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A PHOTOELECTRIC LIGHT CURVE AND ELEMENTS OF THE ECLIPSING BINARY EO AURIGAE

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Abstract

EO Aurigae is an early-type eclipsing binary of large amplitude. A photoelectric light curve consisting of 316 V observations is presented. The period does not seem to be changing significantly. A solution for the elements of the system is derived and a theoretical light curve constructed from these elements is found to fit the data well. These new elements differ considerably from those published previously. Approximate values for the masses, luminosities, spectral types, and radii are determined for the two stars.

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Introduction

EO Aurigae (HD 34333) $\alpha = 05^h\ 11^m\!.6$, $\delta = +36° 31'$ (1900) is a bright β Lyrae-type partially eclipsing binary star of large amplitude. Approximate elements for the system were determined soon after Pearce (1944) suggested, and Gaposchkin (1943) found, EO Aurigae to be an eclipsing system. The most extensive observational study of the star to date was carried out by Schneller (1963). Schneller derived the system's elements from 637 unfiltered photoelectric observations. His results were markedly different from those of his predecessors, essentially because Schneller found the primary eclipse to be a transit, and not an occultation, as had been previously assumed. A recent analysis of Schneller's data by Ramella *et al.* (1980) confirmed that Schneller correctly derived the system's elements from his data. Little has been done to verify Schneller's elements by obtaining new observations, even though EO Aurigae is a particularly significant binary, supposedly consisting of two massive B stars. Since the system is bright, has a large amplitude, and was in need of observations, a photoelectric study of the star was undertaken.

Data

Three hundred and sixteen photoelectric V observations of EO Aurigae were obtained on 42 nights from September 21, 1978, to April 17, 1979. Ninety-three observations were made by Rick Binzel, and the rest were made by the author. The equipment used was described by Hartigan (1980). The observations were transformed to the V of the UBV system using a value of epsilon equal to -0.055. The comparison star used was HD 34921, which Blanco *et al.* (1970) list as having V magnitude $7^m\!.47$. EO Aurigae's magnitude was calculated differentially with respect to the comparison star with atmospheric extinction corrections ignored since the two stars are separated only by $1^\circ\!.03$.

Schneller (1963) gives the following ephemeris:

$$\text{J.D. (Hel.) MIN} = 2421190.7479 + 4^d\!.06563378 * E. \qquad (1)$$

Equation (1) was used to calculate phases for the individual points. The observations are listed in Table 1 and plotted in Figure 1 as points.

Analysis

The observations near primary minimum yielded a minimum time of 2443921.733 ± $0\overset{\mathrm{d}}{.}012$ by the tracing paper method, implying an O-C of + $0\overset{\mathrm{d}}{.}026$ with respect to equation (1). Using this, and the four other available photoelectric timings of minimum (Schneller 1963), we obtain the new ephemeris:

$$\text{J.D. (Hel.) MIN} = 2421190.7414 + 4\overset{\mathrm{d}}{.}06563724 * \text{E}. \qquad (2)$$

To determine the elements of EO Aurigae, a phase of 0.0064 was first subtracted from each observation so as to make phase zero correspond with the observed minimum. The solution then proceeded along lines similar to those outlined by Merrill (1963). Seventy-nine normal points of 4 observations each were constructed from the data. Phases and magnitudes were transformed to degrees and intensities (with unit light fixed at $7\overset{\mathrm{m}}{.}55$), respectively, for each normal point. The angle of external tangency was initially estimated to be $20\overset{\circ}{.}5$. The tracing paper method was used to define a time of minimum light in secondary eclipse, and no significant displacement was apparent.

The normal points outside of eclipse, in light units, were fitted with a function of the form $A_o + A_1 \cos\theta + A_2 \cos 2\theta$. Values obtained were $A_o = 0.9175$, $A_1 = -0.0155$, $A_2 = -0.0538$. Since the eclipses appear partial, we use the approximation recommended by Merrill (1963) for using the angle of external tangency to get $C_o = 0.0110$, $C_1 = 0.0155$, $C_2 = 0.00368$. From these values and the value of A_2, it follows that $z = 0.092$. To obtain the rectified intensities I" from the observed intensities I, the following formula was used:

$$I'' = \frac{I + C_o + C_1 \cos\theta + C_2 \cos 2\theta}{(A_o + C_o) + (A_2 + C_2)\cos 2\theta}\,. \qquad (3)$$

The average intensity of the normal points outside eclipse after rectification was 1.000 with a standard deviation of 0.0195.

