The fine structure constant \( \alpha \) sets the strength of the electromagnetic force. The Standard Model of particle physics provides no explanation for its value, which could potentially vary. The wavelengths of stellar absorption lines depend on \( \alpha \) but are subject to systematic effects owing to astrophysical processes in stellar atmospheres. We measured precise line wavelengths from observations of 17 stars, selected to have almost identical atmospheric properties to those of the Sun (solar twins), which reduces those systematic effects. We found that \( \alpha \) varies by \( \leq 50 \) parts per billion within 50 parsecs from Earth. Combining the results from all 17 stars provides an empirical local reference for stellar measurements of \( \alpha \), with an ensemble precision of 12 parts per billion.

where \( \alpha_0 \) and \( \alpha_{\text{lab}} \) are the laboratory and observed values of \( \alpha \), respectively; \( \Delta \alpha \) is the line shift in velocity units; and the sensitivity coefficient \( Q \) describes how much a given line shifts to the blue (for positive \( Q \)) or red. The approximation is valid for \( \Delta \alpha / \alpha < 1 \). In practice, the velocity shifts are measured for multiple lines and different atoms and ions, which is known as the many multiplet method. Using lines with a wide variety of \( Q \) coefficients increases the sensitivity to variations in \( \alpha \).

Sun-like stars are potentially suitable targets for the many multiplet method: Their spectra contain thousands of narrow, well-defined, strong (but unsaturated) absorption lines (Fig. 1A). The observed wavelengths of these lines could in principle be compared with their laboratory values while simultaneously accounting for the star's radial velocity. However, this simple approach is limited by large systematic errors; several physical mechanisms can shift the lines by up to \( \sim 700 \) km s\(^{-1} \) from their laboratory wavelengths, and the line profiles are asymmetric because they arise over a range of depths in stellar atmospheres (\( \delta, \theta \)). These effects produce velocity shifts (\( \Delta \omega \)) between lines, typically \( \Delta \omega \sim 250 \) km s\(^{-1} \) (\( \delta \)), which is equivalent to \( \Delta \alpha / \alpha \sim 6 \) ppm for a typical range in \( Q \) coefficients of \( \approx 0.07 \) (10). Direct comparison of absorption lines in a single giant star to laboratory values has already reached this systematic error limit (5).

We adopted an alternative technique that compares absorption lines between stars that have intrinsically similar spectra, eliminating the need to compare with laboratory wavelengths. The atmospheric spectrum of an isolated main-sequence star depends primarily on its mass and heavy-element content, which determine three primary observable parameters: the effective temperature \( T_{\text{eff}} \), iron metality [Fe/H], and surface gravity log \( g \). We restrict our analysis to solar twins, which are defined as stars with these parameters within 100 K, 0.1 decimal exponent (dex), and 0.2 dex of the Sun's values, respectively. Spectra of two solar twins used in our analysis are shown in Fig. 1A. We measured the velocity-space separations of pairs of lines and then compared the same sets of lines between stars (Fig. 1B). This approach reduces the systematic errors from astrophysical line shifts and asymmetries because of the similarity of their stellar parameters. The use of pairs of lines removes any dependence on the stars’ radial velocities, including any variations that could be caused by an orbiting companion (such as in a planetary or binary stellar system). For main-sequence stars, line shifts and asymmetries were observed to be correlated with the line's optical depth and wavelength (\( \theta \), so we selected pairs with similar absorption depths (within 20%) and small separations (<800 km s\(^{-1} \)), equivalent to \( \approx 13 \) Å at 5000 Å (11–19). We chose these values to reduce the systematic effects while maintaining sensitivity to variations in \( \alpha \) between stars.

We applied this solar twin method to archival solar twin spectra from the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph mounted on the European Southern Observatory (ESO) 3.6-m telescope at La Silla Observatory, Chile. HARPS is highly stable over time (\( \delta \theta \), and its wavelength scale has been precisely characterized by using laser frequency combs (15, 16). This sets an instrumental systematic error limit of \( \sim 2 \) m s\(^{-1} \) in the velocity separations of line pairs (12). To reach this level, we restricted our analysis to HARPS exposures corrected for nonuniform detector pixel sizes (corrections, \( \sim 25 \) m s\(^{-1} \)) (13, 17) and applied a further correction for sparsely sampled wavelength calibration (corrections, \( \sim 5 \) m s\(^{-1} \)) (13, 16).

