The trail of sulphur: from molecular clouds to life (SUL4LIFE)

Asunción Fuente

Centro de Astrobiología , CSIC-INTA, Spain

Sulfur is the tenth most abundant element in the Universe and one of the six essential elements for life. It plays a critical role in biological systems and has been proposed as a key catalyst in the formation of amino acids in the interstellar medium. Sulfur is also fundamental to our understanding of the physical and chemical evolution of molecular clouds and star formation. Along with carbon, it is a major electron donor in the diffuse and translucent phases of the ISM, influencing the ionization balance and chemistry. However, unlike other key elements such as carbon and oxygen, the gas-phase abundance of sulfur remains uncertain by several orders of magnitude, particularly in dense molecular clouds where more than 90% of the expected sulfur is unaccounted for.

This significant gap in our understanding stems from both observational and theoretical challenges. Observationally, sulfur-bearing species commonly detected in millimeter surveys—such as CS, SO, and SO2—represent only a fraction of the possible sulfur reservoirs. Crucial species like SH, SH+, and H2S are difficult to detect and are often excluded from systematic studies. Furthermore, atomic sulfur, which may constitute a major component of the sulfur budget, is particularly challenging to observe in cold, quiescent environments due to its excitation conditions.

The SUL4LIFE project addresses these challenges by combining different approaches: (1) a comprehensive database of multi-wavelength observations—including recent JWST, ALMA, and NOEMA data—targeting a wide range of sulfur-bearing species; (2) upgrading chemical models with *ab initio* theoretical calculations to derive accurate reaction rates and laboratory experiments to constrain critical parameters such as the photodesorption efficiencies of sulfur species from dust grains; and (4) advanced 3D magnetohydrodynamical simulations with coupled gas-grain chemistry (chemo-MHD) to follow the chemical evolution of sulfur from diffuse clouds to planet-forming disks.

We present most recent results demonstrating the transformative potential of this approach. These include JWST observations of atomic sulfur in the Orion Bar PDR, a survey of H2S in hot corinos, new experimental measurements on SO2 photodesorption that clarify its role in UV-irradiated environments, and the detection of reactive ions SH+ and CO+, as well as S2H—the only molecule with a disulfide bond detected thus far—in the Horsehead Nebula. Together, these findings offer a new paradigm for sulfur chemistry in space and pave the way toward a complete and coherent picture of sulfur journey from clouds to life-bearing worlds.