Methods and Techniques for Measuring the Rotation Surface of the Sun: A Review

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ABSTRACT

This study examines scientific contributions from 1611 to 2024 and investigates techniques for detecting solar rotation velocity, highlighting the discovery of differential rotation through early sunspot observations in the 17th century by Christoph Scheiner and Galileo Galilei. Tools such as helioseismology and magnetographs have provided increasingly precise measurements as technology advanced, revealing significant variations in solar rotation at various depths and latitudes. The work highlights the cumulative aspect of solar rotation research, demonstrating how each discovery enhances previous findings to create a more comprehensive picture of solar dynamics and its influence on space weather.

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1. Introduction

Early 17th century Hans Lippershey's creation of the telescope transformed astronomical observations and opened the path for research of celestial events. One of the first users of such discovery, Thomas Harriot recorded Sun surface sunspot observations in 1610. These first investigations set the groundwork for knowledge of Sun rotational behavior [1]. In 1611, German astronomers David and Johann Fabricius utilized telescopes in northern Europe to observe sunspots. They were the first to calculate that the Sun rotates on its axis. Johann Fabricius authored the first scientific paper on sunspots, contributing significantly to solar science. Although Johann died in 1616, his groundbreaking work influenced subsequent research, including his father's contributions until his passing in 1617 [2]. Galileo Galilei further advanced solar observations in 1612 with his improved telescope. Independently verifying Johann Fabricius's findings, Galileo confirmed that the Sun rotates on its axis and estimated the equatorial rotation period to be approximately 27 days. These findings, depicted in figure (1), challenged the Aristotelian concept of an immutable and perfect celestial body. Galileo's observations of sunspots and Sun's rotation laid the groundwork for future studies on solar dynamics and differential rotation, which Christoph Scheiner later expanded upon [3].

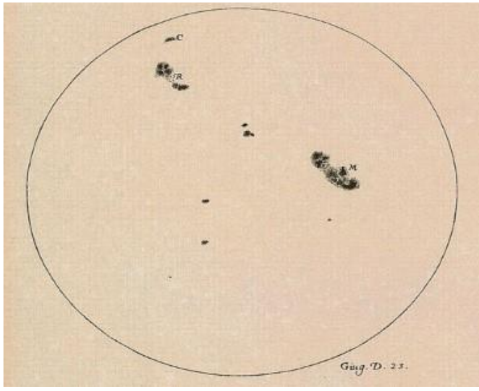


Figure (1) Galileo Galilei sunspot [3]

Around 1611, sunspot observations gained scientific attention, with Christoph Scheiner, a Jesuit scholar in Germany, making key contributions. Initially, Scheiner thought sunspots were planets crossing the Sun, but later realized they were part of the Sun. From his works in the year 1630, Rosa Ursina book, detailed sunspot observations and illustrations, reveals that, where the paths of sunspots vary as the seasons change and These variations are explained using the relationship of the incline in the Sun’s axis to the level of ecliptic, figure 2. Importantly, Scheiner also observed that the Sun rotates faster at the equator than at the poles, contributing to the understanding of differential rotation and solar dynamics [4].

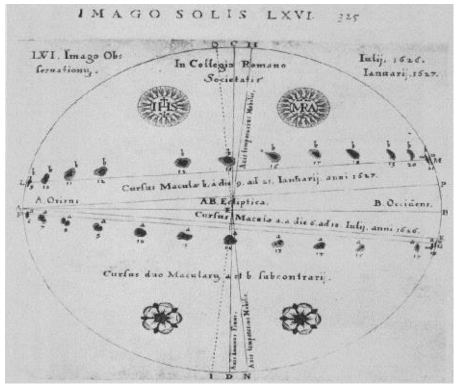
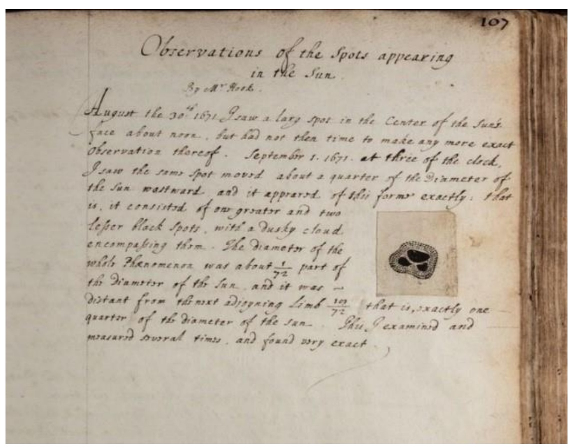


Figure (2) One of a great many sunspot drawings in Scheiner's "Rosa Ursina" [4].

