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The Doppler Widths of Solar Absorption Lines

By Barbara Bell[1] *and* Alan Meltzer[2]

The precise profiles of solar and stellar absorption lines depend upon many factors. Among them are the mechanism of radiative transfer, the form of the line absorption coefficient, atomic collision cross-sections, temperatures, densities, and their gradients in the solar atmosphere. For weak and medium-weak lines, the profiles are determined primarily by the form of the absorption coefficient, which depends in turn upon the mechanisms acting to broaden the lines. Spectral lines are broadened intrinsically by three processes: the Doppler effect due to line-of-sight velocities of the radiating atoms; natural width due to the finite width of the atomic energy levels; and external effects due to perturbation of the radiating atom by neighboring atoms and ions. In the solar atmosphere, Doppler broadening and collision broadening are far more important than natural width.

This paper deals chiefly with Doppler broadening. From observations of the continuous spectrum, astronomers generally agree that the continuum is formed in regions of the solar atmosphere where the kinetic temperature cannot much exceed 5000° K. They also agree, however, that solar absorption lines show a Doppler width substantially in excess of that given by 5000°. Since Doppler broadening can result equally well from the random line-of-sight velocities of individual atoms, or from mass motions of elements of gas, the concept of turbulence, or mass motions of elements of gas, has usually been invoked to explain the extra width of the lines. Any broadening produced by turbulence must by definition be independent of atomic weight, while, according to kinetic theory, the mean square random velocities of individual atoms will be proportional to the kinetic temperature and inversely proportional to the atomic weight. Thus it might appear relatively simple to distinguish between these mechanisms by observing a few well chosen lines. Since the Doppler widths usually have been derived from metallic atoms of nearly equal atomic weights, there has been little evidence to test the correctness of the turbulence hypothesis.

In recent years several studies (Bell, 1951; Rogerson, 1957; Waddell, 1956, 1958) have been made of the profiles of weak and medium-weak solar absorption lines. For the first of these, the Utrecht Atlas (Minnaert et al., 1940) provided extensive observational material, while the other two used photoelectric profiles traced by the respective authors. Bell and Rogerson each used the Voigt profile method of analysis, which assumes in essence that the shape of a weak line is the shape of its absorption coefficient, and involves no assumptions about physical conditions in the solar atmosphere. Waddell, on the other hand, used a model atmosphere—with specific assumptions about temperatures and densities in the regions where his lines were formed—to compute theoretical profiles to compare with those observed. The success of this method presupposes, of course, a reasonably correct idea of physical conditions in the solar atmosphere. These three studies give several contradictory results that are independent of the method of analysis.

Rogerson and Waddell each assumed kinetic temperatures of the order of 5000° K, as indicated by continuum observations, and derived turbulent velocities of 1.4 and 1.8 km/sec respectively. Bell emphasized a comparison

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of profiles from atoms of different atomic weights, from carbon to iron, and concluded that her data indicated a kinetic temperature of 10,000° K and a turbulence of less than 0.5 km/sec for neutral lines of excitation potential of 4 to 7 volts. Rogerson, however, found that the atomic weight dependence of his profiles, from silicon to iron, was adequately accounted for by a kinetic temperature of 5000° K.

Furthermore, Bell found that the Doppler widths of iron lines varied with excitation potential (EP) and hence with depth. In a later study van Regemorter (in press) obtained similar results, while Rogerson finds no evidence in his data for such a variation. Bell found the damping factor in iron lines to depend markedly on the parity—and hence on the binding energy of the electron to the parent ion—and very little on the excitation potential. Rogerson found the converse result, and has suggested that some of the discrepancies between his results and those of Bell may arise from the use of different tables of the Voigt functions (Elste, 1953; van de Hulst and Reesinck, 1947), but we have tried both tables on a few lines and feel that this is not a probable explanation. Further observational study is needed to resolve these discrepancies.

In the present work we have investigated the way in which the width of the line profiles depends on the atomic weight of the atoms producing them.

The observational material was obtained at the Sacramento Peak Observatory where the authors were guest investigators—Meltzer during March and April 1957 and Bell from September to November 1957.

