Reports

Observations of a Probable Change in the Solar Radius Between 1715 and 1979

Abstract. *Solar eclipses were observed from locations near both edges of the paths of totality in England in 1715, in Australia in 1976, and in North America in 1979. Analysis of these observations shows that the solar radius has contracted by 0.34 ± 0.2 arc second in 264 years.*

On the basis of extensive transit circle observations, Eddy and Boornazian (*1*) reported the detection of a large secular decrease of the solar radius, at a rate of approximately 1 arc second (0.1 percent) per century. This result was entirely unexpected on theoretical grounds (*2*). Sofia *et al.* (*3*) had already examined most of the transit data used by Eddy and Boornazian to derive information about changes of the solar constant from changes of the solar radius. Their conclusion, however, was that any secular change in the solar radius in the past century could not have exceeded 0.25 arc second. The disagreement was due to the different criteria used by the two groups to select what they considered reliable data. Since these criteria are somewhat subjective, the disagreement could most convincingly be settled by independent measurements.

One such independent measurement was provided by Shapiro (*4*), who analyzed observations of 23 transits of Mercury between 1736 and 1973 and concluded that any secular solar radius decrease was below 0.15 arc second per century. Another, more sensitive, independent measurement can be made by a technique proposed by Dunham and Dunham (*5*). This method extracts solar radius information from a determination of the edges of the paths of totality of solar eclipses by means of timed observations made just inside the path edges. In this report we present the results obtained when this technique is applied to the solar eclipses of 1715, 1976, and 1979. We find no appreciable change in the solar radius between 1976 and 1979; however, the solar radius determined for 1715 is 0.34 arc second larger than the recent values, a difference that could have important climatic consequences (*3*).

Because of the circular shape of the umbral shadow, the duration of totality for an observer near an edge of the path of totality is very sensitive to his exact distance from the actual edge. The duration of totality for the 26 February 1979 eclipse is plotted for different distances from the edge of the path in Fig. 1. An observer about 1/2 mile from the actual edge of the path would have a total eclipse lasting 15 seconds. If the observer timed the duration of totality to an accuracy of ± 2 seconds, he would determine his position with respect to the true limit to about ± 0.15 mile. Because of the geometry of the 1979 eclipse, this positional uncertainty translates to only ± 0.06 arc second for the determination of the relative positions and apparent radii of the sun and the moon. Hence, accurate results can be obtained by visual observation with simple timing equipment. If there were many observers, one might report only an instant of totality, while another a short distance farther from the center line would report no totality, with one bead of sunlight shining through a lunar valley at maximum eclipse. Timings do not need to be made by such close pairs of observers to accurately fix the location of the eclipse path.

The time scales for lunar surface changes are so long that the moon's size and shape can be assumed to be constant over periods of centuries. But our corrections to the solar radius derived from eclipse observations cannot be compared directly with other measurements since ultimately they are made relative to the bottoms of particular valleys along the moon's limb. Because of the changing lunar orientation (libration), the equatorial part of the lunar profile changes considerably from eclipse to eclipse. Analyses of lunar occultation data show that errors in the heights of individual lunar features specified by Watts's study of the lunar profile (*6*) and libration-dependent systematic errors in the reference datum (*7*) can amount to about 0.5 arc second. These problems directly affect the many accurately timed observations made near the center of the path of totality. Hence, such observations cannot yield accurate solar radius data. However, topography in the polar regions of the moon determines the contact points at locations near the edges of the path of totality. During each eclipse, the libration in latitude, on which the polar lunar profile is almost solely dependent, is within 1° of 0°. Hence, virtually the same features are presented in profile near the lunar poles at each eclipse. This reduces by an order of magnitude the problems associated with errors in Watts's lunar limb data for comparison of results obtained near the path edges at different eclipses. In particular, the difference in topocentric librations, both in longitude and latitude, was only about 0.°1 from the 1715 eclipse to the 1979 eclipse. Moreover, knowledge of limb features in the polar areas can be refined by observations of grazing occultations of stars. Grazes cannot occur in nonpolar areas of the moon.

