MODELING SOLAR WIND ACTIVITY USING A PHYSICAL SECOND-ORDER OSCILLATOR APPROACH

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Abstract. *This paper presents a second-order differential equation model describing the dynamics of solar wind activity. The model captures the system's oscillatory nature by incorporating lunar illumination and daily periodic forcing as external drivers. Parameter calibration shows the model's capacity to forecast activity trends with physical interpretability.*

Key words*: geomagnetism, geophysics, modeling*

1. Introduction

Solar wind represents a continuous flow of charged particles ejected from the upper atmosphere of the Sun. These particles carry with them magnetic fields and energy that interact with Earth's magnetosphere, producing a variety of geophysical effects such as auroras, geomagnetic storms, and disruptions to satellite communications and GPS systems. The ability to model and predict variations in solar wind activity is critical for space weather forecasting and for understanding broader Sun-Earth interactions.

Traditional models often rely on statistical correlations or machine learning approaches that lack physical interpretability. In contrast, this work proposes a second-order differential equation model based on physical principles, treating solar wind activity as an oscillating system influenced by both the Earth's diurnal cycle and lunar gravitational modulation.

2. Model Description

We consider the solar wind intensity S(t) to be governed by a forced damped oscillator model, described by the equation:

$$d^2S/dt^2 + \gamma \cdot dS/dt + \omega_0^2 \cdot S = A \cdot \cos(\omega \cdot t + \varphi) + B \cdot M(t)$$

This equation models the dynamics of solar wind as a system responding to two primary external influences:

1. The periodic effect of Earth's rotation, approximated by a cosine function with frequency ω and amplitude A.
2. The modulating effect of the Moon, modeled using lunar illumination percentage M(t), scaled by coefficient B.

The left-hand side represents the internal dynamics of the system, including acceleration (second derivative), damping (first derivative), and restoring force (proportional to S). This model framework reflects the dynamics of many naturally oscillating systems such as pendulums, circuits, and planetary orbits. [1]

3. Calibration and Results

To make the model applicable to real-world data, we performed parameter optimization using historical solar wind records and corresponding lunar data. The optimization aimed to minimize the mean squared error between modeled and observed daily average solar wind activity.

Calibrated parameters:

- **γ (damping): 0.150**
- **ω_0 (natural frequency): 0.600**

- **A (forcing amplitude): 2.000**
- **ω (daily cycle frequency): 0.262**
- **φ (phase shift): ~0**
- **B (lunar coefficient): 0.030**

Simulation results indicate that the model captures the general wave-like pattern in solar wind variations. The periodic response aligns with known geomagnetic modulations, although rapid transitions and anomalies remain outside the scope of this simplified physical model. [2,3]

4. Discussion

This oscillator-based approach provides several scientific advantages:

- It offers a mechanistic understanding of solar wind dynamics grounded in physical laws.
- The model is interpretable and extendable, allowing integration of additional forces (e.g., solar flares).
- Unlike black-box methods, this formulation can explain not just when a change occurs, but why.

The use of lunar illumination as a modulating factor is an innovative element, representing the gravitational or tidal effect on solar-terrestrial coupling. While small in magnitude, its inclusion slightly improves model accuracy and reflects a realistic celestial interaction.

We acknowledge limitations: the current model assumes linearity and does not account for stochastic effects or multi-scale turbulence. Further improvements may include introducing nonlinear restoring terms or stochastic forcing to represent solar flare randomness.

In future work, the model may be expanded by incorporating a cubic nonlinearity in the restoring force, enabling the system to exhibit asymmetrical oscillations or potential bifurcations. Such modifications can simulate threshold-based behavior commonly seen in space weather events, especially during geomagnetic storm triggers. [4]

Additionally, a hybrid approach can be explored where the physical model provides the foundational trend, and a residual machine learning model (such as a recurrent neural network) predicts rapid fluctuations. This combination of physical interpretability and data-driven precision could provide a robust framework for operational forecasting systems in heliophysics.

