Unveiling Mass Transfer in Solar Flares: Insights from Elemental Abundance Evolutions Observed in Chang'E-2 and MSS Missions

Xiaoping Zhang[1], Man-Hei Ng[1], P. F. Chen[2]
[1] State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, [2] School of Astronomy and Space Science, Nanjing University
e-mail (speaker): xpzhang@must.edu.mo

The Solar X-ray Detector (SXD) onboard the Macao Science Satellite-1B (MSS-1B) enables detailed X-ray investigations of the solar corona across a broad energy spectrum, ranging from a few keV to several hundred keV. This wide energy coverage is achieved through two Soft X-ray Detection Units (SXDUs) and two Hard X-ray Detection Units (HXDUs) [1]. The MSS-1B/SXDUs employ silicon drift detectors to provide energy spectra spanning 0.7–24 keV, with a high energy resolution of 0.14 keV at 5.9 keV and a time cadence of 1 second. The HXDUs extend the coverage to 20–600 keV, offering an energy resolution of 12% at 59.5 keV. In addition, the Solar X-ray Monitor (SXM) onboard the Chinese lunar mission Chang'E-2 have also measured solar X-ray spectra from 0.5 keV to 10 keV, with an energy resolution of 0.3 keV at 5.9 keV [2]. With X-ray data from both detectors, one can extract the elemental abundances of the Sun.

Elemental abundances in the solar corona differ from those in the underlying photosphere. For example, low-first ionization potential (low-FIP; <10 eV) elements such as Ca, Mg, Fe, and Si are typically enhanced by a factor of ~1.5–4 in the solar corona compared to those in the photosphere, while high-FIP elements such as Ar, O, and S retain similar abundances to those in the photosphere. This phenomenon is known as the "FIP effect" and is generally explained by the ponderomotive fractionation model [3,4].

Flares and eruptions have also been of interest in abundance studies. Understanding the evolution of elemental abundances during solar flares is critical for unveiling the mechanisms of mass and energy transfer across solar atmospheric layers. Most previous research has focused on average abundances [5] or specific flare phases [6-8], leaving the entire flare process relatively unexplored. Additionally, some flare observations have suggested that the plasma composition is similar to the photospheric abundances [9]. Furthermore, the inverse-FIP (iFIP) effect——where low-FIP elements are depleted in the corona compared to the photosphere——has sometimes observed around flare peaks [6] or in highly complex solar active regions (ARs) [7, 10-12].

In this presentation, we will discuss our Sun-as-a-Star flare observations using data from the Chang'E-2 and Macao Science Satellite-1B (MSS-1B) missions, focusing on the evolution of elemental abundances throughout the flare process [13]. We report the first detection of the iFIP effect for Fe during solar flares in ARs 11149 and 11158, and reaffirm its existence for Si. Moreover, we have revealed an intriguing feature——the inertia effect——which plays a pivotal role in the chromospheric evaporation process during flares. Based on these findings, we present a CSHKP model-based interpretation to explain both the FIP and iFIP effects in flare dynamics, with the inertia effect being incorporated into the ponderomotive force fractionation model.

In addition, the impulsive phase of solar flares is often accompanied by the depletion of the low-FIP elements, whose abundances decrease from the coronal level to the photospheric level, and then recover back to the coronal level during the decay phase [14-17]. In our analysis of the 2024 February 16 flare event in AR 13576, however, we found that this depletion occurred well before the flare impulsive phase [18]. Using multiwavelength data from the SDO and CHASE missions, we determined that no filament was present 0.4 hours prior to the flare eruption, but an erupting filament was observed in association with the flare. The timing of the abundance change offers important clues about the location of magnetic reconnection. Based on these, we propose for the first time that the flare/filament eruption in this event was triggered by magnetic reconnection in the solar chromosphere, rather than in the corona as described in the standard flare model. These results provide new insights into mass transport and heating mechanisms in solar flare events.

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