Literature Research: Current Solar Composition and Approaching Methods

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1. **Introduction**

Nuclear astrophysics seeks to bridge the gap between nuclear physics and astrophysics by exploring how nuclear reactions in stars generate energy and synthesise elements. The Sun, as the closest star to Earth, serves as a natural laboratory for studying these processes, particularly the nucleosynthesis of isotopes that occur in its interior. Understanding the nuclear reactions within the Sun is crucial for explaining its energy production and the abundance of elements observed in both the Sun and the wider solar system.

The Sun’s energy is primarily generated through the proton-proton (pp) chain reaction, with secondary contributions from the carbon-nitrogen-oxygen (CNO) cycle and helium-burning processes [1]. These nuclear reaction pathways not only produce energy but also transform light elements like hydrogen and helium into heavier nuclei, contributing to the isotopic composition of the Sun.

Solar abundances specifically refer to the chemical composition of the Sun’s photosphere and, to a lesser extent, its deeper layers, as inferred through several approaching methods. These abundances are primarily determined through high-resolution spectroscopic analysis of the solar photosphere, which provides relative abundances of hydrogen, helium, and trace heavy elements. Recent advancements in spectroscopic techniques and solar models have enabled more accurate measurements of these abundances, offering new insights into the processes driving energy production and isotopic evolution within the Sun.

This review focuses on the current solar composition, summarising the observational data that underpin our understanding of the Sun’s chemical makeup and the implications for solar and stellar astrophysics. This study aims to bridge the gap between theoretical models and observational evidence by analysing the Sun’s abundances and their variations.

1. **Current Solar Composition**

**Hydrogen (H)** and **helium (He)** dominate the solar composition, accounting for approximately 98% of the Sun’s mass, while heavier elements—commonly referred to as “metals” in astrophysical contexts—make up the remaining 2%. These abundances are expressed relative to hydrogen, the most abundant element, with values normalised as [2]

Some key elements and isotopes are introduced in this research report. As discussed above, Hydrogen (), the most abundant isotope, forms the backbone of solar nuclear processes such as the proton-proton (pp) chain (releases positron and neutrino) together with(releases gamma-ray). is the second most abundant element, accounting for approximately 28% of its mass, and is a key intermediate in the CNO cycle, especially in stars with higher temperatures where the cycle contributes significantly to energy production. Both H and He determine the characteristics of the Sun’s generation of energies.

There are other elements called *Heavier elements* [3] (C, N, O, Fe, etc.) which dominate the interior of the Sun. Carbon, nitrogen, and oxygen contribute significantly to the solar metallicity and are critical in the CNO cycle, which serves as a secondary energy-generation pathway in the Sun. While the pp chain dominates energy production in the Sun, the CNO cycle becomes more significant in higher-mass stars. Oxygen is the most abundant heavy element in the Sun, with its abundance often serving as a reference for other elements.

Iron () is particularly notable due to its use in helioseismic studies as a marker of the Sun’s opacity. The absorption of radiation by iron and other heavy elements affects the efficiency of energy transport in the radiative zone.

The Sun’s chemical composition is closely related to the broader solar system because both originated from the same primordial solar nebula. Comparing solar and solar system abundances helps us understand the initial conditions of the nebula, validate nucleosynthesis theories, and study the formation and evolution of the Sun and planets. These comparisons provide critical insights into how elements were distributed during the early stages of the solar system.

In addition, the Sun’s chemical composition is determined through spectroscopic analysis of its photosphere, while the solar system’s composition is inferred from the study of **primitive meteorites**, such as CI carbonaceous chondrites, which reflect the solar nebula’s initial conditions. The sun contains more than 99% of the solar system’s mass, and therefore, that’s why a measurement of the Sun’s composition is a good approximation for the solar system’s composition.

1. **Methodology Approaches**

*Helioseismology* is a widely used technique which provides indirect measurements of the Sun’s internal structure, including helium abundance in the convection zone. Helio seismic data help validate or constrain solar models by comparing predicted sound-speed profiles with observed data. It takes 170,000 years for radiation to reach the surface from the Sun’s core, thus, the Sun can be considered opaque to electromagnetic energy. However, it is transparent to neutrinos and sound waves, which point that we can use acoustic energy to penetrate through the Sun, similar to ultrasound imaging for medical purposes. [3]

*Emission and Absorption Spectroscopies* are also used via the properties of emission and absorption lines. Focuses on the emission lines produced when electrons in a star's atoms jump to higher energy levels. Emission Spectroscopy focuses on the emission lines produced when electrons in a star's atoms jump to higher energy levels. Instruments such as modern telescopes equipped with spectrometers are employed to capture and analyse these spectrums. Advances in high-resolution spectrometers, such as those used in space-based observatories like the Hubble Space Telescope, have significantly enhanced the accuracy of abundance measurements by reducing atmospheric interference. Mathematically, the intensity of spectral lines can be represented as:, where is the initial intensity, and τ is the optical depth related to the abundance of elements.