We assume x = 0.6 for both stars, a reasonable value since both are of spectral type B. Schneller also assumed x = 0.6. The phases were subjected to the transformation of Merrill (1963), and both primary and secondary eclipses were plotted with axes of rectified intensity vs. the sine of the rectified orbital angle. The rectified eclipse depths were measured as $1_o{}^{pr} = 0.722$ and $1_o{}^{sec} = 0.881$. The χ function was estimated at n = 0.2, 0.4, 0.5, 0.6, 0.8, and 0.9. Since $\chi^{pr}\,(.8) = 0.380 < \chi^{sec}\,(.8) = 0.473$, there is no doubt that primary eclipse is indeed a transit, as Schneller claimed.

A Russell-Merrill nomograph formed the basis for the solution of the elements. The parameters $\alpha_o{}^{tr}$ and k were found from the intersection of the depth line and the $\chi^{tr}\,(.8)$ contour. Since $\chi^{tr} = \chi^{tr}\,(n, k, \alpha_o{}^{tr})$, new values of $\chi^{tr}\,(.8)$ were found from the five aforementioned values of n. Their average formed a new value of $\chi^{tr}\,(.8)$ which could be used again to determine new values of k and $\alpha_o{}^{tr}$. A similar procedure was followed for the secondary minimum. Three iterations were performed and finally yielded the following values:

	k	x	r_1	r_2	L_1	L_2	i
Hartigan	0.540	0.6	0.291	0.157	0.881	0.119	$82\overset{\circ}{.}85$
Schneller	0.950	0.6	0.26	.25	0.74	0.26	$76\overset{\circ}{.}4$

Other relevant parameters obtained in this study are $J_1/J_2 = 2.16$, $\Delta m = 2\overset{\mathrm{m}}{.}17$, $p_o = -0.9912$, $j = 82\overset{\circ}{.}6$, $i' = 82\overset{\circ}{.}23$, $\alpha^{oc} = 0.9996$, $\alpha_o{}^{tr} = 0.9970$, $b_1 = 0.277$, $b_2 = 0.149$, $c_1 = 0.268$, $c_2 = 0.144$, $\sin\theta_e = 0.431$.

Using the relation

$$P = \frac{1}{r_2}\sqrt{\cos^2 i' - \sin^2 i' \sin^2 \theta} - \frac{1}{k} \tag{4}$$

and the fact that $\alpha = \alpha(x, k, p)$, we can theoretically reconstruct the light curve. This was done for each normal point, and the individual observations near each minimum were plotted on a wide scale to assess the accuracy of the elements, as shown in Figures 2 and 3. The reconstructed theoretical curve is also plotted at each normal point phase in Figure 1. The average systematic deviation of the theoretical points with respect to the observational normal points is $0\overset{\mathrm{m}}{.}003$. The average deviation squared is $0\overset{\mathrm{m}}{.}00032$. Since each normal point is accurate to about $0\overset{\mathrm{m}}{.}015$, there is no reason to try to improve on the elements without better data.

The only noticeable discrepancy is that the computed curve is slightly higher than the observational points on the rising branch of the secondary. To determine the seriousness of this deviation, the entire analysis was redone with more weight given to the χ^{sec} curve. After two iterations, the second solution on the Russell-Merrill nomograph fell between the first two iterations of the first solution. The elements did not change appreciably from the first solution. For this second attempt we get: $k = 0.54$, $r_1 = 0.295$, $i = 83\overset{\circ}{.}16$, $L_1 = 0.881$, $L_2 = 0.119$. Here the eclipses are total, with $\sin \theta_i = 0.043$. The theoretical light curve from this solution fit the secondary better, but the fit to the primary was unacceptable. Since the primary was firmer observationally, the first solution is preferable.

