Analysis of the space weathering effect on the surface of satellites and space debris

Abstract

Space weathering impacts all objects exposed to the space environment, including artificial satellites and space debris. Exposure to high-energy solar particles, micrometeoroids, and atmospheric particles degrades surface materials through oxidation, erosion, and paint peeling, producing wavelength-dependent changes detectable with photometric observations in the BVR_CI_C bands. Understanding the impact of space weathering on artificial space objects is crucial for their long-term monitoring and classification.

These effects were investigated through two observational campaigns targeting artificial space objects. The short-term campaign monitored recently launched CZ-3B rocket upper stages in geostationary transfer orbits over the course of eight months, while the long-term campaign focused on active GEO satellites annually over four years. The two groups differ in both material composition (painted metal vs. multi-layer insulation) and orbital environment.

Results show two distinct color index trends: GEO satellites exhibit darkening and spectral reddening consistent with the aging of multilayer insulation materials (e.g., Kapton, Mylar), whereas CZ-3B upper stages show brightening and spectral bluing, attributed to white paint flaking off and revealing the highly reflective metal surface underneath, accelerated by interactions with atomic oxygen. Differences between the two populations can be attributed to variations in material type, exposure duration, and orbital altitude.

Instrumentation

Our research data were collected using the 70 cm aperture Newtonian reflector (AGO70), equipped with Johnson-Cousins (BVR_CI_C) photometric filters. This instrument is located at the Astronomical and Geophysical Observatory in Modra, Slovakia (AGO). AGO70 is specifically designed for space debris and near-Earth object (NEO) observation, and its ability to track low Earth orbit (LEO) targets with high angular velocity and precision makes it an ideal tool for such research [1]. The color indices (B-V), (V-R_C), etc., are obtained from the object's brightness in individual filters.

Photometric methods

Color indices (CI) are obtained by calculating the difference in magnitudes between two photometric filters. Color indices provide an effective way to quantify the color of an object, which in turn relates to its spectral properties and surface material composition.

Photometric reduction is conducted through the principles of absolute photometry to be able to compare results obtained during different seeing conditions. [2]

The color indices (B-V), (V-R_C), (R_C-I_C), and (B-I_C) are used, where the latter represents the overall spectral slope across the whole visible spectrum, and the former three describe the slopes of smaller sections of the spectrum.

The impact of space weathering was examined on artificial space objects through two observational campaigns: a short-term and a long-term campaign.

Short-term campaign

The short-term campaign monitored recently launched CZ-3B upper stages over an eight-month period, orbiting in geostationary transfer orbits with perigees around 200 km. The surface composed of a white-painted metal typical for rocket bodies. Observations accounted for the phase angle and rotational period of the objects to ensure consistency in the data interpretation. The light curve of one of the CZ-3B rocket bodies is shown in Fig. 1 and the color index of the observed population in Fig. 2.

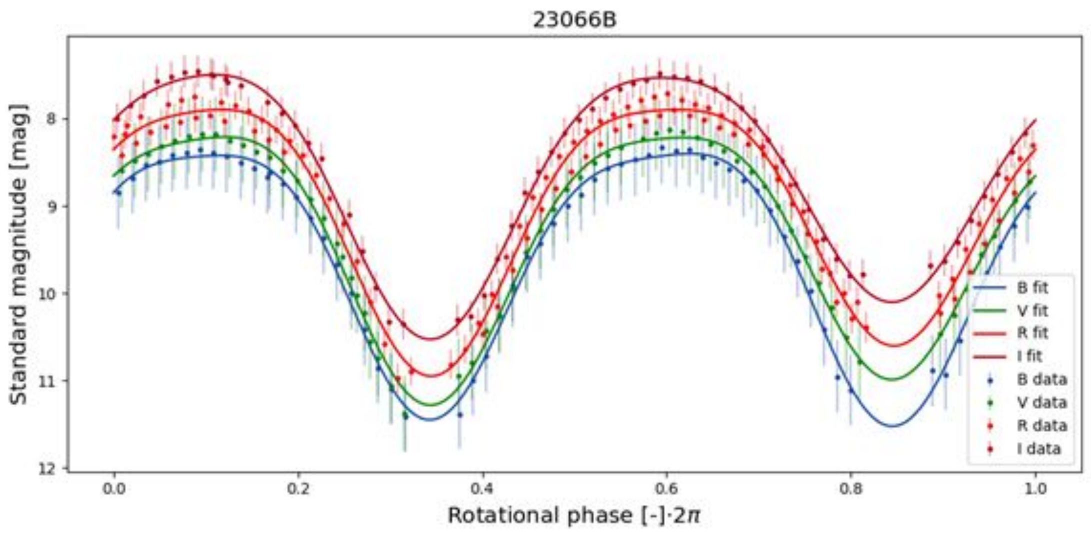

Fig 1: Folded light curve of object 2024-040B from 2024/11/10.

