Oleson *et al.*,[10] the telescope is designed to measure the gravitational deflection of starlight passing near the sun. This astrometric instrument of coronagraphic quality is readily adapted to solar-oblateness measurements by design, because the starlight deflection program uses the sun's diameter as a scale reference.

The solar-oblateness detector basically consists of two parallel slits located at diametrically opposed edges of the solar image and positioned in the radial direction by transducers. For the FFTD, the solar image is scanned sinusoidally across the slits. Below each slit is a filter to pass an 8-nm band centered at 550 nm and a photomultiplier to measure the solar light intensity. The dimensions of the slit are 1 arc sec in the radial direction and 100 arc sec in the direction tangential to the solar edge. Changes in slit position are measured interferometrically. The detector can be rotated so that any particular diameter can be examined.

A measurement of E involved the measurement of the four diameters in Eq. (2) in a sequence that constituted two oblateness measurements with different scan amplitudes but at the same average time. Since E is the difference of these two oblateness measurements, systematic errors are sharply reduced. Consequently, the solar contribution $E_\odot$ to E is easily obtained after a small correction.[11]

During one three-week period in September 1973 and another in November and December 1973, observations were made with $a_1 = 6.8$ arc sec and $a_2 = 27.2$ arc sec. The values of $E_\odot$ obtained during these periods are shown in Fig. 1. The error bars represent a standard deviation based on the standard deviations of diameter measurements.

Data yielding approximately the same value for $E_\odot(a_1, a_2)$ as those of November were obtained in June and July of 1972. However because of the limited amount of data and a long delay between observations at different scan amplitudes, this result was made available only in unpublished works.[12] Although this 1972 result could only suggest the existence of an excess brightness, those data strengthen the conclusions to be drawn from the 1973 results in Fig. 1.

These conclusions are (1) an excess equatorial brightness exists as a result of a difference in

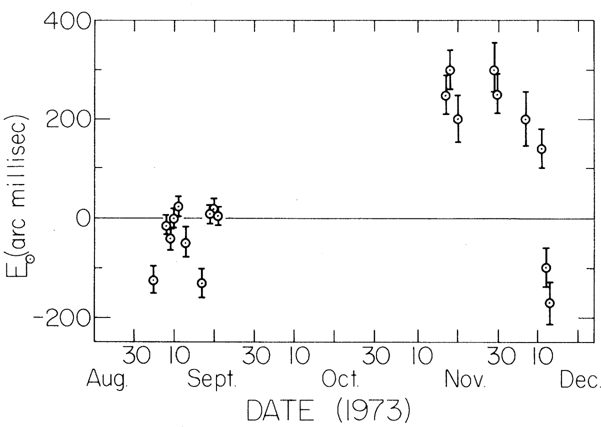

FIG. 1. The excess-equatorial-brightness measure $E_\odot$ as a function of time. The transition from the low level of September to the high level of November and December indicates the long-term variability of $E_\odot$. The persistence of these levels for $\approx \frac{3}{4}$ of a solar rotation manifests their global nature. Local (short-lifetime) structure occurs 5 and 17 September and 11 December.

shape between equatorial and polar limb darkening functions, which is compatible with excess-brightness models,[6] and incompatible with Dicke's conclusions; and (2) the magnitude of the brightness varies with a lifetime of months or longer.

This first conclusion follows from the nonzero value of $E_\odot$ for three weeks in November and December. Since the solar rotation period is ~27 days at the equator, this value of $E_\odot$ *must* represent some global property. Localized structure appears briefly 5 and 17 September and more dramatically beginning 11 December—all corroborated by solar-patrol photographs. These examples illustrate the sensitivity of $E_\odot$ to changes in the limb darkening function and the distinction between local and global effects by their lifetimes.

The second conclusion, concerning the temporal behavior of the excess brightness, is drawn from Fig. 1. The global value of $E_\odot$ changed from essentially zero in September to approximately 225 arc msec two months later, from which a lifetime of months or longer is deduced.