We have shown that ephemeris uncertainties produce an error of ± 0.02 arc second in the determination of the relative solar and lunar radii for the 1715 eclipse in England (*8*). This is considerably less than the observational uncertainties, the main one being caused by the fact that the sun's photosphere does not have a perfectly sharp boundary. However, at visual wavelengths, the gradient of the specific intensity of radiation is very steep at the edge of the photosphere and, at maximum, the intensity drops by a factor of about 10,000 in 1 arc second of radial distance, or 2.5 in 0.1 arc second (*9, 10*). At a distance of 0.5 arc second from the maximum, the in-

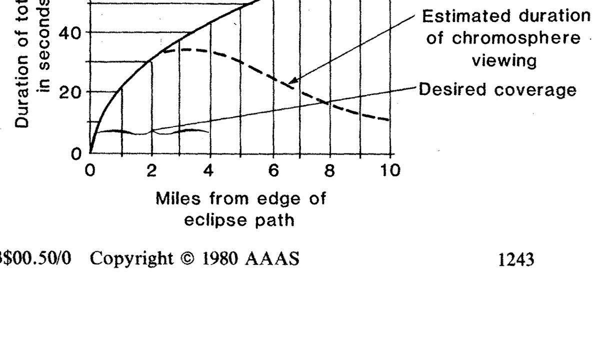

Fig. 1. Duration of totality as a function of distance from the edges of the path of the 26 February 1979 total eclipse. The data were computed by R. Linkletter for longitude 120°W, but changed only slightly along the path across North America.

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tensity gradient is only 0.1 per arc second. The consistency of results from different stations indicates that the relative position of the lunar and solar edges was usually individually determined to an accuracy better than 0.1 arc second. This accuracy has been confirmed by the separations of pairs of path-edge-bracketing observations made during the eclipses of 1979, 1925 (*11*), and 1715.

During the solar eclipses of 23 October 1976 and 26 February 1979, members of the International Occultation Timing Association (IOTA) observed near both edges of the path of totality (*12, 13*). Several timings were made of Baily's beads phenomena produced when the shrinking solar crescent was broken by lunar mountains (*14*). Care was taken to time the disappearance of the last photospheric bead of light marking the start of totality (second contact), and the emergence of the first bead when totality ended (third contact). Corrections to the radius of the sun derived from these observations are given in Table 1. Those corrections are to be added to the sun's radius used for all three eclipse calculations (959.63 arc seconds at a distance of exactly 1 astronomical unit), but with the understanding that the absolute (not relative) values include the uncertainty of ± 0.5 arc second for individual lunar features discussed above.

Instantaneous totalities have been reported by observers at either the northern or the southern limit of some earlier eclipses. Thanks to the promotional efforts of Sir Edmond Halley, such observations were reported at both edges of the path of the 3 May 1715 total solar eclipse in England (*15*). Theophilus Shelton, Esq., observed from Darrington at the northern limit: "The Sun at $9^{h}11^{m}$ was reduced almost to a Point, which both in Colour and Size resembled the Planet *Mars*; but whilst he watched for the Total Eclipse, that Point grew bigger and the Darkness diminished; whence he argued the Limit to have been very little more Southerly." The southern limit in Kent County was closely bracketed, with an observer at Angley House near Cranbrook reporting "Duration instant," while several at Bocton reported a "Point like a star" remained visible, showing them to be just outside the path of totality. The results of Halley's work were far ahead of his time and can only be fully appreciated now.

Local historical records were consulted to ascertain the observation sites involved, and accurate geodetic coordinates were measured from modern large-scale topographic maps (*16*). Using these

Table 1. Corrections to the solar radius.

Date	Radius correction (arc seconds)
3 May 1715	+0.48 ± 0.2
23 October 1976	+0.13 ± 0.05
26 February 1979	+0.14 ± 0.06
Change:	
1976 to 1979	+0.01 ± 0.08
1715 to 1979	−0.34 ± 0.2

positions, we have analyzed these early observations with the same methods of reduction used for the 1976 and 1979 eclipses. The analysis showed that the depth of the eclipse was only 0.11 arc second greater at Angley House than at Bocton, giving a measure of the accuracy of the determination of the southern limit, which passed between the two locations.