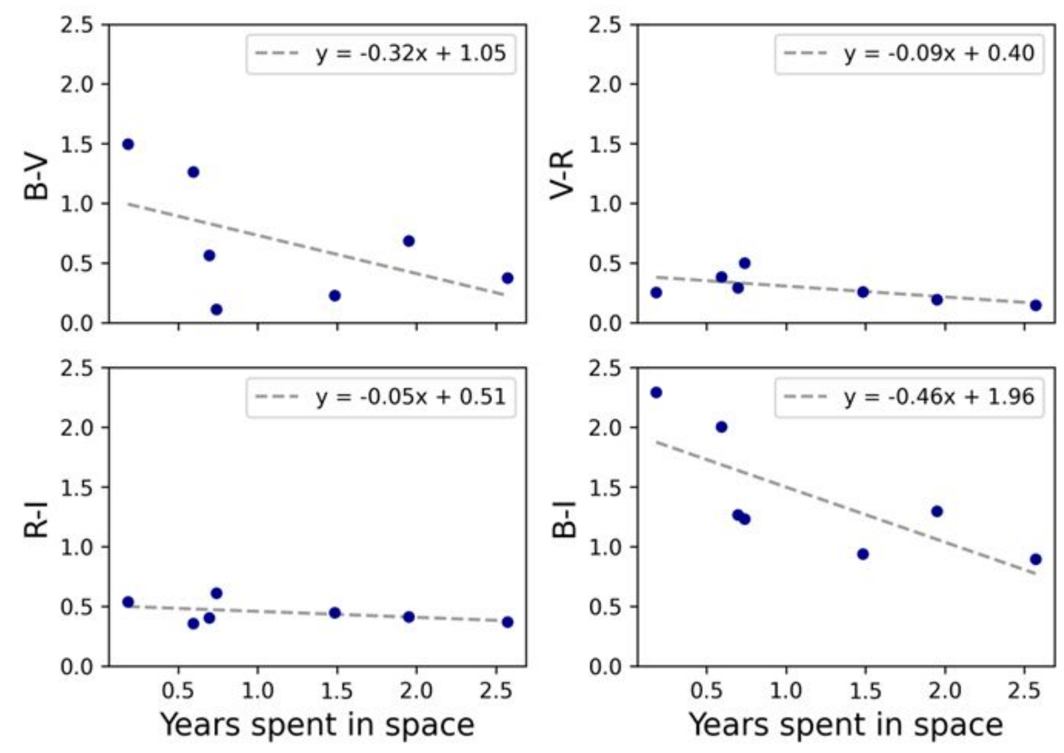

Fig 2: Evolution of color indices for selected CZ-3B upper stages.

Long-term campaign

The long-term campaign focused on active geostationary (GEO) satellites observed annually over a four-year period. These satellites had already spent several years in GEO prior to the study. The surface composition included buses covered in multi-layer insulation and solar panels. An example of color index changes of five GEO satellites with the same platform type is presented in Fig. 3. [3]

Results

The results revealed significant differences between the two groups. GEO satellites experienced darkening and spectral reddening of the surface material over time, typical for multi-layer insulation such as Kapton or Mylar. Meanwhile, CZ-3B upper stages showed brightening of the material and spectral bluing. This is explained by the white paint flaking off, accelerated by interactions with atomic oxygen in the upper parts of the atmosphere. As the paint peels off, the highly reflective metal surface underneath the paint starts to show through, increasing the reflectivity of the object and altering the reflectance spectrum. Differences between the two populations can be attributed to variations in material, age, and orbit.

References

[1] Šilha, J., et al. "Space debris observations with the Slovak AGO70 telescope: Astrometry and light curves." Advances in Space Research 65.8 (2020): 2018-2035.

