

How Do We Know What Stars Are Made Of?

QTC-005 · From Quarks to Consciousness

The Universe, Life, and How We Found Out

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Epistemic profile: Current scientific interpretation

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Article Abstract

We cannot scoop material from the Sun, yet modern astronomy measures stellar chemical abundances with remarkable precision. The route from light to composition is not a direct reading of a cosmic barcode. A spectrum records wavelength-dependent interactions between radiation and matter; atomic physics identifies possible transitions, while temperature, pressure, ionization, excitation, line saturation and atmospheric structure determine how strongly those transitions appear. This article follows that chain from Fraunhofer's unexplained dark lines and Comte's claim that stellar chemistry was inaccessible, through Kirchhoff, Bunsen, Saha, Cannon, Maury and Cecilia Payne, to modern 3D and non-LTE abundance analysis. It also shows where the method remains model-dependent. Spectroscopy works because laboratory physics, atmospheric modelling and multiple observational cross-checks constrain the inference together—not because a dark line automatically states how much of an element a star contains.

In 60 Seconds

We know what stars are made of without touching them because their light has interacted with matter before reaching us. Atoms and ions absorb or emit photons at characteristic wavelengths, so line patterns can identify chemical species. But identification is only the first step. A strong line can result from high abundance, favourable excitation, a particular ionization state, saturation, pressure, temperature or atomic transition probability. Saha's ionization theory helped turn stellar spectra from a classification scheme into physics, and Cecilia Payne used that physics in 1925 to show that hydrogen and helium dominate stellar atmospheres. Modern analyses go further: they compare observed spectra with radiative-transfer calculations, laboratory atomic data and model atmospheres, often using 3D and non-LTE corrections. The result is an inference with uncertainties, not a physical sample. The Sun provides unusually powerful checks—and also a warning: its best photospheric abundances still participate in an unresolved high-precision tension with helioseismology.

Why This Question Matters

Astronomy repeatedly asks us to trust claims about places no human can visit. Stellar chemistry is a particularly sharp test because, in 1835, Auguste Comte argued that it was not merely difficult but fundamentally inaccessible. Within a generation, spectroscopy changed the rules. The important lesson is not that Comte was foolish. It is that science can enlarge what counts as evidence. A distant

star still sends no bottle of gas to Earth; instead, its photons become the sample from which a constrained physical reconstruction is made.

1. A Barcode Made of Missing Light

The Question

If a star is unreachable, what could count as a chemical sample? In 1835 Auguste Comte argued that stellar composition lay beyond observation. Astronomy's answer was not to reach the star, but to discover that the light already reaching us carries physical traces of the matter it crossed.

Comte's argument was coherent on its premises. In the nineteenth lesson of his Cours de philosophie positive, he separated astronomical questions that could be reduced to visual observation from those he believed required other kinds of access. Shapes, motions and distances seemed obtainable; chemical composition, he wrote, did not.[17] The mistake was not a failure of logic so much as an incomplete theory of what light could reveal.

Joseph Fraunhofer had already supplied part of the empirical puzzle. In 1814 he systematically measured hundreds of narrow dark features crossing the solar spectrum, building on an earlier observation by William Hyde Wollaston.[3,4] Fraunhofer used the lines as stable optical markers. He did not yet possess the physical theory needed to read them as chemistry. Observation came before explanation.

Kirchhoff and Bunsen supplied the decisive change. Laboratory substances produced reproducible spectral features, and Kirchhoff connected bright emission lines from heated gases with dark absorption features in the solar spectrum. Matching the sodium signature in the laboratory with solar Fraunhofer lines turned a remote pattern of missing light into evidence for sodium in the solar atmosphere.[5] The star had not become physically accessible. The meaning of its photons had changed.

The word barcode is therefore useful only if we resist taking it literally. A supermarket barcode is designed so that a scanner can map a pattern directly to an item. A stellar spectrum is produced by radiative transfer through a physical atmosphere. It contains identifiers, but those identifiers are embedded in temperature, pressure, motion, opacity and geometry. The spectrum is the observation; chemical composition is the inference.[1,13]

Where That Leaves Us

A star does not have to deliver matter to Earth for chemistry to become accessible. Fraunhofer measured a pattern before its meaning was known; Kirchhoff and Bunsen showed that laboratory physics could decode part of it. Light had become a remote sample. But why can particular wavelengths identify particular atoms in the first place?

