Planetary Magnetospheric Modulation and Cometary Injection Effects on the Outer Heliospheric Boundary

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Abstract

This paper proposes two interacting mechanisms that influence the structure and variability of the heliospheric boundary: (1) Planetary Magnetosphere-Induced Outer Shell Modulation (PMIOSM), and (2) High-Inclination Cometary Injection Effects (HICIE). The first mechanism describes how large planetary magnetospheres—particularly those of Jupiter, Saturn, Uranus, and Neptune—alter the outer heliospheric pressure balance through sustained magnetic field interaction with the solar wind. The second mechanism addresses the role of long-period, high-inclination comets as transient plasma and molecular contributors to heliospheric anisotropy and localized outer boundary disturbances. Observational support is derived from ENA flux asymmetries detected in IBEX-Hi sky maps (1.1 keV), coordinated with planetary orbital data and cometary ephemerides. The analysis suggests that these combined effects modulate both persistent and transient features of the heliosphere's structure.

1 Introduction

The structure of the heliosphere is shaped by both internal solar activity and external interstellar conditions. This paper investigates internal planetary-scale influences and transient solar system events capable of modulating the outer heliospheric boundary. Specifically, we analyze:

- The role of planetary magnetospheres in shaping heliospheric asymmetry.
- The potential for cometary passages to introduce measurable perturbations.

These two mechanisms are modeled independently and in interaction, proposing a hybrid heliophysical feedback system driven by planetary orbital dynamics and cometary material injection.

2 Planetary Magnetosphere-Induced Outer Shell Modulation (PMIOSM)

Large planetary magnetospheres introduce anisotropies in the pressure balance between the outward solar wind and the inward interstellar medium. These field interactions result in measurable distortions in the heliospheric boundary, which manifest as asymmetries in energetic neutral atom (ENA) emissions.

Governing Expression

$$\Delta R_{\text{heliopause}} \propto \frac{B_p^2 R_p^2}{v_{sw} \rho_{sw}}$$

Where:

- B_p: Magnetic field strength of the planet
- R_p: Effective magnetosphere radius
- v_{sw}: Solar wind speed
- ρ_{sw}: Solar wind plasma density

Planetary orbital inclination introduces vertical deformation components, while longitudinal position affects radial symmetry.

3 High-Inclination Cometary Injection Effects (HICIE)

Comets on high-inclination orbits interact with the heliospheric structure in a different manner. As they approach perihelion, thermal activation results in volatile release and possible plasma coupling with the heliospheric environment. These events can locally distort or alter the outer shell structure.

Mechanism

- Comet traverses inner heliosphere on inclined orbit.
- Sublimation near perihelion emits charged particles and dust.
- Momentum transfer and plasma interactions may produce temporary ENA anomalies.

High-inclination comets act as vertical injectors, with exit paths allowing for bidirectional perturbation (entry and departure).

4 Observational Evidence and Data Correlation

ENA maps (IBEX-Hi, 1.1 keV) from 2009–2010 show:

- Asymmetric flux distribution correlating with Jupiter's orbital longitude.
- Reinforced boundary pressure in sectors aligned with Saturn and Neptune.
- Vertical compression aligned with Jupiter's orbital inclination (1.3 degrees).

Overlay comparisons with planetary positions and magnetosphere scales provide visual support for PMIOSM. Future tests will assess comet-induced deviations using perihelion passage timing and flux changes.

5 Conclusions and Next Steps

This paper proposes and partially supports a dual-modulator model for heliospheric boundary variability: planetary magnetospheric influence and cometary passage perturbation. Next-phase research will include:

- Time series analysis of ENA data across planetary conjunctions.
- Cross-correlation with known high-inclination cometary events.
- MHD simulation of magnetosphere-solar wind interactions at heliopause scales.

The combined influence of sustained magnetic fields and transient mass/plasma injections may offer new insight into heliospheric morphology and its evolution across solar cycles.