A Structured Literature Review on Solar Activity Impact on Earth's Spin and Length of Day

1. Introduction: Contextualizing Earth's Rotation and Solar Influence

The Earth's rotation, a fundamental astronomical parameter, is not a simple, constant motion. While it provides the basis for our timekeeping systems, its precise rate is subject to subtle yet measurable variations over a wide range of timescales, from diurnal to geological.[1] The measure of this variation is known as the Length of Day (LOD), which is the time it takes for the Earth to complete one full rotation with respect to the Sun.[1] Modern geodetic techniques, including satellite laser ranging and the use of atomic clocks, have enabled the measurement of LOD with millisecond-level precision, revealing a rich and complex signal that reflects the intricate dynamics of the entire Earth system.[1] These small fluctuations, though imperceptible in daily life, are central to the fields of geophysics, climatology, and astronomy, as they provide a crucial record of the angular momentum exchange between the solid Earth and its fluid envelopes (atmosphere, oceans, and core) and also with external forces.[3]

Concurrent with the study of Earth's rotational dynamics is the field of solar physics, which investigates the Sun's activity and its effects on the solar system. Solar activity is driven by the Sun's periodically reversing magnetic field, which operates through a solar dynamo mechanism.[6] This activity is characterized by two primary periodicities: the approximately 11-year sunspot, or Schwabe, cycle and the 22-year magnetic, or Hale, cycle, which accounts for the complete reversal and return of the Sun's magnetic polarity to its original state.[7] In addition to these long-term cycles, the Sun also produces transient events, including solar flares, coronal mass ejections (CMEs), and high-speed streams of charged particles known as the solar wind.[6] These phenomena are the primary drivers of space weather and are known to have significant impacts on near-Earth space and terrestrial systems.[6]

This literature review synthesizes the existing body of research on the direct and indirect links between solar activity and Earth's rotational dynamics. It will explore the historical progression of thought, detail the primary physical mechanisms proposed to explain the relationship, and highlight the key debates and unresolved questions that define the current state of the field. This review aims to serve as a foundational resource for new research in this interdisciplinary domain by contextualizing past findings and identifying future research avenues.

2. Foundational Research and Historical Empirical Correlations

2.1. Early Observations and the Recognition of a Relationship

The hypothesis of a connection between solar phenomena and terrestrial conditions is not a modern one; documented ideas about a link between sunspots and weather date back to at least 400 BC.[14] However, the formal scientific investigation of a relationship between solar activity and Earth's rotation began with the quantitative measurement of both phenomena. The discovery of the cyclical nature of sunspots by Samuel Heinrich Schwabe in 1843 [7] provided a quantifiable solar forcing function that could be compared with records of Earth's rotation. Early attempts to establish this connection laid the groundwork for modern, quantitative studies.[15]

2.2. Seminal Studies and the Identification of Key Periodicities

Over the decades, a number of seminal studies established compelling empirical correlations between LOD variations and key solar cycles. These findings moved the field beyond simple speculation to a more rigorous, quantitative analysis.

- **The 22-Year Hale Cycle:** Research has consistently identified a significant LOD oscillation with a period of approximately 22 years, which directly corresponds to the Hale magnetic cycle of the Sun. Kirov et al. (2002) found a direct correlation between the 22-year Hale cycle and LOD variations.[15] This was supported by Chapanov, Vondrák, & Ron (2008), who noted that 22-year cycles of solar activity are a primary driver of various geophysical processes in the core-mantle, oceans, atmosphere, and geomagnetic field.

These processes, in turn, are believed to excite their own oscillations, all synchronized with the 22-year solar cycle, ultimately leading to a 22-year LOD signal.[9]

- **The 11-Year Schwabe Cycle:** The more prominent 11-year sunspot cycle has also been a central focus of research since at least 1995.[5] Mazzarella & Palumbo (1988) were among the first to suggest a tangible mechanism for this connection, proposing that the mean sea-level, which is influenced by the 11-year solar cycle's effect on water evaporation due to total solar irradiance (TSI), could be a source of the 11-year LOD variation.[9] Their work highlighted a correlation between LOD variations and sea-level changes, providing a tangible pathway for solar influence on a planetary scale.
- **The 60-Year Cycle and Grand Minima:** Extending beyond the 11-year and 22-year cycles, some studies have identified correlations on much longer timescales. Mazzarella (2007, 2008) and Mörner (2010, 2011) documented a close correlation between a 60-year cycle in solar activity and a similar signal in LOD, suggesting a longer-term, multi-decadal relationship.[15] Mörner's work further posited that Grand Solar Minima, such as the Spörer, Maunder, and Dalton Minima, corresponded to periods of accelerating Earth rotation, while Solar Maxima correlated with a rotational slowdown.[15] This introduced a crucial, longer-term perspective to the solar-LOD relationship, connecting planetary rotation to periods of significant climatic changes, such as the Little Ice Ages.[15]