2. Why Each Element Leaves a Pattern

The Question

A spectrum can contain thousands of lines. Why should any of them belong reliably to hydrogen, sodium, iron or another species rather than being arbitrary marks produced by a complicated star?

The answer begins with quantum structure: atoms and ions do not exchange energy in arbitrary amounts.

Electrons bound in atoms and ions occupy allowed quantum states. A radiative transition between two states corresponds to a photon with a particular energy and therefore a particular wavelength. Laboratories can measure those wavelengths, energy levels, ionization energies and transition probabilities with high precision. Databases such as the NIST Atomic Spectra Database collect critically evaluated values used to identify astronomical lines.[2]

That makes wavelength a powerful identifier, but never an infallible one-line label. Different transitions can lie close together; stellar rotation, pressure and thermal motion broaden features; molecules create dense bands; and many astronomical spectra contain blends. A secure identification therefore uses the right ionization stage, multiple compatible lines and a model consistent with the star's physical conditions.[2,13]

The formation of an absorption line is also subtler than the classroom picture of a cool gas simply blocking a hotter background. At a wavelength where line opacity is high, photons escape from different depths than nearby continuum photons. Because temperature and the radiation source function vary through the atmosphere, that wavelength can emerge darker. Emission lines require different combinations of geometry, excitation and source function.[1,13] The 'cool cloud' picture is a useful limiting case, not a theory of stellar atmospheres.

This distinction matters because the same atomic transition that identifies a species is also sensitive to the environment in which it forms. The atom provides a set of possible wavelengths; the atmosphere decides which transitions are populated, how opaque they become and what profile reaches the telescope. Identification and abundance therefore share the same physics but are not the same problem.

Where That Leaves Us

Quantum energy levels make spectral wavelengths reproducible enough to identify atoms and ions, while radiative transfer explains how those features emerge from an atmosphere. Yet the line that identifies an element also responds to temperature, ionization and opacity. The next trap follows immediately: a stronger line does not necessarily mean more of that element.

3. The Trap: Strong Lines Do Not Mean Lots of Atoms

The Question

If hydrogen is the dominant element in ordinary stars, why are its visible lines not equally dominant in every stellar spectrum? The answer is the key to quantitative spectroscopy: a telescope sees only the atoms and ions that happen to occupy states capable of producing a given transition.

The Balmer lines provide the classic example. They arise from transitions involving hydrogen's $n=2$ level. In a cool atmosphere, relatively few hydrogen atoms are excited into that level. At higher temperatures the $n=2$ population grows, strengthening Balmer absorption; hotter still, increasing ionization removes neutral hydrogen from the relevant population. Hydrogen can remain overwhelmingly abundant while the visible Balmer pattern first strengthens and then weakens. [7,8]

Meghnad Saha gave astronomers the statistical-mechanical bridge. His ionization theory related the populations of ionization stages to temperature and electron pressure, allowing changing spectral patterns to be interpreted physically rather than treated only as categories.[6,7] The equilibrium assumptions are not universally exact—modern non-LTE calculations are needed when radiation and collisions do not maintain local thermodynamic equilibrium—but the conceptual shift was fundamental.

That shift also explains a striking sequence in the history of classification. At Harvard, Annie Jump Cannon reorganized earlier empirical classes into the OBAFGKM sequence and classified hundreds of thousands of spectra in the Henry Draper programme.[10,18] Antonia Maury had pursued a more detailed scheme in which line character and width carried information not captured by a single sequence, foreshadowing the importance of luminosity and surface gravity.[19] Classification worked before its full physical meaning was understood.

Payne then applied Saha's framework to the Harvard sequence. Much of the normal OBAFGKM progression could be understood as a temperature-driven change in excitation and ionization, not as stars being built from entirely different sets of elements.[8] Temperature is not the only axis: gravity, metallicity, peculiar abundances and molecules matter. But the apparent variety of spectra no longer required a different bulk chemistry for every spectral class.[1,13]

Where That Leaves Us

The strongest-looking line can be produced by a favourable atomic population rather than an enormous abundance. Saha supplied the ionization physics; Cannon and Maury showed how much empirical order existed before that explanation was complete. Once classification and composition were separated, one astronomer could ask the harder quantitative question: how much of each element is actually there?