The eclipses are nearly total. The smaller star is about half the size of the larger one. Reflection effects cause the stars to be about 1.5 per cent brighter on the side facing the opposite star. The ratio of the longest to shortest diameter of these ellipsoidal stars is 1.09. A drawing of the system is presented in Figure 4.

The elements presented here differ markedly from those derived by Schneller. Nevertheless, the new elements have been shown to agree with the data obtained, and should not be hastily rejected. A careful analysis of the data in this paper yields an absolute upper bound of $k = 0.65$.

Recently, Ramella et al. (1980) solved the elements of EO Aurigae using Schneller's data and Wood's (1972) computer model. Their elements are very similar to those originally obtained by Schneller, so it is unlikely that the large differences between Schneller's elements and those of this paper are due to an error in Schneller's analysis. Perhaps the fact that Schneller obtained an unfiltered light curve is of relevance, but the discrepancy remains unresolved in the author's mind.

Discussion

The large masses often quoted for EO Aurigae are the result of a spectroscopic study by Pearce (1944). There is evidence that these masses are not accurate. Schneller (1963) noted that Pearce's value of $\Delta m = 0.45$ was inconsistent with his photoelectric data. This value of Δm is even more inconsistent with our data. Stothers (1972) compared EO Aurigae to theoretical models of the upper main sequence and found its mass to lie considerably above both the predicted mass and masses of stars of similar spectral type. Popper (1978) found that the spectral lines of the fainter star were not resolved, so it is clear that the published masses have little relevance.

We can estimate the temperature of the smaller star with the relation

$$T_2 = (r_1/r_2)^{1/2} \quad (L_2/L_1)^{1/4} \, T_1 \tag{5}$$

Note that here L_1 and L_2 represent the bolometric luminosity from the larger and smaller star, respectively. To a first approximation we can substitute the eclipsing elements for these values, although the elements give the ratio L_1/L_2 only in V. We get $T_2 = 0.825T_1$, so that the stars should have similar spectral types. If we assume the fainter star to have spectrum B3III, then the spectrum of the brighter star should be B1 III or so, consistent with Popper's (1978) results.

From the strength of the interstellar K line, Pearce (1944) found the distance to EO Aurigae to be about 1 kpc. Assuming an extinction of 1 mag/kpc, we get $M_V = -3^{m}.17$ and $-1^{m}.0$ for the larger and smaller stars, respectively. This is quite consistent with the probable spectral types.

For the larger star, the bolometric correction is about $-2^{m}.0$ and T_{eff} is about 2.0×10^4K according to Flower (1977). Using these and values for the sun in equation (5), we obtain Log $L_1/L_\odot = 4.0$, $R_1 = 8.4\ R_\odot$, $R_2 = 4.5\ R_\odot$, and $a = 2.0 \times 10^7$km. Assuming a bolometric correction for the smaller star of $-1^{m}.5$, we get Log $L_2/L_\odot = 2.9$. This result implies L_1/L_2 is about 13; this ratio, with equation (5), indicates $T_2 = 0.7\ T_1$; and this ratio of temperatures implies a spectral type for the larger star of BO III, perhaps a better value.

If Pearce's data are indeed correct, then we get $M_1 = M_2 = 20.4\ M_\odot$. If the smaller component is more massive, then the estimated masses are reduced. If $M_2 = 2M_1$, for example, then $M_2 = 11.5\ M_\odot$ and $M_1 = 5.8\ M_\odot$. It is clear that a precise spectroscopic study is needed to make the determination of absolute dimensions more rigorous.

The primary eclipse was easily discernable visually; the secondary was hard to detect. Because the period does not seem to be changing significantly, visual observers would be advised to focus their attention on other variables.

The author is grateful to Rick Binzel, who obtained essential observations at crucial phases when the author could not observe, and to Sherman Schultz, Macalester College Observatory Director, for his work on the instrumentation.

