ON THE UNRESOLVED FINE STRUCTURES OF THE SOLAR ATMOSPHERE
IN THE 3 × 10^4-2 × 10^5 K TEMPERATURE REGION

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ABSTRACT

The solar atmospheres from the chromosphere through the transition zone and all the way up into the corona usually are considered to be parts of one continuous structure. Now that stellar measurements in the far-ultraviolet have become available, an attempt is being made to apply solar physics ideas to solar type stars. The intention of this paper is to reexamine the experimental facts concerning the relations between the solar chromosphere, transition zone, and corona.

Experimental evidence is presented to argue that the solar plasma in the temperature region \(4 \times 10^4-2.2 \times 10^5\) K occurs in structures magnetically isolated from the chromosphere and corona. It is suggested that while a small part of the emission detected in the \(4 \times 10^4-2.2 \times 10^5\) K region consists of the "true" transition zone plasma, i.e., the interface between chromospheric and coronal temperatures, that most of it belongs to an altogether different entity. It is also suggested that this particular entity be called unresolved fine structures.

Subject headings: Sun: chromosphere — Sun: corona

I. INTRODUCTION

Stellar atmospheres in the temperature range of \(10^5-10^6\) K are best observed in the far-ultraviolet. Until recently the Sun was the only star that was well observed in the far-ultraviolet. Therefore, it became one of the main objects for modeling stellar outer atmospheres. Now that far-ultraviolet observations of many solar type stars are becoming available, solar models are being used to describe their atmospheres.

The intention of this paper is to reexamine the experimental facts concerning the relations between the various temperature regions of the solar atmosphere, and thus reexamine some of the solar atmosphere models.

In the first few decades of the space era it was generally assumed that the solar atmosphere is composed of spherically symmetric layers, proceeding from the cold chromosphere through the transition zone and into the hot corona. Such an atmosphere could be described as one-dimensional, with the temperature and density uniquely defined as a function of the solar radius. For a summary of such models, see Athay (1976). This idea persisted as long as the experimental data available did not contradict it. However, as a result of measurements with improved spectral and spatial resolution, it became apparent that the original picture of the solar atmosphere is oversimplified and needs to be modified. Such a need resulted, for example, from high resolution spectral measurements in the vicinity of the solar limb. Solar limb measurements revealed that the solar layers of \(4 \times 10^4-2.2 \times 10^5\) which under the original model were expected to be emitted from atmospheric layers only a few hundreds of kilometers thick are emitted from significantly more extended layers (Brueckner and Nicolas 1973; Doschek et al. 1976; Feldman et al. 1976).

In order to overcome such difficulties, the original plane-parallel model had to be modified. This was achieved as an example by allowing the atmosphere to conform so that it would wrap itself around the cold structures that are known to protrude from the photosphere (i.e., spicules). By using such a model (Withbroe and Mariska 1976), it was possible to argue that the \(4 \times 10^4-2.2 \times 10^5\) K plasma is confined to a very thin region and at the same time explain the detection of emission over an extended height range.

Over the years, a number of other models of the solar atmosphere were constructed in which one property was common to all. In all the models, the lower temperature boundaries of the structures were near \(10^4\) K and the upper temperature boundaries were at about \(10^6\) K. The plasmas at the \(10^5\) K temperatures were assumed to come from such structures (see, for example, Gabriel 1976). The calculations show that in all such structures in which energy is supplied by thermal conduction, the transition zone between the cold and hot boundaries is very thin. The width of the layers between \(4 \times 10^4\) K and \(2.2 \times 10^5\) K is a very small fraction of 1" (1" = 725 km).

In the following parts of the paper, I will review some of the relevant observations that can shed light on the above mentioned models. I will show that it is rather unlikely that most of the plasma responsible for the emission in the intermediate temperature range is part of structures that encompass the entire temperature range from \(10^4\) to \(10^6\) K. An attempt will be made to show that the plasma responsible for most of this radiation is an entity by itself composed of unresolved fine structures.
II. ON THE PROPERTIES OF THE 4 × 10⁴–2.2 × 10⁵ K PLASMA REGION FROM HIGH RESOLUTION SPECTRA