We made photoelectric tracings of the line profiles by means of a Lallamand cell and Brown recorder attached to the large Littrow spectrograph. A 1200-line grating was used in the second order, giving a dispersion of 4.45 mm/Å. A Jena OG–2 filter prevented the overlapping of higher spectral orders. The entrance and exit slits were kept at a width of 30 microns and at a length of one inch. The scale of the tracings was about 6 inches per Å.

All tracings were made as near as practicable to the center of the sun's disc. Because the level of solar activity was high during 1957, special care had to be taken to avoid plage and spot areas.

The instrumental profile was studied from tracings of the mercury 5461 line of isotope 198. The half-width of the instrumental profile is small, about 0.030Å. The wings, unfortunately, do not fit a Voigt profile. For this reason an instrumental correction to the Voigt damping parameter cannot be determined, and we have not attempted to study the damping from our observed line profiles. However, since the instrumental profile is completely independent of atomic weight, the uncorrected profiles should suffice to give the kinetic temperature, and the known half-width of the instrumental function permits a reasonably good estimate of the turbulence.

We made at least six tracings of every line, reversing the direction of scan after each trace. For two reasons, we made additional tracings for some of the lines. Because of the possibility of getting into a weak unnoticed plage area, Bell traced the vital 5380 line of carbon each day for comparison with other lines observed that day. Also, a random slippage in the motion of the grating, and hence in the rate of scan, introduced errors into the individual tracings. Since we made two independent sets of observations which give essentially the same results, we feel justified in presenting our findings in spite of such errors in the individual tracings.

We analyzed our lines by the Voigt profile method. By definition, a Voigt function results from the superposition of a damping or dispersion type function,

$$f(x)=\frac{c_1}{1-x^2/\beta_1^2},$$

and a Gaussian probability function,

$$f(x)=c_2e-x^2/\beta_2^2,$$

where c_1, c_2, β_1, and β_2 are constants and x is the distance from the line center. Thus Voigt functions are characterized by two parameters, β_1 and β_2, and the strength of their wings depends on the ratio of β_1/β_2.

The line absorption coefficient similarly is given by the superposition of a Maxwellian velocity distribution function and a damping function. The parameters β_1 and β_2 can thus readily be equated to factors in the absorption coefficient, the first relating to the damping half-width, the second to the Doppler half-width.

In an analysis by Voigt profiles, one assumes that the profile of the observed line is the average of the absorption-coefficient profile appropriate to the regions of the solar atmosphere over which the line is formed. Thus the method can properly be applied only to comparison of lines that arise at the same average depth in the solar atmosphere.

It is difficult to find suitable lines sufficiently different in atomic weight and reasonably similar in excitation level. For this study we selected lines of carbon, silicon, and iron having excitation potentials of 7.6, 4.9, and 4 to 5 volts, respectively, as shown in tables 1 and 2. Although the comparison of 7.6-volt carbon lines with those of silicon and iron may be open to criticism, we have included carbon because it provides a long base line in atomic weight. However, the greater emphasis probably should be given to results arising from comparison of iron and silicon lines, since these are quite similar both in excitation and ionization potential.

A Voigt profile is completely specified by three quantities: $\Delta\lambda$, the width at half intensity, generally called simply the half-width; c, the central depth; and p, a function of β_1/β_2, determined by the width of the profile in the wings relative to that at the half-intensity point and varying from 1.06 for a pure Gaussian to 1.57 for a pure damping profile.

We measured the width of each trace at its half-intensity point and at four points in the wings, $0.1c$, $0.15c$, $0.2c$, and $0.3c$. The measures for the individual tracings were combined to give mean quantities for each line. Most of the mean observed profiles showed a good fit to a Voigt function. From Elste's (1953) tables we obtained the Voigt parameters, p, b_1, b_2^2. From the measured half-width, the more convenient quantity $h=\frac{\Delta\lambda}{\lambda}10^6$ was obtained. We then computed $\beta_1=b_1h$ and $\beta_2^2=b_2^2h^2$. The β_1 and β_2^2 of the line, after correction for the respective instrumental β_1 and β_2^2, should yield a good first approximation to the damping constant and the Doppler velocity, respectively. Our collection of lines is not suitable for testing the parity effect; furthermore, the instrumental β_1 is indeterminate, so we shall not further discuss the β_1's here, except to note that they suggest that damping is not negligible even for weak lines.