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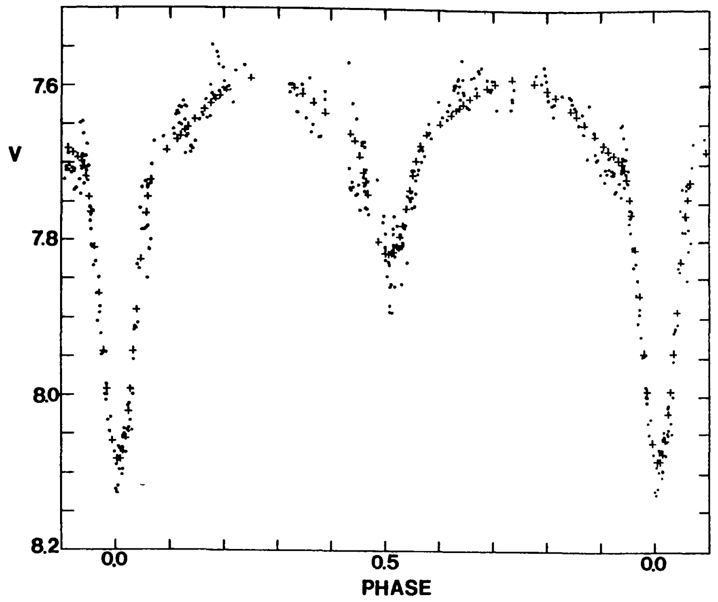
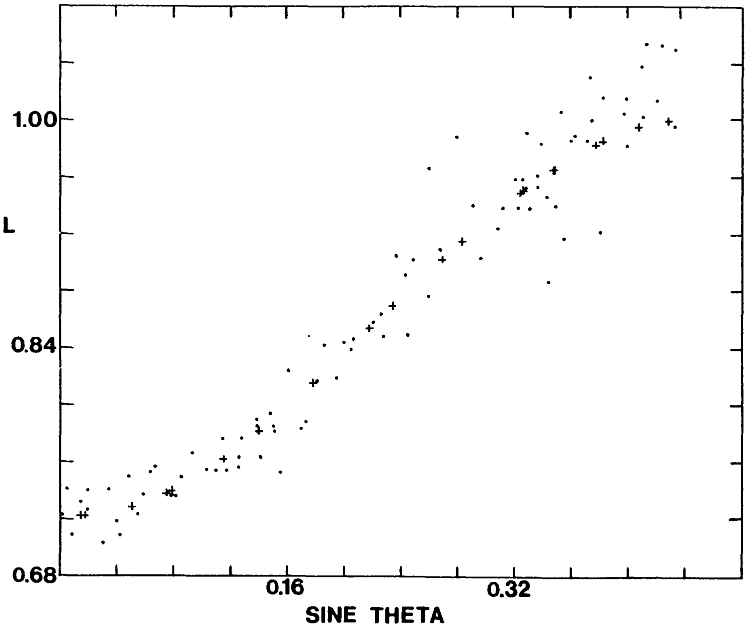


Figure 1. A photoelectric light curve of EO Aurigae. Dots are actual observations; crosses are theoretical magnitudes for each normal point. Phases are calculated according to Equation (1).

Figure 2. Primary minimum of EO Aurigae. Rectified intensity vs sine of the rectified phase. Dots are actual observations; crosses are theoretical points calculated for each normal point phase.