In the last decade solar observations have reached a rather high level of sophistication. For example, space instruments flown several times on rockets by the Naval Research Laboratory (NRL) have observed the Sun in the 1100–1700 Å region simultaneously with high spatial resolution (1″–2″) and high spectral resolution (0.06 Å) (the High Resolution Telescope Spectrograph [HTRS]; Brueckner, Bartoe, and VanHoosier 1977). Also the NRL Skylab SO 82-A instrument (Tousey et al 1977) and similar rocket instruments have obtained full disk solar images in the 200–600 Å range, with about 2″ spatial resolution and high spectral resolution. In none of these observations with high spatial resolution, nor in any other observation known to the author, is there a clear-cut image of a typical solar structure showing that the plasma at lower transition zone temperatures is part of a larger and continuous structure that extends into the corona. For example, in order to have a “clear-cut image” in the SO 82-A spectroheliograph data, one would need to find a set of images formed by increasingly hotter plasmas which, if reconstructed (i.e., overlaid), would form complete structures, perhaps loops that reach coronal temperatures. These structures would have to contain most of the transition zone temperatures plasma available in the immediate vicinity of the structures. Although on occasion one can see isolated loops of transition zone temperatures in the ATM SO 82-A images, OSO 8, and SMM, and in other instruments as well, these loops consist primarily of the 10⁵ K temperatures, and are not the typical structures under discussion. The transition zone emission does not unambiguously appear to arise in a thin interface separating chromospheric from coronal emission. Therefore, such structures cannot be used either to prove or to disprove the fact that most of the transition zone emission arises in a thin interface. However, not directly observing such structures certainly does not rule out their existence. In order to settle the issue, types of evidence other than direct images must be considered.

a) On the Distribution of Temperature versus Height

The SO 82-B normal incident spectrograph on Skylab (Bartoe et al. 1977) produced high resolution solar spectra in the wavelength range 1100–4000 Å. The spatial resolution achieved by the instrument was 2″ × 60″, and the pointing stability was much better than 1″. The instrument produced a great number of spectra from various solar regions. One type of observation called “limb scan mode” proved to be extremely valuable. For such a scan the slit was placed tangent to the solar limb, and spectra were taken at a number of positions inside and outside the white light limb (–12″, –4″, –2″, 0″, +2″, +4″, +6″, +8″, +12″, and +20″). The spectra contained many lines from neutral atoms and singly ionized atoms that give information on plasmas at low temperatures (Tₑ ≤ 2 × 10⁴ K). In addition, two-, three-, and four-times ionized atoms give information of plasmas at intermediate temperatures (4 × 10⁴ < Tₑ < 2.2 × 10⁵ K). Finally a group of highly ionized atoms produce forbidden lines in the 1100–4000 Å range that give information on coronal plasmas (Tₑ ≥ 10⁶ K). The intensity behavior of optically thin lines as a function of height outside the limb of a coronal hole, derived from such spectral scans, is shown in Figure 1 (for more details see Feldman et al. 1976).

![Figure 1](image_url)
The lines from the cold and intermediate plasmas are grouped according to temperature of formation, and their average limb brightening curves are shown. The intensities are normalized to the peak intensities of lines above the limb. As can be seen from the figure, the lines divided according to approximate temperature of formation into two main groups. The first group comprises the cold lines with \( T_e < 2 \times 10^4 \) K. These lines peak in intensity at the limb \((0^\circ)\) and decrease in intensity very rapidly with height outside the limb. At \(+4^\circ\) the intensity for most of the lines relative to their intensity at the limb has decreased by more than an order of magnitude. The second group of lines contains the intermediate temperature lines with \( T_e \) ranging from \( 4 \times 10^4 \) to \( 2.2 \times 10^5 \) K. These lines peak in intensity between \(+2^\circ\) and \(+6^\circ\) above the limb.

The second group of lines can be further subdivided. The hottest lines from ions such as \( \text{N v} \) and \( \text{O v} \) decrease in intensity more slowly with height above the limb than lines from ions such as \( \text{O iv} \) and \( \text{C iii} \). The hot lines peak in intensity between \(+4^\circ\) and \(+5^\circ\) outside the limb, while the colder lines from ions such as \( \text{C iii} \) and \( \text{O iv} \) peak at heights near \(3^\circ\). Although this particular effect is best seen in the extended atmosphere of the coronal hole, the same conclusion can be drawn from spectra of quiet regions analyzed by Kjeldseth Moe and Nicolas (1977), Doschek et al. (1976), and Mariska, Feldman, and Doschek (1978).