The observational results are given in tables 1 and 2, where the data obtained by Meltzer and by Bell are presented separately in order to show clearly that, in spite of the grating slippage, the independent sets of observations gave results in close agreement.

TABLE 1.—*Parameters of line profiles observed by Meltzer, April 1957*

Element	*Wavelength*	*Excitation potential*	*Observed quantities*			*Voigt parameters*		*Number of tracings*
			c	$\Delta\lambda$(Å)	h^2	p	β_2^2	
C	5380. 32	7. 65	0. 12	0. 142	700	1. 18	185	6
Si	*5665. 56	4. 90	. 26	. 118	431	1. 25	91. 2	6
	5772. 15	5. 06	. 32	. 130	505	1. 30	89. 6	10
	5793. 08	4. 91	. 28	. 126	477	1. 27	93. 5	6
Fe	5386. 34	4. 15	. 26	. 088	270	1. 23	60. 7	6
	5441. 35	4. 35	. 25	. 092	288	1. 29	52. 0	5
	5752. 04	4. 59	. 41	. 106	340	1. 28	62. 8	8
	5793. 93	4. 24	. 26	. 100	297	1. 23	66. 5	9
	5852. 23	4. 59	. 30	. 108	342	1. 30	59. 5	6
	5856. 10	4. 28	. 27	. 103	308	1. 26	62. 0	8

*Violet half only; red half blended.

TABLE 2.—*Parameters of line profiles observed by Bell, September–November 1957*

Element	*Wavelength*	*Excitation potential*	*Observed quantities*			*Voigt parameters*		*Number of tracings*
			c	$\Delta\lambda$(Å)	h^2	p	β_2^2	
C	5052. 16	7. 65	0. 21	0. 156	950	1. 20	235	12
	5380. 32	7. 65	. 13	. 156	840	1. 23	190	22
Si	*5665. 56	4. 90	. 26	. 122	466	1. 25	98	6
	5690. 43	4. 91	. 34	. 121	450	1. 24	96	6
	5701. 11	4. 91	. 26	. 120	443	1. 22	102	7
	5772. 15	5. 06	. 32	. 132	526	1. 30	89	11
	5793. 08	4. 91	. 27	. 128	488	1. 27	96	13
Fe	5293. 96	4. 12	. 25	. 092	303	1. 27	58	8
	5295. 31	4. 35	. 24	. 092	306	1. 22	70	8
	5386. 34	4. 15	. 26	. 095	310	1. 23	70	18
	5395. 22	4. 35	. 16	. 096	319	1. 25	68	7
	5401. 27	4. 35	. 20	. 096	316	1. 26	64	6
	5441. 35	4. 35	. 25	. 101	344	1. 29	62	8
	5464. 29	4. 12	. 31	. 095	305	1. 24	67	6
	5705. 48	4. 24	. 29	. 099	302	1. 24	64	6
	5793. 93	4. 24	. 26	. 099	292	1. 26	58	13
	5852. 23	4. 59	. 30	. 105	324	1. 31	52	10
	5855. 09	4. 59	. 17	. 100	294	1. 24	64	11
	5856. 10	4. 28	. 26	. 102	303	1. 25	63	11
	5927. 80	4. 59	. 31	. 104	312	1. 29	56	6
	6089. 58	5. 00	. 29	. 102	287	1. 28	54	4

*Violet half only.

The quantity β_2^2 is proportional to the Doppler width of the line. From the definition of Voigt functions it can easily be shown that

$$\beta_2^2 \propto \frac{2RT}{\mu} + (v_T^2 + \beta_{2i}^2), \qquad (1)$$

where T is the kinetic temperature, v_T is the turbulent velocity, and β_{2i}^2 is the instrumental profile correction. The quantity in parentheses is independent of μ, the atomic weight. If this term were zero, the β_2^2's of the lines should be inversely proportional to the atomic weight of the element producing the line. When this quantity is not zero, the quantity $[\beta_2^2 - (v_T^2 + \beta_{2i}^2)]$ should be inversely proportional to μ. Solving equation (1) for the kinetic temperature, we obtain

$$T = 5.41\,[\beta_2^2 - (v_T^2 + \beta_{2i}^2)]\mu. \qquad (2)$$

We computed a mean β_2^2 for each element. By trial and error we determined that a correction of $(v_T^2 + \beta_{2i}^2) = 26$ would yield the best inverse relation between the quantity in square brackets and the atomic weight, and the best agreeing values of T for the three elements. The results appear in table 3. We also solved equation (2) for each pair of elements, with the results shown in table 4.