In the 1650s, astronomers like Gregorius Ostreichus advanced solar studies by observing sunspots,



107

Observations of the Spots appearing in the Sun.
By Mr. Hook.

August the 30th 1671 I saw a large spot in the Center of the Suns face about noon, but had not then time to make any more exact Observation thereof. September 1. 1671. at three of the clock, I saw the same spot moved about a quarter of the Diameter of the Sun westward and it appeared of this forme exactly: that is, it consisted of one greater and two lesser black Spots, with a dusky cloud encompassing them. The diameter of the whole Phenomenon was about $\frac{1}{72}$ part of the Diameter of the Sun, and it was distant from the next adjoyning Limb $\frac{10}{72}$ that is, exactly one quarter of the diameter of the Sun. This I examined and measured severall times, and found very exact.

Figure (3) Observations of the Spots appearing in the Sun' by Robert Hooke [5].

confirming the Sun’s rotation. Around the same time, Francesco Maria Grimaldi improved optical technology for sunspot observation, though he is better known for wave theory. By 1665, Robert Hooke used enhanced telescopes for precise sunspot observations, Figure 3, improving accuracy in studying the Sun’s rotation and paving the way for future solar research [5]. And in the 1670s, Jean-Dominique Cassini discovered differential rotation, revealing varying solar speeds and advancing solar dynamics [6]. In 1687, Isaac Newton put the final nail in the coffin for the Aristotelian, geocentric view of the Universe. Building on Kepler’s laws, Newton explained why the planets moved as they did around the Sun and solar rotation about herself and he gave the force that kept them in check a name: gravity [7]. In the 1670s, Jean-Dominique Cassini made a groundbreaking discovery of differential rotation, revealing that the Sun's rotational speeds vary at different latitudes, thus advancing the field of solar dynamics [8]. The 17th century was a period of significant progress in solar studies, despite technological limitations and religious challenges, setting the stage for modern solar science. At the start of the 18th century, James Bradley and Johann Tobias Mayer were pivotal figures in advancing astronomical precision [9]. In 1727, Bradley uncovered the phenomenon of light, enhancing the precision of both stellar and solar observations and role in observing solar rotation. Bradley's emphasis on star positions helped to provide more exact Sun position measurements, therefore facilitating knowledge of Sun rotation. Johann Tobias Mayer improved celestial body positions, especially the Sun, by refining astronomical tables in the 1740s. Understanding solar movement equation required an understanding of the rotation velocity equation [10]:

$$v = \sqrt{\frac{GM}{R}} \; \ldots\ldots (1)$$

G: gravitational constant; M: Sun mass; v: orbital velocity at Sun's surface; R: Sun radius, Mayer's exact observations prepared the path for next investigations on solar rotation. also, William Herschel noted sunspots in the 1770s and linked solar activity with the climate of Earth, his studies advanced knowledge of Sun rotation and equatorial speed, which determine the Sun's rotational velocity by applying and represent it as [11]:

$$v = \frac{2\pi R}{P} \ldots\ldots (2)$$

R: Sun's radius; v: rotational velocity at the equator (~2 km/s); P: rotational period (~25 days). Fundamentally, Herschel's sunspot observations produced information regarding Sun rotation. He connected increased sunspot activity with greater Earth temperatures, therefore setting the stage for more research on Sun rotations well as their final impact on climate conditions [12]. Around the same time, Jean-Dominique Cassini II, in 1772, continuing his family's legacy, made groundbreaking discoveries regarding differential solar rotation. He observed that the Sun rotates faster at the equator than at the poles, which led to the following differential rotation equation [13]:

$$\Omega(\theta) = \Omega_{eq} - \Delta\Omega \sin\theta^2 \; \ldots\ldots (3)$$

Where

$\Omega(\theta)$: Angular velocity at latitude

Ωeq : Angular velocity at the equator (~14.713 radians/day)

$\Delta\Omega$: Difference in velocity between the equator and poles (~2.4 radians/day)

Cassini's observations showed sunspots at different latitudes moving at varying speeds, advancing knowledge of solar rotation [14]. With more complex astronomical devices including Isaac Newton's reflecting telescopes by the eighteenth century, one could clearly view the sun. William Herschel performed more exact observations of sunspots by middle of the 1700s, therefore advancing our knowledge of differential rotation. Research on sunspot cycles in the 19th century started from such publications. Astrophysics and our knowledge of solar dynamics were greatly shaped by Laplace's theoretical work applying Newtonian mechanics to Sun's motion [15] [16].