The current theory which treats the transition zone as an interface between the chromosphere and corona predicts that the entire transition zone emission must arise in a rather thin layer, much less than \(1^\circ\). Furthermore, the theory also predicts that small variations of the properties of the models such as the peak temperature of the coronal loop or its density do not change the slope of the emission measure versus temperatures between, say, the \( 4 \times 10^4 \) K plasma and the \( 2.2 \times 10^5 \) K plasma (Mariska 1982). However, in order to reproduce the limb brightening curves in which the peak intensities of the \( 1 \times 10^5 \) K and \( 2 \times 10^5 \) K plasmas are separated by more than \(1^\circ\), and at the same time retain the thin properties of the transition zone, one needs to assume not only that the transition zone conforms to local changes in height of the chromosphere, but also that the emission measure versus temperature distribution changes dramatically with height of formation. This is a contradiction between observations, and theoretical predictions.

Observations of the intensity of the coronal emission as a function of height above the limb using the SO 82-B instrument are more difficult. The intrinsic intensities of the coronal forbidden lines are low and some of them are blended with colder lines. However, a close inspection of the \( \text{Fe xii} 1242 \) Å line in the Skylab data indicates that the line intensity is more or less constant between \(0^\circ\) and \(+8^\circ\) (Doschek et al. 1976). Furthermore, higher spatial resolution observations from HRTS (Brueckner, Bartoe, and VanHoosier 1977) show that the intensity actually appears to peak at the white light limb. Such observational facts have been known for many years to solar observers engaged in studies of coronal lines in the visible spectral range (Canfield 1982). If indeed most of the emission from the \( 4 \times 10^4 - 2.2 \times 10^5 \) K plasma comes from a thin transition zone interface, it is expected that the coronal emission from \( \text{Fe xii} \) would reach peak intensity at heights greater than the height of maximum transition zone emission, i.e., greater than \(4^\circ\). Thus, the coronal line observations also contradict the thin interface concept.

b) On the Spectral Line Widths versus Temperature and versus Height

In structures in which the temperature is changing in a continuous manner it is generally expected that certain physical properties will also show some degree of continuity. One property that can be investigated for continuity is the nonthermal mass motion, a property that has been determined from the profiles of optically thin emission lines. Observations near the limb \((+4^\circ)\) have shown that the low temperature lines \((T_e < 2 \times 10^4 \) K\) exhibit nonthermal mass motions of about \(10 \) km s\(^{-1}\) or less. Lines formed at increasingly higher temperatures exhibit higher nonthermal mass motions. At heights for which the intermediate temperature \((2 \times 10^5 \) K\) lines reach their maximum intensity the nonthermal mass motions reach a value of about \(26 \) km s\(^{-1}\) (Doschek et al. 1976; Feldman et al. 1976; Kjeldseth Moe and Nicolas 1977; Mariska, Feldman, and Doschek 1978). However, at coronal temperatures the mass motions are only \(20 \) km s\(^{-1}\) (Cheng, Doschek, and Feldman 1979). Also, the intermediate temperature line profiles increase in width at increasingly higher limb positions, and therefore the nonthermal mass motions for the intermediate temperature range increase with limb height. At \(12^\circ\) above the limb the motions generally are some \(10 \) km s\(^{-1}\) higher or about \(36 \) km s\(^{-1}\) (Mariska, Feldman, and Doschek 1979). On the other hand, the nonthermal mass motions of the coronal lines do not show such behavior. They are at about \(20 \) km s\(^{-1}\) all the way out to the limit of our measurements, at about \(30^\circ\).

c) On the Electron Density as a Function of Temperature in Different Solar Regions

High resolution spectroscopy in the 1100–4000 Å region is a very effective tool for the determination of electron densities in the solar atmosphere. The Stark effect that broadens hydrogen Balmer lines is a sensitive indicator of the electron density of the \(8 \times 10^3 \) K plasma. Stark effect measurements of Balmer lines emitted at \(+2^\circ\) and \(+4^\circ\) above the limb are available for spectra of a coronal hole, a quiet Sun region (Rosenberg, Feldman, and Doschek 1977), and three active regions (Feldman and Doschek 1977). An electron density of \(2 \times 10^{11} \) cm\(^{-3}\) was measured for the five regions. The uncertainties for the densities obtained from the active regions are about \(\pm 10\%\) while in the quiet Sun and coronal hole they are less than a factor of 2.