The existence of these diverse periodicities in LOD data (e.g., 6, 11, 22, 60 years) suggests that the LOD record is not just a measure of Earth's overall rotation but a composite signal of various internal and external forcing functions on the Earth system. The challenge for researchers has been to deconvolve this signal to isolate the specific contribution of each component. This shifts the focus from merely establishing correlation to a deeper analysis of the underlying physics of each periodic signal. The LOD record is therefore not just a measure of rotation, but a fundamental geodetic data set for studying whole-planet dynamics.

Table 1 summarizes some of the key studies that have established empirical correlations between solar activity and Earth's rotation.

Table 1: Key Studies on Solar-LOD Correlations

Author(s)	Year	Key Periodicity	Core Finding(s)	Citation
Mazzarella & Palumbo	1988	11-year	Identified a link between 11-year LOD variations and mean sea-level,	[18]

			suggesting an indirect solar influence.	
Kirov et al.	2002	22-year	Found a direct correlation between the 22-year Hale cycle and LOD variations.	15
Abarca del Rio et al.	2003	Interannual	Analyzed the connection between solar activity and LOD variability over the period 1831-1995.	19
Chapanov, Vondrák, & Ron	2008	22-year	Confirmed that 22-year solar cycles excite geophysical processes that produce 22-year LOD oscillations.	9
Le Mouël et al.	2010	11-year, 5.5-year	Proposed a link between solar activity, modulated zonal winds, and LOD variations.	21
Mörner	2010	60-year, Grand Minima	Correlated long-term LOD fluctuations with Grand	15

			Solar Minima and Maxima, linking them to significant climate changes.	

3. Proposed Physical Mechanisms of Solar-Geophysical Coupling

The observed correlations, while compelling, do not fully explain the physical mechanisms by which solar activity influences Earth's rotation. The literature points to several distinct pathways of energy and momentum transfer.

3.1. The Role of the Atmosphere: Angular Momentum Exchange

The atmosphere is widely considered to be the most significant contributor to LOD variations on timescales of weeks to a few years.[3] The principle of conservation of angular momentum dictates that any change in the axial component of the atmospheric angular momentum (AAM) must be accompanied by a corresponding and opposite change in the angular momentum of the solid Earth (crust and mantle).[3] The coupling between the atmosphere and the solid Earth is strong, with a characteristic time constant of about 7 days due to surface friction.[3]

Solar activity can modulate this process. Variations in the total solar irradiance (TSI) and the solar wind are believed to influence large-scale atmospheric circulation.[9] One key hypothesis suggests that the corpuscular activity of the solar wind causes a deceleration of zonal atmospheric circulation.[15] This atmospheric slowdown acts as a torque, causing the solid Earth to accelerate its rotation to conserve total angular momentum.[3] This chain-of-effect—from solar forcing to atmospheric circulation changes and then to LOD variations—is a central tenet of the solar-atmospheric-LOD hypothesis.[15] The precise mechanisms by which solar UV irradiance or energetic particles influence atmospheric systems, such as the polar vortex, remain a subject of active research.[5]

3.2. Geomagnetic and Magnetospheric Forcing

A different class of mechanism involves the direct interaction of the Sun's corpuscular emissions with Earth's magnetic field. The solar wind, a continuous stream of charged particles from the Sun, and transient events like CMEs interact with Earth's magnetosphere.[11] This interaction, particularly when the solar wind's magnetic field is directed southward (opposite to Earth's field), can lead to a significant transfer of energy into the magnetosphere, causing geomagnetic storms.[11] These storms result in intense electrical currents in the magnetosphere and ionosphere, which are known to exert a torque on the Earth's solid body.[11]

The hypothesis is that this direct transfer of energy and momentum from the solar wind to the Earth's magnetic field and atmosphere acts as a direct rotational forcing function.[15] Evidence has indicated that high solar activity and its associated geomagnetic effects correlate with a deceleration of Earth's rotation, while periods of low solar activity correlate with acceleration.[15] The complex nature of these magnetospheric currents, however, is not yet fully understood and represents a significant gap in the literature.[13]