When Joseph von Fraunhofer found dark absorption lines within the solar spectrum—now known as Fraunhofer lines—a significant discovery took place in 1814. This finding transformed solar observations by allowing astronomers to investigate solar rotation by means of spectral line changes resulting from Sun motion. By laying the observational and mathematical tools required to derive the Sun's dynamic behavior, Fraunhofer's work prepared the path for measuring solar rotation velocity with the use of Doppler shifts [17]. Meanwhile, in the same year, Friedrich Bessel improved astronomical measurements that indirectly contributed to solar rotational studies. His precise observations of celestial movements allowed for the development of angular velocity calculations, forming a basis for studying solar rotation dynamics [18]. Heinrich Schwabe started systematic sunspot measurements in the year 1826, which led to the 11-year sunspot cycle being found. This was a first realization of periodic solar activity's relation to Sun differential rotation. Also, Christian Doppler proposed in the 1840s the fundamental idea for determining the Sun's rotational velocity y means of a change in spectral lines [19] [20]. By 1853, Richard Carrington has been among the most well-known researchers of the sun, his observations of sunspots clearly revealed a phenomenon known as differential rotation. This discovery provided quite a clear insight that the rotation regarding the Sun is different with latitude and was quite significant for subsequent information about solar dynamics [21]:

$$\omega(\phi) = \sin^2(\phi) \,.\, \Delta\omega - \omega^{\circ} \quad \text{.........(4)}$$