[2] Zigo, M., et al. "Space debris surface characterization through BVRcIc photometry." Advances in Space Research 72.9 (2023).

[3] Zigo, M., et al., "Investigation of the space weathering rate of the geostationary satellites' surface materials using BVRI photometry." Advances in Space Research (2025).

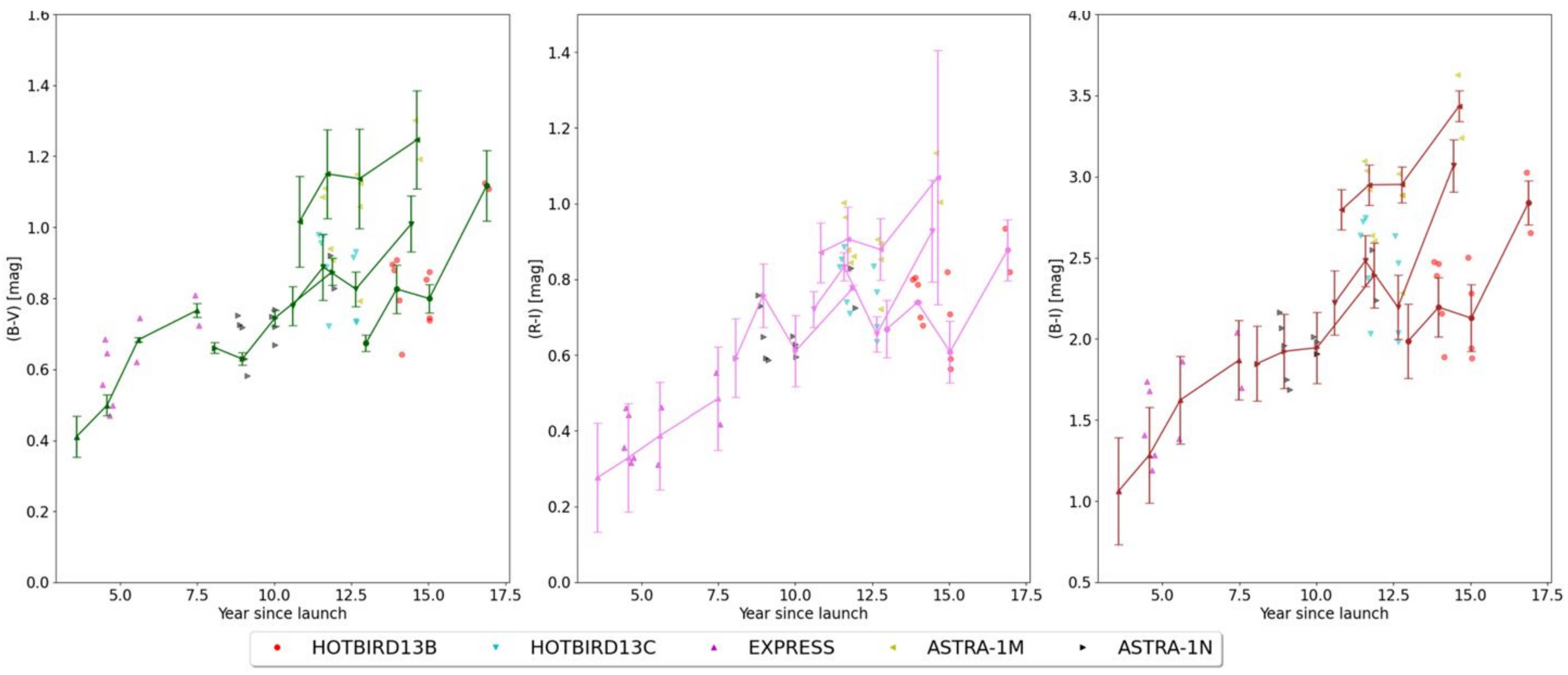

Fig 3: Evolution of color indices of HOTBIRD13B, HOTBIRD13C, EXPRESS, ASTRA-1M, and ASTRA-1N in terms of shared platform type EUROSTAR-3000. [3]

FAKULTA MATEMATIKY, FYZIKY A INFORMATIKY
Univerzita Komenského v Bratislave

MATFYZ CONNECTIONS

Katarína Sabolová, Jiří Šilha

Department of Astronomy, Physics of the Earth, and Meteorology, FMPH UK