We selected 16 bright (nearby) solar twins with HARPS spectra, with signal-to-noise ratio (SNR) > 200 per 0.8 km s\(^{-1} \) pixel, plus the Sun through reflection of its light from the asteroid Vesta (with SNR > 150) (table S1) (13). With these SNRs, the statistical uncertainty in the velocity separation of two unresolved absorption lines is \( \sim 25 \) m s\(^{-1} \) from a single exposure, assuming that they absorb 50% of the stellar flux at their cores (18). The median number of HARPS exposures available was 10 exposures per star (range of 1 to 128), so by combining results from multiple exposures, we expected median statistical uncertainties to reduce to 8 m s\(^{-1} \) per line pair, per star. By averaging over the sample of 17 stars, the uncertainty approaches that imposed by the available instrument calibration (12).

From 8843 lines listed in a solar atlas (19), we selected 22 that are separated from each other and not blended with other nearby
stellar or telluric (Earth atmosphere) lines (12, 13). All 22 lines are strong but unsaturated, absorbing 15 to 90% of the continuum in the HARPS spectrum of the Sun. The 22 lines, which form 17 different pairs (some share common lines), arise from the neutral atoms sodium (Na), calcium (Ca), titanium (Ti), vanadium (V), chromium (Cr), iron (Fe), and nickel (Ni), plus singly ionized Ti. Their Q coefficients have been calculated previously (10). The 17 pairs of lines have a wide range of sensitivity to variation, with differences in Q within each pair from ~0.08 to ~0.18 (10).

We measured pair separations using a fully automated process for all of the 423 HARPS exposures. In each exposure, the core of each line—the central seven pixels, spanning ~5.7 km s⁻¹—was fitted with a Gaussian model to determine the centroid wavelength. We then computed the wavelength differences between line pairs in each exposure, incorporating the corrections for the effects discussed above (11–13).

We denote these pair separations $\Delta v_{\text{sep}}$ for pair $i$. In principle, they can be compared to gauge any $\alpha$ variation between these 17 solar twins. However, an analysis of 130 stars spanning a larger range in $T_{\text{eff}}$, [Fe/H], and log $g$ (300 K, 0.3 dex, and 0.4 dex around solar values, respectively) has shown that pair velocity separation varies systematically with the stellar parameters, typically by ~60 m s⁻¹ across this range (12, 13). We fitted a quadratic model to those correlations and used it to compute the expected line pair separation for each star in our sample, denoting the resulting values $\Delta v_{\text{sep,mod}}$. We also incorporated an intrinsic star-to-star scatter, $\sigma_i \approx 0$ to 15 m s⁻¹ (11, 13). We then used $\Delta v_{\text{sep}} – \Delta v_{\text{sep,mod}}$ to correct the observed separations for each individual star:

$$\Delta v_{\text{sep}} = \Delta v_{\text{sep,raw}} – \Delta v_{\text{sep,mod}} (T_{\text{eff}}, \text{[Fe/H]}, \log g)$$

For each line pair $i$, the value of $\sigma_i$ is the systematic error in $\Delta v_{\text{sep}}$; it is the typical absolute value of the intrinsic deviation from the model.