4. Payne: Turning Spectra into Composition

Cecilia Payne's 1925 *Stellar Atmospheres* was built around precisely that distinction. She treated stellar spectra with ionization and excitation physics rather than assuming that line strength directly represented abundance. The result was radical: her calculations implied that hydrogen was about a million times more abundant than the metals in stellar atmospheres, with helium also enormously enhanced relative to the terrestrial-like mixture then commonly assumed.[8,15]

The historical record is more interesting than the simplified triumph story. Payne printed the large hydrogen and helium abundances, but she also wrote that the exceptional values were 'almost certainly not real.'[8] Henry Norris Russell later obtained the same qualitative result by a different analysis and explicitly cited Payne's earlier work.[9,15] That independent route matters scientifically: it was a triangulating cross-check on Payne's inference, not the source of her priority. The chronology therefore preserves both her discovery and the genuine caution surrounding a result that contradicted prevailing expectations.

Modern solar work confirms the broad physical conclusion while changing the precision and the machinery. A current 3D/non-LTE analysis gives present-day photospheric mass fractions near $X = 0.7438$ for hydrogen, $Y = 0.2423$ for helium and $Z = 0.0139$ for all heavier elements combined.[11]

Rounded, that is roughly 74.4%, 24.2% and 1.4% by mass. Those numbers are not universal stellar constants; they are a model-dependent inference for the present solar surface.

The importance of Payne's result is therefore not that one 1925 calculation supplied today's final table. It is that the correct physical question had been formulated. Once temperature, ionization and excitation were accounted for, spectra could be used to infer a composition dramatically different from the terrestrial mixture astronomers had expected. Quantitative values could then improve as atomic data, observations and atmospheric models improved.

Where That Leaves Us

Payne showed that decoding a spectrum requires physical modelling, not visual line counting, and the modern Sun still confirms her central conclusion: ordinary solar matter is overwhelmingly hydrogen and helium. The exact abundance numbers, however, have continued to move as the models improve. So how does a present-day abundance analysis turn a measured line profile into a number?

5. How Abundance Is Measured Now

A modern high-resolution spectrum first gives observables: wavelengths, line profiles, depths and equivalent widths. Equivalent width compresses the area removed by an absorption feature into the width of a hypothetical completely dark line with the same missing flux. It is useful because it measures total line strength without depending only on the central depth.[1,13]

But even equivalent width is not linearly proportional to abundance in all regimes. The classical curve of growth makes the reason visible. Weak lines lie on an approximately linear branch: more absorbers produce proportionally more equivalent width. As the line core saturates, adding absorbers changes the equivalent width much more slowly. In very strong lines, broad damping wings make the equivalent width grow more strongly again than on the saturated branch, but still sublinearly with abundance in the classical damping regime.[1,13] This curve is the bridge between 'line strength is not abundance' and a usable abundance diagnostic.

Many analyses now fit complete synthetic spectra instead. A model atmosphere specifies temperature, pressure, density and opacity as a function of depth; radiative-transfer calculations predict what spectrum should emerge for a trial chemical mixture. The abundances are adjusted until many observed lines and profiles are reproduced simultaneously.[1,13] High-quality work does not ask one line to carry the entire conclusion.

The atomic inputs matter just as much. Wavelengths identify transitions; oscillator strengths or transition probabilities help set their intrinsic strengths; ionization energies and collision rates influence populations; broadening data shape the profiles. An inaccurate atomic parameter can masquerade as a chemical abundance error, which is why laboratory measurements and critically evaluated databases remain part of observational astronomy.[2,13]

Astronomers also have to state what their abundance number means. On the common logarithmic number scale, hydrogen is defined to have $\log \epsilon(\text{H}) = 12$. The notation $[\text{Fe}/\text{H}]$ compares a star's iron-to-hydrogen number ratio with the solar value. By contrast, X, Y and Z are mass fractions for hydrogen, helium and everything heavier than helium. 'Metal' in stellar astronomy therefore means any element heavier than helium, not the everyday chemical category.[11,13]

Finally, the atmosphere itself is a model. Classical work often assumed a static one-dimensional atmosphere in local thermodynamic equilibrium. Three-dimensional hydrodynamic models represent convective inhomogeneities, and non-LTE calculations allow atomic level populations and radiation fields to depart from local equilibrium. Their corrections are not universally large or one-directional, but for some elements and stellar parameters they materially change the inferred abundance.[12,13]

Where That Leaves Us

Modern abundance analysis is an inversion problem: measure a spectrum, adopt atomic data and an atmosphere, calculate the emergent light, and adjust abundances until many diagnostics agree. Equivalent widths, curves of growth and full synthesis all make the dependence explicit. But an inference can be internally elegant and still wrong. What independent checks show that the reconstruction is attached to reality?