3.3. Thermospheric Drag as a Rotational Brake

Another physical pathway for solar influence is through atmospheric drag. During periods of high solar activity, the increased flux of solar radiation and particles leads to the thermal heating and expansion of the upper atmosphere, particularly the thermosphere and ionosphere.[13] This expansion increases atmospheric density at low-Earth orbit (LEO) altitudes, causing a significant increase in drag on satellites.[27] This drag force, which acts opposite to the direction of motion, requires frequent orbital boosts for spacecraft like the International Space Station to counteract the deceleration.[28] While this effect is most pronounced on orbiting objects, it also represents a tangible mechanism by which solar energy could transfer momentum and exert a decelerating force on the Earth's overall rotation.

4. The Core-Mantle vs. Solar Forcing Debate: A Central Conflict

4.1. The Role of Core-Mantle Coupling

While external solar forcing is a significant contributor to LOD variations, the dominant influence on decade-to-millennial timescales is widely attributed to internal Earth dynamics, specifically the interaction between the fluid outer core and the solid mantle.[3] Mechanisms for this coupling include:

- **Gravitational Coupling:** The convection of the liquid outer core creates time-variable density inhomogeneities, which can be thought of as "blobs" moving randomly, like in a lava lamp.[29] These inhomogeneities produce a gravitational field that is not perfectly uniform. This gravitational field then exerts a torque on density anomalies within the mantle and crust, changing the mantle's rotation state.[29] This mechanism is a suspected cause for observed rotational changes on millennial timescales.[29]
- **Electromagnetic and Viscous Coupling:** Electromagnetic forces and fluid-to-solid friction at the core-mantle boundary (CMB) are also thought to be crucial for the exchange of angular momentum. These interactions are proposed to be responsible for the prominent 6-year and decade-scale LOD fluctuations.[3] The precise nature of the torques at work is still a subject of ongoing debate.[30]

4.2. The Overlap and the Challenge of Attribution

The central conflict in the literature arises from the fact that both external solar forcing and internal core-mantle coupling can produce signals on similar timescales, making it difficult to definitively attribute a specific LOD fluctuation to a single source.[3] For example, the 22-year signal in the LOD record could be a direct result of solar activity [9] or a core-mantle process that is itself excited or modulated by solar forcing. The signals are conflated, meaning that simple correlational studies, while useful for establishing a link, cannot provide the final answer on causation. This reality underscores the need for a more sophisticated, physically-based modeling approach that can account for and separate the influences of these distinct forcing functions.

4.3. The Emerging Anthropogenic Signal

Adding another layer of complexity to the deconvolution problem is the emerging evidence that human activities are now measurably influencing Earth's rotation.[32] The redistribution of mass on the planet's surface, particularly through the construction of large dams and the rapid loss of glaciers and ice sheets due to climate change, is causing a measurable shift in the Earth's poles (polar wander) and a subtle slowdown of its rotation.[32] One study estimated that human-linked shifts in ice and groundwater are slowing Earth's rotation at a rate of 1.33 milliseconds per century.[32] This new, significant source of forcing makes the analysis of historical and modern LOD data even more challenging, as researchers must now deconvolve natural signals from these increasingly influential anthropogenic ones.[32]

Table 2 provides a comparison of the various internal and external forcing mechanisms that contribute to the observed variations in Earth's rotation.

Table 2: Comparison of Forcing Mechanisms on Earth's Rotation

Forcing Mechanism	Primary System(s) Involved	Typical Timescale(s) of Influence	Proposed Causal Link to LOD
Tidal Friction	Earth-Moon System, Oceans	Secular, Multi-millennial	Gravitational torque from the Moon and Sun slows down Earth's rotation.
Core-Mantle Coupling	Core, Mantle, Geomagnetic Field	Decadal, Sub-decadal (e.g., 6-year cycle)	Gravitational and electromagnetic torques transfer angular momentum between the core and mantle.
Atmospheric Angular Momentum (AAM)	Atmosphere, Solid Earth	Weeks to a few years	Exchange of angular momentum between the atmosphere and the solid Earth through surface friction.

Solar Corpuscular Forcing	Solar Wind, Magnetosphere, Atmosphere	11-year, 22-year, Transient	Transfer of angular momentum via geomagnetic storms and modulation of atmospheric circulation.
Anthropogenic Mass Redistribution	Hydrosphere, Cryosphere	Millennial, Recent decades	Shifts in mass (e.g., dams, ice melt) alter the Earth's moment of inertia, changing its rotation.