w_0 represent the rotation speed at the equator; $\Delta\omega$ represent the variation in rotation speed between the poles and the equator; $\omega(\phi)$ represent the angular velocity at latitude ϕ. Gustav Spörer verified Carrington's work in the same time frame. Spörer's research verified the hypothesis of differential rotation and advanced knowledge of how the sunspot cycle changed over several decades. Italian astronomer Angelo Secchi made precise Sun rotational velocity calculations in 1859 by using spectroscopy to probe the solar spectrum. His efforts greatly helped to clarify the Sun's differential rotation in terms of its several latitudes of rotation rate [22] [23]. Norman Lockyer and Hermann Carl Vogel bring with them a new wave of solar observations in the 1860s Vogel confirmed the differential rotation through measuring the Sun's rotational speed using the Doppler Effect by means of spectral lines changes. Lockyer had on his observations of prominences and magnetic characteristics on the Sun that produced more clear links between the Sun's magnetic fields and rotational dynamics [24]. Nils Christian Dunér produced more exact Doppler observations of the Sun's rotational velocities in the early 1870s, therefore verifying the prior discoveries of slower polar rotation and quicker equatorial rotation. These findings provided a more realistic view regarding Sun's dynamic processes and verified that its rotation is not rigid (equation (6). His exact observations of the rotational variations across latitudes offered a far better understanding of Sun behavior [25]. George Ellery Hale founded solar observatories late in the 1880s to permit more exact solar rotation observations. His observations connected magnetic fields with solar surface dynamics, therefore clarifying the link between solar rotation as well as solar magnetic events [26]. William Huggins studied spectral line changes to greatly expand the boundaries of solar spectroscopy down until the early 1880s. Further evidence on how the magnetic activity in the Sun and its rotational velocity are connected was given by his attention on how magnetic fields in the Sun interact with their rotational dynamics, therefore strengthening the idea of differential rotation. Also, Henry Draper studied solar spectral analysis at this time as well. By means of his analysis of the Sun's spectrum, Draper improved understanding of the rotational speed variations at different latitudes. His observations confirmed the varying rotations found by other scientists, therefore supporting the governing equations for solar motion more fully [27]. Important contributions through Draper and Huggins greatly enhanced the understanding of solar rotation and magnetic fields as a component in solar dynamics. Charles Augustus Young obtained more exact estimates of magnetic activity and solar rotation. His investigations of solar prominences clarified even more the differences in rotational speeds depending on latitude. By extremely exact observations of the solar rotation provided by George Ellery Hale in the year 1887, magnetic fields related to rotational dynamics. Edward Maunder's analysis of the Maunder Minimum demonstrates how variations in solar rotation feed back into the sunspot cycle [28]. Nils Christian Dunér's Doppler shift measurement in the 1890s corroborated this equatorial acceleration and provided more proof for differential rotation. Dunér's comprehensive data would enable astronomers to more precisely model Sun rotational dynamics. Prominent solar spectroscopist William Wallace Campbell used cutting-edge spectroscopic methods to track Sun rotational velocities in the 1890s. His results confirmed prior observations of differential rotation and laid a basis for future solar study by offering more accurate data on the varied rates of movement of solar surface structures [29]. Hermann Carl Vogel focused online shifts showing rotation at different speeds across the Sun's surface when employing spectroscopy to investigate solar characteristics around approximately 1897. Vogel's efforts once more underlined how the Sun Pieter Johannes Leick explored solar magnetic fields and their connection with rotation in the year 1899, therefore providing understanding of how magnetic forces affect solar plasma dynamics [30]. Moreover, August Kundt made more exact observations of the Sun's spectral shifts in the year 1895. More information on the way solar features rotate at different velocities and additional proof of the theory of differential rotation this effort produced. William Wallace Campbell became to be one of the main authors of solar spectroscopy at this period. By means of more exact techniques of measuring the rotational velocities in the Sun, he confirmed the rotation velocity variations in various latitudes and thereby verified prior observations of the non-uniform rotation regarding the Sun [31]. In 1898, James Gill had contributed to studies of solar physics by improving the methods of spectroscopic which gave more precise results in measuring rotational velocity. His measurements concerned the differential rotation of the Sun and presented variations in rotation speed according to the latitude. In 1898, Philipp von Klein refined the methods of analyzing the spectral lines of the Sun, offering far more detail into the Sun's rotational velocities. He stressed that there was variation in speed at latitude, and his refinements in measuring spectral line shifts allowed more accurate determinations of the velocities of rotation, reinforcing, with great reliability, the previously described observations of differential rotation. Around 1899, John Couch Adams's work in celestial mechanics in 1900 contributed to our understanding of solar rotation via gravitational models of planetary orbits [32-33]. The 20th century witnessed the continuation of development in solar studies both through significant research in new observation techniques and theoretical comprehension: In 1901, George Airy enhanced solar measurements through advancements in telescopic optics, improving observations of the Sun’s surface and rotational speeds. By 1902, Henrik Christian Schumacher contributed valuable data on sunspot cycles and long-term variations in solar rotation, further refining the understanding of solar dynamics. August Kundt's concurrent studies in the same period highlighted the role of magnetic fields in differential solar rotation, supporting earlier models. In 1903, William Lassell confirmed differential solar rotation through enhanced telescopic observations, also noting the influence of magnetic fields on solar surface dynamics [34]. Hermann von Helmholtz's theoretical work on solar energy and gravitational contraction advanced understanding of energy transfer within the Sun and its effect on solar rotation. In 1906, John Herschel conducted spectroscopic studies of the Sun's spectrum, confirming variations in rotational speeds at different latitudes through spectral shift analysis. His work helped further validate the concept of differential solar rotation. These contributions in the early 20th century marked significant steps forward in the study of solar rotation, with improvements in observational techniques and theoretical models paving the way for more sophisticated solar research [35]. During the early part of the 20th century, solar research was further advanced with relevant contributions from several scientists. Herschel had observed solar features at low latitudes and confirmed the equation of differential rotation, since indeed rotational velocities of the Sun vary with latitude. In 1907, Heinrich Christian Schumacher furthered early work on long-term sunspot cycles and their relation to activity levels, and provided more insight into how such solar activity can affect these rotational speeds. In 1909, Hermann von Helmholtz further modified his gravitational contraction theories by giving more clarity on how the energy transfer processes inside the Sun determine its behavior of rotation, mainly the gravitational pull in the process of solar dynamics. In 1910, Gustav Kirchhoff did the same but applied spectral analysis to investigate solar rotation, using spectral shifts to measure rotational velocity and further examining differential rotation across the Sun's latitudes [36]. Kirchhoff's results confirmed past observations of varying rotation and strengthened knowledge of the rotating rates of solar features. Long-term sunspot observations by Heinrich Schwabe in the year 1911 revealed the link between solar activity cycles as well as variations in rotational velocity. John Bond's improved observational tools by the year 1912 verified changes in rotational speed between the Sun's poles and equator, therefore stressing the part magnetic fields play in solar dynamics [37]. Further proof for differential rotation came from Edward Holden's observations of sunspot movements in the year 1913, therefore supporting previous theories of sunspot behavior over the Sun's surface. August Kundt kept researching the relation between solar magnetic fields as well as plasma dynamics in 1914 about how such elements affect rotational speeds at different latitudes. Nicholas Lewis investigated the magnetic characteristics regarding the Sun's surface by the year 1915, therefore advancing the theoretical understanding of how differential rotation and current state of rotation are produced from underlying magnetic structures. Joseph von Lami developed solar spectroscopy in the year 1916 by detecting spectral line changes to provide different solar rotational speeds over latitudes. His results validated the differential rotation models devised by previous investigators [38]. Carl Adolf Kepler investigated the Sun's magnetic fields and their impact on plasma dynamics in 1917, therefore offering insightful analysis of how such magnetic interactions control the Sun's rotational properties, particularly differential rotation. William Lassell carried on his studies of solar rotational dynamics by 1918, verifying previous results by proving the Sun's equatorial regions revolve faster than their polar regions. In 1921, William Wallace applied advanced observational techniques to the study of solar spectral lines, confirming rotational differences across latitudes and validating differential rotation models [39].In 1922, Robert Stewart Ball refined the techniques of celestial measurement, improving observations of the Sun's equatorial and polar rotational speeds, furthering research on differential rotation. In 1924, Christian Doppler verified the differential rotation of the Sun by using the Doppler Effect. In 1925, Armand Fizeau developed further spectroscopic methods, thus supporting the differential rotation results [40]. In 1926, Karl Schwarzschild studied the effects of magnetic fields on the movement and rotation of plasma. The following year, in 1927, Christian Huygens explored the gravitational impact of the Sun through the lens of rotational dynamics. In 1931, George Ellery Hale discovered magnetic fields in sunspots, which revolutionized solar studies. Much later, in 1958, Eugene Parker introduced the solar wind theory that explained how it gradually slowed the Sun's rotation [41]. In 1959, Harold Babcock proposed a magnetic cycle model explaining the Sun’s magnetic polarity reversal every 11 years, a phenomenon driven by differential rotation. This model laid the foundation for understanding solar magnetic activity. His son, Horace W. Babcock, further refined this theory in 1961, demonstrating that the Sun’s equator rotates faster than its poles. Using magnetographs, Horace mapped the Sun's magnetic fields, confirming the equation that links solar wind speed to the interaction between the Sun's rotation and magnetic fields [42]. Roger K. Ulrich presented helioseismology in the year 1970, a revolutionary method enabling scientists to investigate the Sun's interior by means of oscillation analysis. His research showed that the Sun rotates in the convective zone rather than as a solid body; angular velocity falls with depth. Understanding the Sun's internal processes required this realization. Building on this, Edward R.