Density diagnostics for the higher temperature regions are also available and have been applied to spectra.
C III and Si IV are two ions emitted at approximately the same temperature \( T_e \approx 7 \times 10^4 \) K. At solar densities the ratio of the 1403 Å Si IV line to the 1909 Å C III line is a direct measure of the electron density (Feldman and Doschek 1978). Figure 2 shows the above ratio for two of the active regions mentioned before as well as for the coronal hole and quiet Sun region mentioned above. As can be seen from the figure, the electron density in the coronal hole at a height of +2" to +4" is about a factor of 2 below that of the quiet region while the active regions are as much as an order of magnitude more dense than the quiet Sun region.

The electron density in the corona can be measured from line ratios of high temperature forbidden lines. The UV lines available belong to Fe xii and S x ions emitted at \( T_e \approx 1.2 \times 10^6 \) K. Measurements of coronal densities above active and quiet regions (Feldman et al. 1978; Feldman, Cohen, and Doschek 1983) show that the electron densities in the two types of regions are the same to within the measurement uncertainties, which are better than a factor of 2. Although the measurements were done at heights larger than +6" in order to avoid contamination from low temperature lines, they are not expected to change significantly at +4".

As seen before, the intermediate temperature plasmas behave differently than the chromospheric and coronal plasmas. While the densities of the chromosphere and corona above the various regions do not vary from region to region, the densities of the intermediate temperature plasma vary significantly. It is also interesting to note that the chromospheric pressure \( T_e N_e \) is \( (8 \times 10^7) \times (2 \times 10^{11}) = 1.6 \times 10^{15} \) cm\(^{-3}\) K, and the coronal pressure is \( (1.2 \times 10^6) \times (1 \times 10^9) = 1.2 \times 10^{15} \) cm\(^{-3}\) K. These pressures are about the same, while the intermediate temperature plasma pressure in active regions is \( (1.2 \times 10^5) \times (1 \times 10^9) = 1.2 \times 10^{16} \) cm\(^{-3}\) K, an order of magnitude higher.

d) The Emission Measure Distribution from Observations and from Model Calculations

The emission measure distribution EM(\( T_e \)) derived from spectral line intensities may be defined as (Athay 1981),

\[
\int_0^1 EM(T) = \int_0^1 \frac{N_e^2}{d \log T_e} \, da,
\]

where \( N_e \) is the electron density, \( ds \) is measured along magnetic field lines, and \( da \) is measured along isotherms. The length \( da \) is the unit length of the isotherm. A plot of the empirical \( \log EM(T) \) versus temperature for a typical quiet Sun region reveals a minimum in \( \log EM \) at about \( \log T_e \approx 5.4 \) (see Fig. 3 and Fig. 5 in Athay 1982). When compared with solar model calculations the following picture emerges. At higher temperatures the slopes of the two curves resemble each other rather nicely, while at lower temperatures there is a large

![Fig. 2.—Variations in electron density relative to the quiet sun as revealed by variations in the 1403 Å Si IV to 1909 Å C III ratio. The original data for the quiet Sun is discussed by Doschek et al. (1976); the coronal hole is discussed by Feldman et al. (1976); active region B and active region C are discussed by Feldman and Doschek (1978).](image-url)
discrepancy. At $T_e < 10^5$ K the measured emission measure exceeds the calculated one by more than an order of magnitude (see Fig. 3). In a recent paper Athay (1982) reinvestigated the properties of the empirical and calculated emission measure curves and came to the following conclusions: "Models of the chromosphere-corona transition region in which energy is supplied by thermal conduction and downflow of hot material and lost by radiation are investigated for different magnetic field geometries and for different dependences of downflow velocity on the local temperature. It is shown that neither the field geometry nor the dependence of velocity on temperature are important factors in the comparison of empirical and theoretical emission measures. Each of the models works well for $T > 2.5 \times 10^5$ K but fails badly for $T < 2.5 \times 10^5$ K." He also stated that "the total failure of all models for $T < 2.5 \times 10^5$ K is a clear indication that the models have either a grossly incorrect geometry or they are omitting or misrepresenting a fundamental energy transport process."