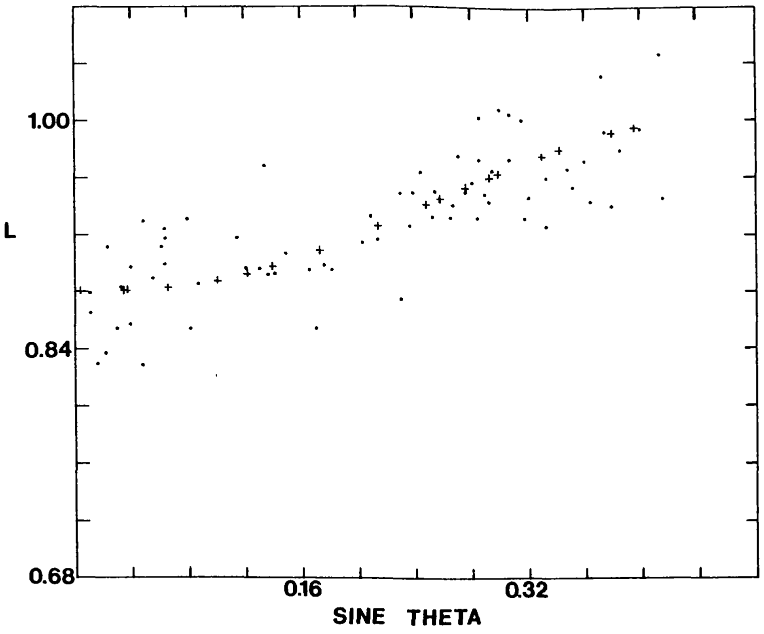


Figure 3. Secondary minimum of EO Aurigae. Rectified intensity vs sine of the rectified phase. Dots are actual observations; crosses are theoretical points calculated for each normal point phase.

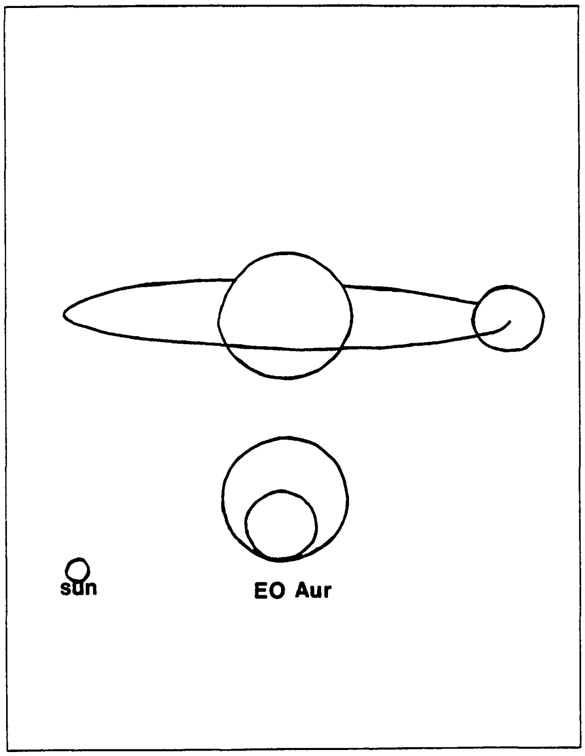


Figure 4. The system of EO Aurigae, based on elements in this paper, shown above at quadrature and below at conjunction. The sun is shown to provide scale.