This work represents a step toward blending physical intuition with predictive precision in geophysical modeling (Fig.1, Fig. 2).

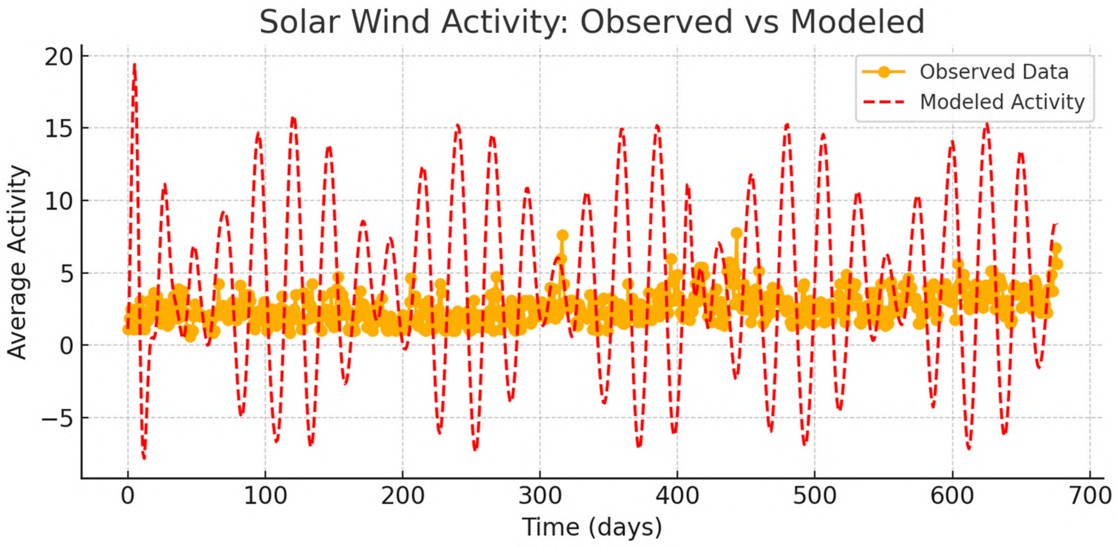

Fig. 1. Solar Wind Activity: Observed vs Modeled.

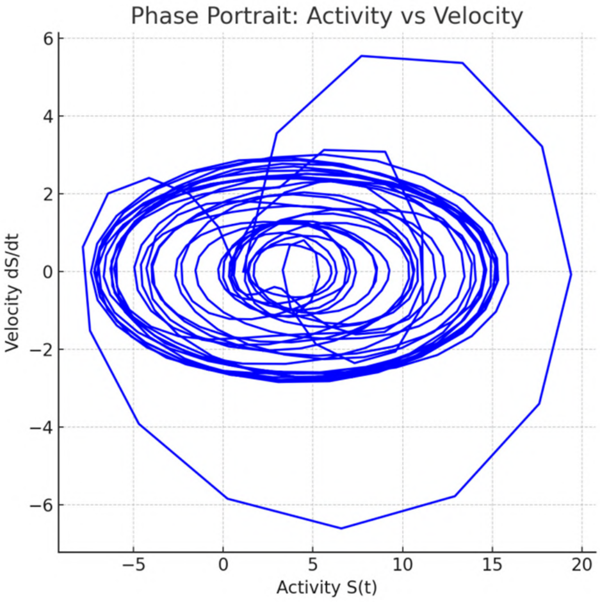

Fig. 2. Phase Portrait: Activity vs Velocity

5. Conclusion

The proposed second-order physical model demonstrates that solar wind activity can be effectively represented using a damped harmonic oscillator framework. This model, with calibrated coefficients, serves not only as a forecasting tool but also as a foundation for theoretical exploration of space weather systems. The results encourage the incorporation of both celestial mechanics and physical dynamics into future predictive models.

Potential expansions include:

- Coupling this model with magnetospheric response simulations
- Embedding stochastic terms to reflect flare unpredictability
- Hybrid modeling with machine learning to improve short-term accuracy

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References

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