Absorption Spectroscopy measures the absorption lines when light from a star passes through its atmosphere, telling us what elements are present. When the star's light passes through the cooler gas in the photosphere, atoms and ions in the photosphere absorb specific wavelengths, forming absorption lines in the spectrum, and each element has a unique spectral fingerprint enabling identification. Machine learning techniques are increasingly being used to automate the analysis of stellar spectra, enabling rapid processing of large datasets from surveys like Gaia-ESO and APOGEE. Photometry, when coupled with spectroscopy, allows the estimation of a star's effective temperature, which is critical for interpreting spectroscopic data and determining abundance ratios.

1. **Challenges in Spectroscopy**

Spectroscopic analysis, while invaluable for determining stellar abundances, faces several significant challenges that can impact the accuracy and precision of measurements. These challenges include line broadening, magnetic and hyperfine effects, spectral crowding, and atmospheric conditions [4].

Line broadening arises from several phenomena. Natural broadening is a quantum mechanical effect due to the Heisenberg uncertainty principle, which limits the precision of simultaneously measuring energy and time. It causes spectral lines to have a finite width. Thermal broadening occurs because of the random thermal motion of particles in a star’s atmosphere, leading to Doppler shifts in the wavelengths of spectral lines, broadening them further. Collisional broadening, on the other hand, results from collisions between atoms and ions in a dense stellar atmosphere, disturbing energy levels and leading to additional broadening of spectral lines.

Magnetic and hyperfine effects further complicate spectroscopic measurements. Zeeman splitting, for instance, is caused by the presence of magnetic fields in stellar atmospheres, which can split spectral lines into multiple components, complicating the identification and measurement of individual lines. Hyperfine structure arises from interactions between the nucleus and electrons in certain atoms, causing further splitting of spectral lines, which must be carefully accounted for in abundance calculations.

Spectral crowding and blending are also significant challenges. In stars with complex atmospheres or high metallicity, spectral lines often overlap or blend, making it difficult to distinguish individual elements or isotopes. Accurate analysis in such cases requires advanced techniques like spectrum synthesis, where simulated spectra are compared with observed data to disentangle blended lines and refine abundance estimates.

Lastly, variations in the star’s atmospheric opacity can affect the depth and intensity of spectral lines, leading to potential inaccuracies in abundance measurements. These effects must be modelled carefully to interpret observations correctly.

These challenges necessitate sophisticated modelling and analytical techniques, such as leveraging Boltzmann and Saha equations to calculate excitation and ionization states and employing high-resolution spectrometers to minimize uncertainties [5]. Despite these difficulties, ongoing advancements in instrumentation and computational modelling continue to improve the precision of spectroscopic measurements, enhancing our understanding of stellar composition and evolution.

1. **A Brief Introduction to Standard Solar Model**

The Standard Solar Model (SSM) is a theoretical framework that describes the Sun’s internal structure and evolution under the assumptions of hydrostatic equilibrium, thermal equilibrium, and spherical symmetry. It is calibrated using key observational inputs such as the Sun’s luminosity (), radius (), and age (4.57 Gyr).

A crucial input to the SSM is the initial chemical composition, particularly the ratio of heavy elements to hydrogen (Z/X). Historically, models based on high-metallicity abundances, such as those proposed by Grevesse & Sauval (1998), have been highly successful in reproducing solar observations, including sound-speed profiles obtained through helioseismology. However, more recent low-metallicity estimates, such as those by Asplund et al. (2009), have led to significant discrepancies between SSM predictions and observations, most notably in the depth of the convection zone and the Sun’s sound-speed profile. These issues, collectively termed the “solar abundance problem,” have driven renewed efforts to refine both the observational data and the physical inputs to the SSM.

Recent studies, such as Buldgen et al. (2024) [6], have explored the implications of updated opacity tables and high-metallicity abundances, suggesting that increased opacities may partially reconcile the differences between SSM predictions and helioseismic constraints. Additionally, Acharya et al. (2024) have emphasized the importance of revising nuclear reaction rates, particularly for the reaction in the CNO cycle, which influences the energy generation in the Sun’s core. These updates, alongside improvements in solar neutrino flux measurements, highlight the dynamic interplay between theory and observation in refining the SSM.

Despite ongoing challenges, the SSM remains a cornerstone for understanding stellar structure and evolution, serving as a benchmark for broader studies in astrophysics. Future advancements in spectroscopic precision, helioseismic analyses, and nuclear physics experiments are expected to further enhance the model’s accuracy and resolve outstanding discrepancies.

**References**

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