e) Conclusions

In previous sections, experimental evidence was presented in order to argue that the properties of the intermediate temperature plasma are different from the properties of the chromosphere and corona. By doing so I brought evidence against the idea that all the plasmas observed in the $10^4-10^6$ K temperature region are part of the same continuous structures. Furthermore, I do not know of any experimental evidence that supports the type of model criticized above. The main reason for proposing this model was the simplification that results in lumping all the plasma seen above the photosphere into one set of structures. I would like to propose that while a very small part of the emission detected in the $4 \times 10^4-2.2 \times 10^5$ K region consists of the "true" transition zone plasma, which is a physical interface between the chromosphere and corona, that most of the observed emission from intermediate temperatures belongs to an altogether different entity. This entity is present as part of the solar atmosphere independent of the corona. I would also like to suggest that the volumes of plasma responsible for the $4 \times 10^4-2.2 \times 10^5$ K emission be called "unresolved fine structures" (UFS).

III. ON THE PROPERTIES OF THE UNRESOLVED FINE STRUCTURES

In previous sections we have already discussed some of the properties of the unresolved fine structures (UFS):

(1) We have shown that the nonthermal mass motions in the UFS are rather high. They vary between 18 and 26 km s$^{-1}$ over the temperature range $4 \times 10^4-2.2 \times 10^5$ K. The measurements at Sun center and near the limb are very similar. However, high above the limb the nonthermal mass motion in the UFS increases with height. The increase is on the average by about 10 km s$^{-1}$ between $+4^\circ$ and $+12^\circ$.

(2) It was shown that the emission from the UFS peaks at about $+2^\circ$ to $+4^\circ$ above the limb and is still visible at heights of about $+12^\circ$ and higher.

(3) The emission measure distribution of the UFS changes as a function of height above the limb. The ratio of hotter to colder material increases with height.

(4) The electron density of the UFS is different at the same temperature for different types of solar regions. The electron density in a quiet Sun region is twice the density of the coronal hole discussed above while the density in active regions is a factor of 10 larger than the density in the coronal hole.

In this section I would like to discuss several more properties of the UFS: The 1909 Å C III line originates from the metastable energy level $2s2p^3P_1$. At solar densities $N_e > 10^9$ cm$^{-3}$, the population of this level approaches a state of quasi equilibrium with the ground state $2s^21S_0$. Under such conditions the population of the $2s2p^3P_1$ level relative to the $2s^21S_0$ level is almost independent of the electron density of the plasma. Its dependence on the electron temperature is also small. The intensity of the 1909 Å C III line is primarily a function of the number of C III ions along the line of sight (Feldman and Doschek 1978). Figure 4 shows the intensity of the line as a function of limb position in a coronal hole, quiet Sun region, and two active regions. As can be seen, the values at each limb position below $+6^\circ$ do not change by more than a factor of 2. At higher heights above the limb the coronal hole C III intensity falls much more slowly than for the other regions. Integrating the 1909 Å C III line intensity between 0° and $+8^\circ$ shows that the number of ions for all the observed regions is the same to within a factor of 2 despite the fact that the electron density in the regions changes by more than a factor of 10.

(e) Thus, one more property of the UFS can be stated as follows: The production of C III ions, or, in general,
the production of plasma at $6 \times 10^4$ K in these particular structures, depends very little on the nature of the solar region. We have mentioned only C III because we do not have any other line with similar properties in the available spectral region. However, it may well be that this conclusion can be extended to all the $4 \times 10^4$–$2.2 \times 10^5$ K plasma.

In a paper by Feldman, Doschek, and Mariska (1979) we have used the height distribution of the plasma, the absolute intensity of emission lines at the limb and at Sun center, as well as the electron density in the region, to calculate the filling factor of the intermediate temperature emitting structures. One assumption in the calculations was that the structures are at least 2" long. Under this assumption it was found that at heights of +4" above quiet regions, the net area occupied by plasma at intermediate temperatures covers only $\sim 1\%$ of the solar surface and at higher heights even less. In the high density active regions which have similar amounts of plasma, the area occupied by intermediate temperature material is significantly smaller. The area of the solar surface imaged on the entrance slit of the SO 82-B spectrograph is $2'' \times 60'' = 120$ square arcsec. One percent of this area is only 1.2 square arcsec. It is rather unlikely that only one structure lies within each slit position. If this would be the case, one would expect large intensity variations between the various slit pointing positions. Assuming several, say 10, structures in each imaged slit area, the cross-sectional area of each structure in a quiet Sun region is only 0.1 square arcsec and in active regions still smaller.