TABLE 1 Individual V Magnitudes for EO Aurigae

J.D. (Hel.) 2,443,000+	Phase	V
773.803	.6211	7.622
773.866	.6366	7.588
774.752	.8545	7.627
774.841	.8764	7.690
775.814	.1157	7.668
775.843	.1228	7.650
776.755	.3471	7.598
779.777	.0904	7.665
782.783	.8299	7.609
782.836	.8429	7.610
789.743	.5417	7.741
789.779	.5505	7.709
793.757	.5291	7.792
794.784	.7817	7.582
794.822	.7911	7.594
801.713	.4859	7.721
801.766	.4989	7.768
801.835	.5159	7.790
804.714	.2240	7.580
804.778	.2397	7.573
809.739	.4601	7.671
811.723	.9481	7.710
811.754	.9557	7.768
811.793	.9653	7.827
811.823	.9727	7.893
811.869	.9840	7.986
811.903	.9923	8.028
811.924	.9975	8.073
813.697	.4336	7.568
813.729	.4414	7.621
813.757	.4483	7.641
816.715	.1758	7.599
816.732	.1800	7.548
820.720	.1609	7.636
820.786	.1771	7.640
837.740	.3472	7.604
837.796	.3610	7.589
875.604	.6604	7.587
875.626	.6659	7.586
875.632	.6673	7.600
875.657	.6735	7.578
875.665	.6754	7.580
875.680	.6791	7.574
875.717	.6882	7.600
875.724	.6900	7.589
875.751	.6966	7.604
875.758	.6983	7.601
875.765	.7000	7.591
875.801	.7089	7.595
876.794	.9531	7.775
876.802	.9551	7.786
876.817	.9588	7.805
876,825	.9608	7.831
876.849	.9667	7.868
876.858	.9689	7.904
876.883	.9750	7.921
876.890	.9768	7.947
876.917	.9834	8.005
877.751	.1885	7.557
877.760	.1908	7.563
877.766	.1922	7.573
877.796	.1996	7.577
877.804	.2016	7.594
877.837	.2097	7.601
877.848	.2124	7.605
877.876	.2193	7.621
878.748	.4338	7.706
878.754	.4353	7.731
878.762	.4372	7.732
878.770	.4392	7.723
878.778	.4412	7.730
878.803	.4473	7.741
878.813	.4498	7.738
878.821	.4517	7.726
878.833	.4547	7.760
878.862	.4618	7.736
878.867	.4631	7.728
878.878	.4658	7.757
878.885	.4675	7.758
878.896	.4702	7.766
881.580	.1304	7.687
881.590	.1329	7.667
881.598	.1348	7.663
881.617	.1395	7.686
881.625	.1415	7.678
881.633	.1434	7.681
881.659	.1498	7.672
881.687	.1567	7.643
881.712	.1629	7.638
881.736	.1688	7.618
881.742	.1702	7.642
881.769	.1769	7.609
881.776	.1786	7.620
881.795	.1833	7.613
881.826	.1909	7.618
881.832	.1924	7.606
881.862	.1998	7.604
884.737	.9069	7.722
884.744	.9087	7.705
884.751	.9104	7.710
884.758	.9121	7.710
884.767	.9143	7.689
884.773	.9158	7.703
884.790	.9200	7.712
884.798	.9219	7.706
884.804	.9234	7.712
884.810	.9249	7.708
884.817	.9266	7.734
884.823	.9281	7.733
884.850	.9347	7.722
884.858	.9367	7.741
884.864	.9382	7.708
884.873	.9404	7.689
884.880	.9421	7.704
884.887	.9438	7.728
887.553	.5996	7.618
887.582	.6067	7.639
887.617	.6154	7.642
887.625	.6173	7.629
887.660	.6259	7.629
887,680	.6309	7.598
887.721	.6409	7.615
888.541	.8424	7.611
888.552	.8451	7.614
888.564	.8481	7.619
888.586	.8535	7.635
888.593	.8552	7.628
888.607	.8586	7.647
888.635	.8655	7.648
888.640	.8668	7.632
888.654	.8702	7.659
888.695	.8803	7.621
888.733	.8896	7.684
888.741	.8916	7.694
888.749	.8936	7.690
888.776	.9002	7.711
888.782	.9017	7.679
891.738	.6288	7.602
891.746	.6308	7.597
891.752	.6322	7.596
891.759	.6340	7.606
891.766	.6357	7.591
891.776	.6381	7.598
891.795	.6428	7.565
891.802	.6445	7.590
891.808	.6460	7.607
891.815	.6477	7.609
891.843	.6546	7.625
891.850	.6563	7.627
891.859	.6586	7.588
897.753	.1084	7.656
897.760	.1101	7.664
897.767	.1118	7.637
897.777	.1143	7.634
897.784	.1160	7.635
897.795	.1187	7.627
897.803	.1207	7.650
897.809	.1221	7.629

TABLE 1 (continued)