6. How Do We Know the Method Works?

One historical check is almost theatrical. During the 1868 solar eclipse, Pierre Janssen observed a bright yellow spectral feature in a prominence, and Norman Lockyer independently studied the same solar line; Lockyer and Edward Frankland argued that it indicated a new element. Helium was isolated from terrestrial minerals in 1895, and its spectrum matched the previously solar identification.[14,16] A chemical species inferred from light before it was isolated on Earth later appeared in a laboratory sample.

The modern checks are more systematic. Abundances inferred from different lines of the same element, different ionization stages and sometimes different molecules can be compared. In the Sun, many refractory-element photospheric abundances can also be compared with primitive CI chondritic meteorites. The agreement is generally strong, although volatiles and some individual elements are poor or discrepant meteorite checks.[11,13] Triangulation is valuable precisely because no single diagnostic is perfect.

The Sun also exposes the method's limits. Improved 3D and non-LTE analyses lowered important heavy-element abundances relative to older compilations. Standard solar models using these compositions then disagreed more strongly with helioseismic constraints on the solar interior—a tension known as the solar abundance or solar modelling problem.[11,20] Recent helioseismic work indicates that radiative opacity is an important part of the discrepancy, but different opacity calculations and experiments do not yet close the problem.[21] This is an Open Problem inside an otherwise mature method, not evidence that spectroscopy has failed.

There is a second boundary that matters. For most stars, ordinary spectroscopy measures the photosphere or another line-forming layer, not the nuclear-burning core directly. Diffusion, mixing, mass loss, accretion and evolution can alter surface composition.[1,13] A photospheric abundance is therefore not automatically a pristine birth composition or a direct core measurement. The inference must always name the physical region it describes.

The same spectrum can encode more than chemistry. Doppler shifts can reveal radial velocity, while line shapes constrain rotation, pressure and turbulence.[1] But distance is a separate inference problem: a chemical spectrum does not by itself tell us how far away the star is. That

boundary leads directly to QTC-006, where geometry, calibrated luminosities and cosmological redshift build a very different ladder of evidence.

Where That Leaves Us

Stellar chemistry is credible because different routes converge—and informative because they sometimes fail to converge perfectly. Laboratory spectra, multiple stellar lines, meteorites and solar models constrain the same inference from different directions. The remaining solar tension shows what precision science looks like when the method works but the model is incomplete. Next comes another remote quantity: distance.

What We Know, and How

Atoms and ions have characteristic quantum transitions whose wavelengths can be measured in laboratories and identified in stellar spectra. This establishes chemical species from remote light, while radiative-transfer modelling explains how those features form.[2,5,13]

Quantitative abundance is inferred rather than directly observed. Temperature, ionization, excitation, opacity, saturation, atomic data and atmospheric structure affect line strengths, so modern work uses equivalent widths or spectral synthesis together with model atmospheres and cross-checks among multiple diagnostics.[1,12,13]

For the Sun, current photospheric modelling still supports the broad Payne-era result that hydrogen and helium dominate by mass, while giving model-dependent modern values near 74.4% H, 24.2% He and 1.4% heavier elements.[11]

What We Still Don't Know

- The solar abundance/modelling problem remains unresolved: the best surface composition, helioseismic structure and radiative-opacity calculations do not yet form a completely consistent high-precision picture.
- For many stars and elements, abundance uncertainties are still limited by atomic data, atmospheric structure, non-LTE physics, blends and signal quality rather than by a single universal error source.
- Surface spectra do not generally reveal stellar core composition directly, and evolutionary changes can complicate the relation between present photospheric abundance and birth composition.

What Could Change Our Minds

- New laboratory spectroscopy or atomic calculations that systematically revise transition probabilities, collision rates or line identities would propagate into stellar abundance scales.
- A new generation of 3D/non-LTE models that shifts benchmark solar or stellar abundances beyond current uncertainties would update the quantitative composition while leaving the observed spectra themselves unchanged.
- A self-consistent solar model that simultaneously satisfies spectroscopic, helioseismic, neutrino and opacity constraints could close the present solar abundance problem—or reveal that a different missing ingredient is responsible.

If You Remember Only One Thing

A stellar spectrum is the observation, not the composition: chemistry emerges only when atomic physics, atmospheric models and independent checks turn patterns in light into constrained abundance inferences.

Related Articles

- QTC-001 — Everything You See Is the Past
- QTC-004 — Where Were the Atoms in Your Body Made?