The $\Delta v_{\text{sep}}$ values have previously been calculated (11) from the HARPS solar twin exposures. For each line pair in each solar twin, the velocity separation measurements from multiple exposures were combined by using a weighted mean, with outliers excluded through an iterative process (12, 13). Multiple exposures were available for 14 of the solar twins, allowing us to check for systematic errors as a function of time. The optical fibers that feed light from the telescope into HARPS were changed in mid-2015, resulting in large calibration changes. Analysis of the pre- and post-fiber change epochs separately—including the determination of $\Delta v_{\text{sep,mod}}$—has shown no evidence for systematic differences in $\Delta v_{\text{sep}}$ between them (11). We therefore combined their weighted mean $\Delta v_{\text{sep}}$ values. Three of the 17 line pairs appear twice in each exposure because they are in the overlapping wavelength ranges of neighboring diffraction orders. We treat these two instances separately because we found differences of ~20 m s⁻¹ between their $\Delta v_{\text{sep}}$ values, which we ascribe to optical distortions within HARPS. Nevertheless, their weighted mean $\Delta v_{\text{sep}}$ values show no systematic differences for our 17 stars or the larger sample (12), so we combined the $\Delta v_{\text{sep}}$ value for two instances of a pair using a weighted mean.

Our derived values of $\Delta v/\alpha$ for each star are shown in Fig. 2. The $\Delta v_{\text{sep}}$ value for a line pair $i$ is converted to $\Delta v/\alpha$ by using Eqs. 1 and 2 and the $Q$ coefficient calculations (10). For each star in Fig. 2, the $\Delta v/\alpha$ values from all pairs were consistent with each other, so they were combined by using a weighted mean. The weights in that process and the final uncertainties include the statistical uncertainties, derived from the SNR of the HARPS spectra, and systematic errors that incorporate the star-
to-star scatters for all line pairs ($\sigma\nu_{\lambda}$) and a smaller contribution from the uncertainties in the $Q$ coefficients. Because a line can be shared by multiple pairs, its statistical and systematic uncertainties cause correlated errors across those pairs; we used a Monte Carlo method to compute the combined $\Delta\nu/\nu$ and its statistical and systematic uncertainty for each star ($I3$).

We found no variations in $\alpha$ between nearby solar twins (<50 parsec), with a typical (median) uncertainty in $\Delta\nu/\nu$ of ≈50 parts per billion (ppb) (adding statistical and systematic errors in quadrature). The precision reaches ≈30 ppb for some stars, which is ≥30 times more precise than individual quasar absorption systems ($2, 4$). The systematic error term dominates in these cases (Fig. 2), mainly because of the intrinsic star-to-star scatter, $\sigma_{\alpha}$ ≈ 10 to 15 m s$^{-1}$ per line pair $i$. The solar twins method provides ≥100 times more accuracy than comparison between lines in individual white dwarfs or giant stars with their laboratory counterparts ($5, 6$). The results for the 17 stars are formally consistent with each astrophysical and instrumental effects that the combined uncertainties cause correlated errors across those stars because they share common line pairs ($I3$). The weights are the inverse variances from quadrature addition of the statistical and systematic uncertainties in $\Delta\nu/\nu$ for each star. The combined result (Eq. 3) acts as an entirely empirical reference for stellar measurements of $\alpha$. This and the ability of our automatic analysis procedure to recover shifts in $\alpha$ between stars were tested by altering the wavelength measurements for half our twins by amounts corresponding to a $\alpha$ variation of 100 ppb ($I3$). Re-running the full analysis but removing these stars from the determination of $\Delta\nu_{\text{model}}$ recovered an 86 ± 19 ppb difference between the shifted and unshifted twins. The discrepancy arises because some measurements of shifted lines are excluded as outliers; the shifts introduced are much larger than the total uncertainties (including $\sigma_{\alpha}$).

This confirms that our analysis process would still have detected any large (~100 ppb) discrepancies between some twins if they were present in the data.

Combining the results from all 17 stars provides a weighted mean with 12 ppb ensemble precision:

$$\langle \Delta\nu/\nu \rangle_w = 7 \pm 5_{\text{stat}} \pm 1_{\text{sys}} \text{ ppb} \quad (3)$$

where $\langle \Delta\nu/\nu \rangle_w$ and its $\sigma$ statistical uncertainty and systematic error were calculated from the Monte Carlo simulations to account for the correlations between results for different stars because they share common line pairs ($I3$).

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**SUPPLEMENTARY MATERIALS**

science.org/doi/10.1126/science.abi9232

Materials and Methods
Figs. S1 to S4
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Submitted 1 April 2022; accepted 14 October 2022
10.1126/science.abi9232