We obtain a kinetic temperature of the order of 10,000 to 11,000° K, in substantial agreement with Bell's (1951) earlier work on comparable lines.

If the entire quantity $(v_T^2 + \beta_{2i}^2)$ is due to turbulence (i. e. if the instrumental β_{2i}^2 is negligible), we obtain $v_T = 1.6$ km/sec. This is, of course, an upper limit to the turbulence. The maximum instrumental correction will be obtained if we assume the instrumental profile is a Gaussian, so that its entire half-width goes into β_{2i}^2. Such an assumption gives $\beta_{2i}^2 = 10$, and a turbulence of 1.2 km/sec. However interpreted, our Doppler half-widths are somewhat larger than those previously obtained. The reason for this is unknown. If real, the effect may be related to the remarkably high level of general solar activity observed throughout 1957.

In addition to the profiles observed at the center of the solar disc, in September we observed the profiles of 13 of these lines near the north limb. The 1-inch long slit of the spectrograph was centered one inch from the limb, on a 10-inch image of the sun; thus, at $r/R=0.8$.

Table 5 gives the parameters of the lines, while the third section of table 4 gives the indicated kinetic temperatures. The half-widths of the lines increase markedly to the limb, but the weighted mean temperature is 11,400°, only slightly higher than that obtained at the center of the disc. The turbulence increases to between 1.9 and 2.1 km/sec, which is 0.6 to 0.7 km/sec greater than the center-of-disc values.

TABLE 3.—*Determination of apparent kinetic temperature at center of disc*

Observer	*Element*	*Mean* β_2^2	β_2^2–26	*Ratio of atomic weights* $(56/\mu)$	*Ratios of* $(\beta_2^2$–26)	*Temperature*	*Weight*
Meltzer	C	185	159	4. 67	4. 60	10, 300° K	6
	Si	92	66	2. 00	1. 90	10, 000	22
	Fe	61	35	1. 00	1. 00	10, 500	42
						10, 300 (mean)	
Bell	C	206	180	4. 67	4. 87	11, 700	34
	Si	95	69	2. 00	1. 86	10, 400	43
	Fe	63	37	1. 00	1. 00	11, 200	122
						11, 000 (mean)	

Any thorough study of center-to-limb changes in the Doppler width of lines would of course require observations at several points along the radius. Until we obtain such data, we shall not attempt to interpret the present north limb observations. Our observations suggest, however, that the well-known increase in line half-width to the limb (see Allen, 1949) results largely from increased turbulence rather than from significantly higher kinetic temperatures.

Houtgast (1953) has criticized Bell's (1951) work on the grounds that some of the lines she compared (specifically, carbon and oxygen with iron) differed in excitation potential and hence must arise at different depths in the solar atmosphere. This argument may apply to the carbon lines, but it should not apply to the comparison of silicon with high excitation lines of iron which should arise from the same average level in the atmosphere. (Bell's determination of the kinetic temperature depended as much on a comparison of silicon and iron as on that of iron with carbon and oxygen; also, only 4–5 volt lines of iron were used in these comparisons precisely because of the difficulty mentioned by Houtgast.)

A definitive analysis of a line profile cannot be made without detailed consideration of the processes of line formation and of the variation of the absorption coefficient with depth in an appropriate model atmosphere. The method of this paper has been criticized as too simple even for a first approximation. Therefore, to examine the relationship between results obtained by this method and one using a model atmosphere, we made a Voigt profile analysis of a theoretical profile computed by Waddell (1956) for the titanium line, λ6126, from a standard model atmosphere and Pecker's (1953) method of weighting functions (see Waddell, 1958). We obtained a turbulence 0.2 km/sec greater than Waddell put into his line.

As a second test, we made a Voigt analysis of a pair of iron and silicon theoretical profiles, computed by Doherty and Hazen (unpublished) from the Claas (1951) model of the solar atmosphere, with the assumption that scattering plays no part in the formation of the lines. From comparison of their iron and silicon profiles, we obtained $T=6600$°K, which is the Claas temperature at the optical depth 1.2 in the continuum; a turbulent velocity of 2.1 km/sec, which is 0.35 above the assumed value of 1.75 km/sec; and a damping of $a=0.23$, slightly below the original 0.25.