With use of the properties of the FFTD and any of the excess-brightness models referenced,[6] the percentage intensity differences between equator and pole implied by the excess brightness can be obtained from $E_\odot$ and can be less than 1%. Until the radial properties of the excess brightness are known, these intensity differences impede the extraction of an intrinsic visual oblateness from an apparent oblateness obtained with *either* the FFTD or the Dicke-Goldenberg integral definition of the sun's edge. However, when the excess brightness is understood, an intrinsic visual shape can be extracted from the FFTD measurements through the parameter $E_\odot$ while data obtained with the integral definition cannot be recovered for want of an excess-brightness measure. Further, the cited excess-brightness models (not now excluded by the work of Altrock and Canfield[7]) with the November-December value for $E_\odot$ would predict for a Dicke-Goldenberg type of measurement a solar-oblateness signal as large as they reported. Consequently the extraction of a new mass quadrupole cannot progress beyond the second step with Dicke-Goldenberg and earlier observations. Further, the execution of step (3) is frustrated by the uncertainty surrounding the brightness mechanism.

The immediate impact of the current work removes the relevance of all earlier solar-oblateness observations to tests of gravitation theories. In addition, since different edge definitions have different sensitivities to excess brightness, discrepancies may be expected in general among Dicke-Goldenberg and earlier results.

Examination of Fig. 1 shows that the excess brightness was sufficiently low in September to permit the extraction of the intrinsic visual oblateness *without reliance on an excess-brightness model.* A value of $\Delta_\odot = 1.84 \pm 12.5$ arc msec is presented in another paper.[11] This new solar-oblateness result is consistent with the 16 arc msec expected for a uniformly rotating sun. The incompatibility with the Dicke-Goldenberg result is easily reconciled by the excess equatorial brightness.

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Search for $\Delta I = 2$ Electromagnetic Currents in Pion Photoproduction

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Differential cross sections for the reactions $\gamma p \to \pi^0 p, \pi^+ n$ and $\gamma n \to \pi^- p, \pi^0 n$ were measured in a single experiment using tagged photons in the energy region 240–450 MeV incident on $^1H_2$ and $^2H_2$ targets. Results of the measurements of the ratios $\pi^0 n/\pi^0 p$ and $\pi^- p/\pi^+ n$ are presented. The ratio of isotensor to isovector amplitude is found to be 0.00 ± 0.02.

The violation of isospin invariance in electromagnetic interactions has traditionally been limited to $\Delta I \leq 1$. This minimal violation conforms to an SU(3) U-spin singlet structure for the photon. The validity of this selection rule has been questioned[1] on the basis of existing data on charged-pion photoproduction and the inverse reaction $\pi^- p \to \gamma n$ in the first resonance region. In this region, the dominating $I = \frac{3}{2}$ resonance enables a sensitive test for a $\Delta I = 2$ term to be made. Since neutral-pion photoproduction is almost completely dominated by the $\Delta(1236)$, the effect of an isotensor component is larger (relative to the more model-dependent nonresonant terms) than in the charged-pion case. The ratio

$$\frac{d\sigma(\gamma n \to \pi^0 n)/d\Omega}{d\sigma(\gamma p \to \pi^0 p)/d\Omega},$$

which is expected to be slowly varying and close to 1 in the first resonance region on the assumption of $\Delta I \leq 1$, thus provides a sensitive and rather model-independent test of the isotensor hypothesis.

In the present experiment all the low-energy photoproduction reactions were measured simultaneously by using the same apparatus with both a hydrogen and a deuterium target, thus eliminating most normalization and energy-scale problems. In addition, the use of a tagged photon beam simplified the detection apparatus and eliminated the inherent problems of an untagged bremsstrahlung beam. Hence a strong degree of constraint exists among the various reactions such that it is not possible to alter one yield very much without affecting others in a similar way.