(f) In conclusion, we can state that the net area occupied by the intermediate temperature plasma is extremely small in size and the structures are as yet unresolved by current instrumentation.

(g) One more interesting fact about the UFS concerns absolute wavelength measurements. When comparing the absolute wavelengths of lines emitted by the $4 \times 10^4$–$2.2 \times 10^5$ K plasma to wavelengths of lines from $10^4$ K plasma, relative-wavelength shifts of lines can in many cases be detected. When observing quiet regions, with a slit that covers a large area ($\geq 1'' \times 1''$), primarily redshifts of the $10^5$ K type plasma are detected that correspond to velocities of about five km/sec (see Doschek, Feldman, and Bohlin 1976; Gebbie et al. 1981). When observing active regions, the redshifts are even larger (Feldman, Cohen, and Doschek 1982). This is seen at Sun center as well as near but inside the limb. From the available small sample of HRTS data there are indications that the same shifts persist also above the limb (Dere 1982). It is important to notice that the shifts are only a fraction of the line width. It is also important to note that effects other than net mass motions may produce small shifts of line centers.

IV. ON THE SHAPES OF THE UNRESOLVED FINE STRUCTURES

Perhaps the most intriguing property of the UFS is the fact that generally they exhibit redshifts, and it is immaterial if the observations are at Sun center, or near the east or west limbs. The average amount of redshift does not show significant center to limb variation. In order for such an effect to take place the emitting system has to exhibit some unique asymmetric properties. In

Fig. 4.—The intensity of 1909 Å C III lines in different solar regions; from Feldman and Doschek (1978)
particular these unique properties have to apply to limb observations.

A somewhat opaque spherical shell in which the downfalling emission measure is larger than the uprising emission measure will produce such an effect. A pulsating spherical shell in which the $10^5$ K plasma is brighter during the phase in which the radius is decreasing than during the phase in which the radius is increasing would also produce the types of line shifts observed. Such a model will produce asymmetric line shapes. The extent of the asymmetry can be determined from theoretical modeling. It is known that the solar line shapes deviate slightly from Gaussian shapes particularly far in the wings (Kjeldseth Moe and Nicolas 1977).

If indeed these are the shapes of the UFS, other properties of the UFS discussed above could also be explained, at least qualitatively. In particular the non-thermal mass motion could be explained as the average rate of pulsations, which are on the order of $20$ km s$^{-1}$. Assuming that the shells reach an average size of about $1''$, the pulsation time will be of the order of $10$ s, i.e., between a diameter of $0.5$ and $1.5$. It is expected that such spherical shells would have to be influenced by the local magnetic field. A stronger magnetic field, such as that present in active regions, may produce a large pressure in such spheres.

V. CAN WE DETECT THE “TRUE” TRANSITION ZONE PLASMA?

In the previous section it was shown that the filling factor of the unresolved fine structures is very small. Therefore, it is reasonable to expect that occasionally, fairly large areas of the solar surface (several arcsec in size) will be free from the UFS.

When looking at the very high resolution images of lines emitted by the $4 \times 10^4$–$2.2 \times 10^5$ K plasma that have been recorded by the HRTS instrument, one can see large intensity variations on scales of a few arcsec. These types of variation are sometimes more than an order of magnitude. They appear over quiet regions as well as over active regions. I would like to suggest that the features with the lowest intensities observed by the HRTS instrument correspond to the “true” transition zone, i.e., the interface plasma separating the chromosphere and corona in a particular structure. I suggest that the high intensity features are a superposition of the two types of plasma, i.e., the “true” transition zone and the UFS. If this is correct, the properties of the “true” transition zone should be more in line with the properties of the chromosphere and corona. The pressure should be about the same, e.g., $1 \times 10^{15}$ cm$^{-3}$ K. The nonthermal mass motion should be not more than 20 km s$^{-1}$ for the $10^5$ K plasma, and the differential emission measure should agree with the theoretical calculations.

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