From this analysis we conclude that the single layer approximation, implicit in the Voigt profile method, is not unrealistic as a first approximation for elements such as iron and silicon. Integration through an atmosphere does make the width of the lines moderately greater than the width of their absorption coefficients, but when a Voigt analysis is used this width appears in a spuriously large turbulence rather than in a spuriously high kinetic temperature.

Our profiles have not been corrected for instrumental scattered light. The Voigt method is insensitive to this correction, however, so that its neglect results in only a minor error at worst and cannot account for our high temperatures. We tested this point by applying an arbitrary scattered-light correction of 10 percent to our mean observed silicon and iron profiles. Voigt analysis of this pair of corrected profiles gave $T=12{,}000°$, as compared with 10,600° from the same pair of profiles before correction. The correction decreased the apparent turbulence by about 0.2 km/sec.

Hazen (private communication) has pointed out that the Voigt profile method is very sensitive to small changes in the assumed level of the continuum, because the shape of the wings is so important in determining the Voigt parameters. If the continuum were drawn 1 or 2 percent higher, the two mean profiles would give a temperature of 8,000 or 6,000°K respectively. In the spectral regions we studied, so large a systematic error in drawing the continuum appears extremely unlikely. However, this sensitivity may account for much of the scatter among individual tracings (and individual lines in the Utrecht Atlas), and indicates the importance of making several tracings of each line. Moreover this source of error would similarly distort the results from more sophisticated methods of analysis, insofar as they attempted to fit the damping wings.

One other comment may be made on the Voigt profile method of analysis. Waddell, in his model atmosphere analysis, assumed that weak lines were undamped. In terms of Voigt parameters, this implies that $\beta_1=0$ and $p=1.06$. Under the assumption of no damping, the entire half-width is considered to result from temperature and turbulence, and the wing measures may be disregarded. When we applied this assumption to our lines, Meltzer's observations yielded temperatures of about 11,000° from carbon and iron and a substantially higher temperature for silicon, as one might expect, since its p's (Voigt parameters) are substantially larger than those for carbon and iron. From Bell's observations we can obtain good agreement among the three elements at around 17,000°K. We thus feel that the damping cannot properly be ignored, and indeed any attempt to do so only aggravates the problem of high kinetic temperatures.

TABLE 4.—*Apparent kinetic temperatures, determined from comparison of Doppler half-widths of lines of pairs of elements of different atomic weight*

Observer	*Elements (paired)*	*Temperature*	*Weight*
Meltzer (center of disc)	C–Si	10, 600° K	28
	C–Fe	10, 300	48
	Si–Fe	9, 400	64
		10, 000 (mean)	
Bell (center of disc)	C–Si	12, 600	77
	C–Fe	11, 900	156
	Si–Fe	9, 800	165
		11, 100 (mean)	
Bell (0.2R from north limb)	C–Si	12, 800	43
	C–Fe	11, 800	65
	Si–Fe	10, 300	74
		11, 400 (mean)	

Waddell (1958) has pointed out a discrepancy between observed and Voigt profiles in the far wings, within about one percent of the continuum. But such a deviation is far smaller than that between the observed profile and any theoretical profile computed under the assumption of zero damping. While other interpretations of the line wings are conceivable, damping is the most simple and straightforward. The parity effect (Bell, 1951; Carter, 1949) would appear to provide the best test of the correctness of this interpretation. According to theory, the damping is proportional to the binding energy of the electron to its parent term of the ion. In iron these binding energies have values that lead one to expect the damping arising from odd terms to be about double that arising from even terms of comparable excitation potential, although parity in itself has no bearing on the problem (see Bell, 1951). We hope to explore this question further with additional observations.

If we accept the hypothesis that the 22 lines—or at least the 20 lines of silicon and iron—compared in this paper are formed through the same average layer of the solar atmosphere, we are faced with the conclusion that the atoms possess a kinetic temperature of 10,000 to 11,000° K, although all continuum studies indicate electron temperatures of the order of 5000° K.