The interpretation of the Darrington observation is more ambiguous. Shelton thought that he was just outside the path of totality, but the fact that the last remaining part of the sun became red (color like Mars) shows that the photosphere completely disappeared, leaving part of the chromosphere visible. A short totality must have occurred at Darrington, but its onset and end were so gradual, due to the grazing geometry and relatively smooth northern limb of the moon, that Shelton perceived no sudden dimming or brightening which he called second or third contact. The edge-bracketing observations, including a northern-limit pair at Cle Elum, Washington, in 1979, would indicate a position within 0.15 arc second of the actual limit. Although everyone who sent reports to Halley in 1715 was warned of the eclipse phenomena and was asked to time the duration of totality, we do not know whether Shelton was as competent as the observers who bracketed the path edges mentioned above (*17*). If Darrington had been 1.3 km south of the northern limit (eclipse depth, 0.6 arc second), totality would have lasted 35 seconds. At the contacts, the luminosity of the last bead would have changed by a factor of 10 within 3 seconds, with considerably more gradual changes before and after. If this had occurred at Darrington, it is doubtful that Shelton would have claimed no totality, as he did. Consequently, we believe that Shelton was between the actual northern limit and 1.3 km south of it, so that his eclipse depth was 0.3 ± 0.3 arc second. An uncertainty of ±200 m, corresponding to ±0.09 arc second in depth, is also present since Shelton's exact position within the small town of Darrington is not known (*18*). The positional and observational uncertainties are much smaller at the southern limit (0.11 arc second) than at the northern limit (0.38 arc second in the worst case), so the error in the radius is effectively half the northern-limit uncertainty.

There is an element of subjective uncertainty in the interpretation of old historical records such as these. Some information which we would like to have is not available. However, we feel that our 0.2 arc second error in the radius is an estimate of the maximum error of the measurements, as discussed above. Table 1 shows that no change was measured between the 1976 and the 1979 eclipses, whereas between 1715 and 1979, a decrease in the solar radius of 0.34 ± 0.2 arc second was observed. This value is in disagreement with the contraction of about 2.5 arc seconds expected in 264 years from an extrapolation of the result of Eddy and Boornazian (*1*), but consistent with the value ≤ 0.65 arc second obtained by Sofia *et al.* (*3*) and with the (90 percent confidence limit) value ≤ 0.4 arc second of Shapiro (*4*). Finally, if we accept the radius-luminosity relationship for the sun proposed by Sofia *et al.*, the solar luminosity was larger in 1715 than it is at the present time. This may be responsible for the end of the "little ice age" that occurred in coincidence with the Maunder minimum.

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17. At a future eclipse it would be useful to station several people, with no more instructions than those given in Halley's pre-eclipse notice, at close intervals across the northern limit, to determine the distance over which ambiguous reports like Shelton's would be made.
18. Since Halley's objective—to accurately determine the edges of totality—depended critically on Shelton's location during the eclipse, we accept his statement that Shelton was *at* Darrington to be informed and precise, and not to mean, for example, *in the vicinity of* Darrington. Because of the very small size of the town, this pinpoints Shelton's location well within 200 m.
19. We thank T. C. Van Flandern for providing the lunar ephemeris for 1715; R. Linkletter, P. Asmus, F. J. Howell, and K. Strait for helping with the organization of the 1979 IOTA eclipse project; and all observers who reported observations from near the edges of the 1976 and 1979 eclipse paths.

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Origin of Lead in Andean Calc-Alkaline Lavas, Southern Peru

Abstract. *Lead isotope data from Quaternary andesitic lavas of the Arequipa and Barroso groups of southern Peru and from regional Precambrian granulitic gneisses reveal a lead component in the lavas from the gneisses. The lava leads can be accounted for by two-component mixtures of lead from mantle and lower crustal sources, although the mixing process need not have occurred in the lower crust.*

The origin of andesitic lavas is a problem of fundamental importance in earth science because various models of the earth's continental crust (*1*) lead to bulk chemical compositions that approximate that of andesite. Thus the problem is probably closely related to the origin of the continents. The widespread occurrence of andesitic rocks in belts along continental margins (for example, in the Andes and Cascade Mountains) is in accord with this concept.

Although numerous theories for andesite petrogenesis can be found in the literature, the theories are now based on some form of plate tectonic mechanisms in which partial melting occurs at depth as one plate is subducted beneath a second one. Both plates may be of oceanic affinity (for example, Mariana arc), or one may be of continental affinity (for example, the Andes). The main questions are the nature of the source material and the extent of possible contamination as the lavas rise to the surface.