J.D. (Hel.) 2,443,000+	Phase	V
897.829	.1271	7.621
897.836	.1288	7.627
897.843	.1305	7.645
897.849	.1320	7.628
898.752	.3541	7.642
898.795	.3647	7.660
898.802	.3664	7.650
903.744	.5818	7.647
903.752	.5838	7.658
903.760	.5857	7.665
905.735	.0716	7.671
909.539	.0073	8.067
909.548	.0095	8.069
909.557	.0117	8.068
909.566	.0139	8.053
909.575	.0161	8.049
909.587	.0191	8.074
909.608	.0243	8.047
909.615	.0260	8.011
909.622	.0277	7.991
909.641	.0324	7.999
909.648	.0341	7.953
909.660	.0370	7.913
909.664	.0380	7.910
909.678	.0415	7.906
909.748	.0587	7.768
909.756	.0607	7.782
909.764	.0626	7.727
909.789	.0688	7.702
911.587	.5111	7.859
911.598	.5138	7.893
911.608	.5162	7.782
911.615	.5179	7.767
911.619	.5189	7.859
911.622	.5197	7.820
911.639	.5239	7.780
911.643	.5248	7.806
911.650	.5266	7.806
911.653	.5273	7.810
911.657	.5283	7.810
911.671	.5317	7.808
911.674	.5325	7.856
911.678	.5334	7.802
911.681	.5342	7.805
911.695	.5376	7.782
911.698	.5384	7.760
911.702	.5393	7.779
911.712	.5418	7.828
911.730	.5462	7.745
911.735	.5475	7.747
911.741	.5489	7.735
911.747	.5504	7.756
911.753	.5519	7.743
911.761	.5539	7.708
911.768	.5556	7.755
911.771	.5563	7.737
911.778	.5580	7.720
911.789	.5607	7.712
911.796	.5625	7.706
911.805	.5647	7.681
911.813	.5667	7.696
911.822	.5689	7.678
911.830	.5708	7.681
911.837	.5726	7.689
912.745	.7959	7.573
912.753	.7979	7.582
912.762	.8001	7.591
912.769	.8018	7.608
912.775	.8033	7.615
912.806	.8109	7.622
912.812	.8124	7.636
912.819	.8141	7.620
921.581	.9692	7.849
921.592	.9719	7.886
921.633	.9820	7.944
921.640	.9837	7.999
921.647	.9854	7.999
921.654	.9871	8.033
921.665	.9899	8.047
921.706	.9999	8.120
921.713	.0017	8.126
921.720	.0034	8.089
921.727	.0051	8.118
921.734	.0068	8.096
921.741	.0085	8.082
921.757	.0125	8.103
921.766	.0147	8.096
921.774	.0167	8.043
921.781	.0184	8.073
921.786	.0196	8.056
921.797	.0223	8.045
921.804	.0240	8.013
921.811	.0258	8.043
921.821	.0282	8.032
921.828	.0299	8.046
921.840	.0329	7.992
921.848	.0349	7.916
923.566	.4575	7.677
923.572	.4590	7.673
923.580	.4609	7.718
923.586	.4624	7.678
923.596	.4649	7.708
923.606	.4673	7.737
923.613	.4690	7.723
923.616	.4698	7.741
923.726	.4968	7.775
923.732	.4983	7.815
923.740	.5003	7.806
923.745	.5015	7.824
923.751	.5030	7.790
923.758	.5047	7.845
923.765	.5064	7.826
923.772	.5081	7.830
923.776	.5091	7.892
923.779	.5099	7.883
923.790	.5126	7.855
923.805	.5163	7.804
924.585	.7081	7.628
929.586	.9381	7.649
929.593	.9398	7.647
929.600	.9415	7.647
929.603	.9422	7.664
929.610	.9440	7.691
929.621	.9467	7.691
929.627	.9482	7.677
929.634	.9499	7.723
929.641	.9516	7.705
929.652	.9543	7.758
929.659	.9560	7.762
929.662	.9568	7.762
943.619	.3898	7.606
947.639	.3786	7.665
947.646	.3803	7.665
947.681	.3889	7.616
959.609	.3228	7.607
959.619	.3253	7.598
959.626	.3270	7.598
959.661	.3356	7.612
959.668	.3373	7.603
959.675	.3391	7.634
966.602	.0428	7.833
966.610	.0447	7.837
966.617	.0464	7.757
966.630	.0496	7.731
966.637	.0514	7.786
966.651	.0548	7.786
966.658	.0565	7.786
966.662	.0575	7.724
966.669	.0592	7.731
966.672	.0600	7.848
966.679	.0617	7.809
966.690	.0644	7.726
966.696	.0659	7.800
981.607	.7335	7.628
981.611	.7345	7.628
981.618	.7362	7.613
981.625	.7379	7.617
981.628	.7387	7.602