TABLE 5.—*Parameters of line profiles observed at 0.2 of the solar radius from the north limb, September 1957*

Element	Wavelength	Excitation potential	Observed quantities			Voigt parameters		Number of tracings
			c	$\Delta\lambda$(Å)	h^2	p	β_2^2	
C	5052.16	7.65	0.17	0.154	930	1.17	250	8
	5380.32	7.65	.10	.152	800	1.17	215	9
Si	5665.56	4.90	.25	.134	555	1.23	125	8
	5772.15	5.06	.30	.140	585	1.28	111	10
	5793.08	4.91	.26	.134	542	1.22	124	8
Fe	5386.34	4.15	.26	.102	362	1.18	94	7
	5395.22	4.35	.16	.101	348	1.26	70	5
	5441.35	4.35	.25	.107	388	1.24	85	6
	5464.29	4.12	.30	.105	370	1.25	77	4
	5793.93	4.24	.25	.111	366	1.18	95	8
	5852.23	4.59	.28	.116	393	1.25	80	6
	5855.09	4.59	.16	.109	347	1.21	83	6
	5856.10	4.28	.25	.115	385	1.19	98	6

Three possible explanations for this discrepancy present themselves: (1) equipartition of energy between the atoms and electrons does not occur; (2) the electrons actually have a kinetic temperature of 10,000°; or (3) the continuous and the absorption-line spectra are formed in significantly different regions of the solar atmosphere. Because of the great frequency of atom-electron collisions, the first hypothesis cannot be regarded seriously (see Bhatnagar et al., 1955). With the second hypothesis, the electrons would be much too energetic for capture in sufficient numbers by hydrogen to form H^-, and it would seem virtually impossible to account for the observed continuum. Only the third hypothesis appears to offer any possibility of a reasonable explanation.

If we postulate that the lower chromosphere makes a substantial contribution to the absorption lines, while the continuous absorption arises from photospheric levels, there is hope that the temperature differences can be reconciled. Recent work by Zirker (1956, 1958) on the metallic flash spectrum from the 1952 eclipse and by Pecker (1957) on the CH and CN bands makes such a postulate appear more tenable than it did a few years ago. The similarity between the intensity and velocity fluctuations in the strong magnesium λ5167 line and in medium-weak neighboring lines, observed with the vacuum spectrograph at the McMath-Hulbert Observatory (McMath et al., 1956), also suggests that the chromosphere may make significant contributions to the cores of at least medium-weak solar absorption lines.

The mere existence of such velocity shifts makes it obvious that some form of macroturbulence must be broadening the profiles of lines coming from an area of the sun large enough to take in many granules. A complete picture of velocities can, therefore, come only from analysis of such detailed spectra.

As an alternative to chromospheric contributions, Pecker suggested (in conversation) that inhomogeneities in the photosphere such as described by the 3-stream model of Bohm (1954) and Voigt (1956) might account for the apparent high kinetic temperature. By assuming values for the stream velocities, microturbulence, and stream temperatures, one could compute profiles for two lines of different atomic weight, analyze them by the method used in this paper, and determine the apparent kinetic temperature for comparison with observations. The 3-stream model as used by Voigt, however, predicts that the violet wings of profiles should be stronger than the red wings. Our observations, as well as those in the Utrecht Atlas, suggest that the red wings are the stronger (i. e., more depressed).

To test any of these hypotheses, of course, we should have to make detailed models, taking account of the contributions of each layer—photospheric as well as chromospheric—to the line formation, and this has not yet been attempted.

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Abstract

In an attempt to distinguish the contributions of turbulence and kinetic temperature to the half-widths of solar absorption lines, photoelectric tracings where made of the profiles of 22 moderately weak lines of three elements covering a wide range in atomic weight (μ): carbon (12), silicon (28), and iron (56). The tracings were analyzed by the method of Voigt functions. In iron, to be as nearly comparable as possible with the available lines of silicon and carbon, only lines of relatively high (>4.1 e. v.) excitation potential were used.

When the μ-dependent and the μ-independent parts of the Doppler half-widths were separated, a kinetic temperature of the order of 10,000° K was obtained. Temperatures of the same order, or somewhat higher, are indicated if the damping is neglected and the entire half-width is assumed to arise from Doppler broadening.

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