In principle, isotope tracer studies with Sr, Pb, and Nd, which are produced by the decay of Rb, U and Th, and Sm, respectively, may provide answers or place limitations on possible answers to these questions. Some of the more definitive studies have been done in oceanic settings where the possible complications introduced by rocks of the thick continental crust are removed. In the Mariana (*2, 3*) and Tonga-Kermadec (*4*) island arcs, isotope tracer studies have shown that andesitic lavas are generated by partial melting of mantle or mantle-derived materials. One cannot, however, generalize the Tonga-Mariana studies to all oceanic rocks because there is strong evidence for subduction of sediments in the Banda arc (*5*) and possibly in other localities such as parts of the Aleutian arc (*6*).

Less definitive information is available for andesitic lavas from continental margins, although several investigations indicate that it may be possible to sort out the complexities of the interaction of continental and oceanic lithospheric slabs in those environments. The most detailed data are available for the Andes Mountains, the topic of these discussions. One of the first and most comprehensive geochemical studies of Andean volcanic rocks was initiated by James *et al.* (*7*), who studied two groups of andesitic rocks in the vicinity of Arequipa, Peru: the Arequipa and Barroso volcanics, of Quaternary age. On the basis of data for trace elements and Sr isotope relationships, James *et al.* (*7*) concluded that the late Cenozoic andesitic-dacitic lavas of southern Peru are derived from partial melting in the continental lithosphere that underlies the crust. This model was favored even though the high $^{87}Sr/^{86}Sr$ ratios (0.706 to 0.708) in the lavas are typical of continental crust (as opposed to mantlerocks where the range is generally 0.7025 to 0.7045) because in a Rb/Sr isochron diagram the Arequipa and Barroso volcanic data defined "pseudo-isochrons" corresponding to apparent ages of 400×10^6 years. These regularities were considered unlikely to result from contamination of mantle-derived lavas with various crustal materials. Instead, disequilibrium partial melting in mantlerocks was favored (*8*). Later investigations that added O isotopic data (*5*) showed that the Arequipa and Barroso volcanics require at least a small crustal component to account for their $^{18}O/^{16}O$ ratios. This component was attributed to subducted graywacke sediments, which

Table 1. Isotopic composition and concentration data for Andean igneous rocks; ppm, parts per million.

Sample No.	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb (ppm)	U (ppm)	Th (ppm)	Th/U (by weight)
			Arequipa volcanics				
PE 24	17.794	15.623	38.784	12.47	0.87	5.27	6.06
PE 26	18.019	15.626	38.737	12.20			
PE 47	17.845	15.612	38.724	11.35			
PE 49	17.844	15.610	38.643	16.40	0.77	5.07	6.58
PE 82	17.984	15.592	38.603	13.38	0.66	3.16	4.79
PE 83	17.948	15.603	38.657	16.17			
			Barroso volcanics				
PE 129	18.277	15.597	38.527	22.11	3.77	12.84	3.41
PE 130	18.291	15.589	38.471	10.66			
PE 131	18.246	15.584	38.467	15.67	3.84	12.79	3.33
PE 144	18.157	15.581	38.540	15.90	2.86	11.30	3.95
PE 145	18.166	15.588	38.708	16.46	1.63	8.81	5.41
			Charcani gneiss				
PE 37	16.940	15.552	38.950	10.70	0.213	23.23	109.1
PE 111	17.029	15.587	38.973	26.15	0.346	18.50	53.5
BAR 37	16.997	15.561	38.951	7.53	0.281	3.60	12.8
BAR 39	17.046	15.540	39.392	10.32	1.483	20.69	13.9
BAR 40	16.950	15.552	39.333	18.28			
BAR 43	17.088	15.548	39.610	6.35	0.834	15.0	18.0
BAR 44	16.792	15.556	37.987	17.97	0.164	8.4	51.0
BAR 45	16.847	15.544	38.592	10.67	0.254		
BAR 46	16.929	15.586	38.689				
			Mollendo granulites				
PE 18	16.110	15.463	40.455	12.26	0.164	5.62	34.3
PE 19	16.008	15.435	40.196	11.31	0.132	17.42	132.0
BAR 64	16.091	15.477	41.015	5.75	0.212		
BAR 68	16.496	15.531	38.789	16.20	0.281	1.49	5.3

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