References

- [1] David F. Gray. The Observation and Analysis of Stellar Photospheres, 4th ed.. 2021. DOI 10.1017/9781009082136. <https://doi.org/10.1017/9781009082136>
- [2] NIST ASD Team. Atomic Spectra Database, SRD 78, v5.12. 2024 update. DOI 10.18434/T4W30F. <https://physics.nist.gov/asd>
- [3] Joseph von Fraunhofer. Bestimmung des Brechungs- und Farbenzerstreuungs-Vermögens verschiedener Glasarten.... 1814. <https://books.google.com/books?id=HQk68aXiqeQC>
- [4] Fraunhofer-Gesellschaft. Joseph von Fraunhofer — Fraunhofer Lines. 2026 consulted. <https://www.fraunhofer.de/en/about-fraunhofer/profile-structure/chronicles/joseph-von-fraunhofer.html>
- [5] G. Kirchhoff; R. Bunsen. Chemische Analyse durch Spectralbeobachtungen. 1861. DOI 10.1002/jlac.18611180314. <https://doi.org/10.1002/jlac.18611180314>
- [6] M. Saha. Ionisation in the Solar Chromosphere. 1920. DOI 10.1038/105232b0. <https://doi.org/10.1038/105232b0>
- [7] Megh Nad Saha. Ionization in the Solar Chromosphere. 1920. DOI 10.1080/14786441008636148. <https://doi.org/10.1080/14786441008636148>
- [8] Cecilia H. Payne. Stellar Atmospheres: A Contribution to the Observational Study of High Temperature in the Reversing Layers of Stars. 1925. <https://www.gutenberg.org/cache/epub/73996/pg73996-images.html>
- [9] Henry Norris Russell. On the Composition of the Sun's Atmosphere. 1929. DOI 10.1086/143197. <https://doi.org/10.1086/143197>
- [10] Annie Jump Cannon; Edward C. Pickering / Harvard College Observatory. The Henry Draper Catalogue. 1918–1924. https://www.si.edu/object/siris_sil_176585
- [11] M. Asplund; A. M. Amarsi; N. Grevesse. The chemical make-up of the Sun: A 2020 vision. 2021. DOI 10.1051/0004-6361/202140445. <https://doi.org/10.1051/0004-6361/202140445>
- [12] M. Asplund. New Light on Stellar Abundance Analyses: Departures from LTE and Homogeneity. 2005. DOI 10.1146/annurev.astro.42.053102.134001. <https://doi.org/10.1146/annurev.astro.42.053102.134001>

- [13] Carlos Allende Prieto. Solar and stellar photospheric abundances. 2016. DOI 10.1007/s41116-016-0001-6. <https://doi.org/10.1007/s41116-016-0001-6>
- [14] American Physical Society. August 18 and October 20, 1868: Discovery of Helium. 2014. <https://www.aps.org/apsnews/2014/08/discovery-of-helium-1868>
- [15] American Astronomical Society / Harvard Plate Stacks. Cecilia Payne-Gaposchkin: history of thesis and Russell confirmation. 2022 / consulted 2026. <https://aas.org/posts/news/2022/04/month-astronomical-history-april-2022>
- [16] William Crookes. The Spectrum of Helium. 1895. DOI 10.1038/052428a0. <https://doi.org/10.1038/052428a0>
- [17] Auguste Comte. Cours de philosophie positive, Tome II. 1835. <https://www.gutenberg.org/cache/epub/31882/pg31882-images.html>
- [18] Center for Astrophysics | Harvard & Smithsonian, Wolbach Library. Astronomy and Spectroscopy — Annie Jump Cannon. 2018 / consulted 2026. <https://platestacks.cfa.harvard.edu/annie-jump-cannon/astronomy-and-spectroscopy>
- [19] Center for Astrophysics | Harvard & Smithsonian, Harvard Plate Stacks. Antonia Maury — stellar spectral classification. consulted 2026. <https://platestacks.cfa.harvard.edu/women-at-hco/antonia-maury>
- [20] G. Buldgen; P. Eggenberger; A. Noels; R. Scuflaire; A. M. Amarsi; N. Grevesse; S. Salmon. Higher metal abundances do not solve the solar problem. 2023. DOI 10.1051/0004-6361/202245448. <https://doi.org/10.1051/0004-6361/202245448>
- [21] G. Buldgen et al. Helioseismic inference of the solar radiative opacity. 2025. DOI 10.1038/s41467-024-54793-y. <https://doi.org/10.1038/s41467-024-54793-y>