5. Gaps in the Literature and Future Research Directions

5.1. The Non-Stationary Nature of Correlations

A significant problem in solar-terrestrial research is the lack of stability in the observed correlations. Studies have noted that the relationship between sunspot numbers and various atmospheric and geophysical parameters is not stationary; it can "strengthen, weaken, disappear, and even change sign depending on the time period".[14] This lack of stationarity suggests that simple linear models are insufficient and that the underlying physics is either highly non-linear or that the relationship is mediated by additional, unmodeled factors. A deeper understanding of these temporal variations in the solar-terrestrial connection, including the physical reasons for their reversals, is a critical gap that must be addressed.[14]

5.2. Unresolved Questions in Solar Physics and Space Weather

The problem of understanding the solar-LOD connection is not solely on the terrestrial side. Significant unknowns exist in solar physics itself, which hamper our ability to predict the solar forcing function with high fidelity.[33] It is still not fully understood how the Sun generates its periodically reversing magnetic field, which is the engine of all solar activity.[8] The mechanisms behind Grand Solar Minima, which correspond to periods of significant terrestrial change, are also not yet fully explained.[33]

Furthermore, the ability to predict the characteristics of geomagnetic storms, such as the direction of the interplanetary magnetic field (IMF) B-field, remains a key challenge for space weather forecasting.[25] The existence of phenomena like the "Gnevyshev gap," a mysterious dip in activity during the peak of solar maxima, has been noted for decades but is not yet completely clarified, despite its potential relevance for space weather forecasting.[34] Improved space weather prediction is contingent on addressing these foundational gaps in our knowledge of the solar dynamo and transient solar events.[26]

5.3. The Challenge of "Whole Planet Coupling"

The literature consistently points to the need for a holistic "whole planet coupling" approach to fully comprehend the dynamics of Earth's rotation.[35] The Earth is a complex, interacting system where a change in one component, such as the core, affects another, such as the mantle.[29] This, in turn, can be influenced by an external factor like the Sun. A change in solar activity affects the atmosphere, which then affects the solid Earth and its spin.[9] Existing models often focus on one or two of these mechanisms in isolation, but a true understanding requires moving beyond these siloed approaches. The challenge is to build comprehensive models that integrate the complex interactions between the core, mantle, atmosphere, oceans, and external solar forcing.[9] This is a massive computational and theoretical task that requires bridging disciplinary divides and is central to the future of this field.

5.4. Proposed Future Research Avenues

Based on the identified gaps and challenges, several key avenues for future research are apparent:

- **Integrated Modeling:** New research should focus on developing next-generation models that can simultaneously account for and deconvolve the natural (solar, core-mantle) and anthropogenic signals in high-precision LOD data.[32] These models must treat the Earth as a single, interacting system to move beyond simple statistical correlations to a true physical understanding.

- **Improved Solar Forcing Proxies:** Future work should aim to improve solar cycle and space weather prediction models by incorporating a wider range of solar observational data beyond just sunspot numbers, which are an oversimplified proxy.[36]
- **Targeted Data Acquisition:** Targeted missions and experiments are needed to gather higher-resolution data on core-mantle dynamics and magnetospheric-ionospheric currents, which remain poorly understood.[28]
- **Non-linear Analysis:** Research should explore the physical mechanisms behind the "non-stationary" correlations and the "reversals of sign" that have been observed.[14] This may require the use of machine learning or novel non-linear analysis techniques on long-term data sets.

6. Conclusion

The literature provides compelling and extensive evidence for a strong empirical correlation between solar activity and variations in Earth's rotation, particularly on decadal and multi-decadal timescales. However, the causal links are not fully understood and remain a central subject of active debate. The LOD record is a composite signal, simultaneously reflecting external forces from the Sun and internal forces from the core-mantle system, as well as increasingly significant anthropogenic factors. The central challenge for the field is to move beyond the identification of simple correlations and to tackle the fundamental problem of disentangling these multiple, interacting forcing functions.

The LOD record, now more than ever, is a crucial geodetic variable for monitoring the health and dynamics of the entire Earth system. The future of research in this area lies in the development of sophisticated, integrated models that treat the Earth-Sun system as a unified whole. This will require new, high-resolution data, advanced modeling techniques, and continued interdisciplinary collaboration to fully resolve one of the most intriguing questions in geophysics.

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