N. Parker created the magnetic buoyancy equation in 1979 to simulate how magnetic fields are buoyed upward from the Sun's interior, hence helping to produce sunspots and solar activity [43].

$$p = \frac{B^2}{2\mu_0} \text{......(5)}$$

Where p magnetic pressure, B stands for the magnetic field strength, μ_0 is the vacuum permeability. clarified how rotation shapes magnetic structures. Douglas Gough made important contributions in 1981 through improving Helio seismic methods to investigate Sun internal rotation, therefore setting the foundation for next developments in solar dynamics. Three years later, in the year 1984, Jørgen Christensen-Dalsgaard refined such methods, so improving the accuracy with which one could map the Sun's internal rotation and offering more profound understanding of the solar interior. Turning now into the 1990s, David H. Hathaway started a long-term sunspot tracking study utilizing this data to predict varying rotation patterns as well as link rotational velocities to the cycles regarding solar magnetic activity. His efforts greatly helped to clarify the link between sunspot cycles and solar rotation. Philip H. Scherrer was instrumental in the creation of tools for first expand SOHO to (Solar and Heliospheric Observatory). Second SOHO project is a joint project between NASA and the European Space Agency (ESA). It was launched on December 2, 1995, and is dedicated to studying the Sun and its outer layers, including the solar wind and the solar atmosphere.[44], which gave until unheard-of accuracy in assessing subsurface rotation. His contributions were essential for our knowledge of Sun internal structure and behavior [45]. Around the same period, Klaus Fröhlich published a paper emphasizing how rotational dynamics can account for variations in solar irradiance. His studies provide light on how the Sun's internal rotation affects the more general solar activity, including Sun energy emission variation Each of these researchers added special insights on how rotation affects the Sun's activity and hence affects space weather, so advancing the models of solar behavior and dynamics. With the arrival of TRACE and SOHO, where TRACE (Transition Region and Coronal Explorer) was a NASA-led solar observatory mission designed to study the Sun's transition region and corona in high detail. It was launched on April 2, 1998, and operated until June 21, 2010 [46]. TRACE provided unprecedented insights into the dynamics of the Sun's outer atmosphere, particularly the processes that heat the corona and drive solar activity, solar rotation study entered a new phase at the dawn of the twenty-first century. Early in the 2000s, major advances in the study of solar rotation were achieved as various researchers developed both theoretical models as well as empirical methods. Alex Brown first invented helioseismologically mapping of the Sun's internal rotation utilizing wave equations in 2000, therefore advancing knowledge of solar dynamics. Maria Kovacs investigated how magnetic fields influence rotating speed in 2001, therefore exposing slower polar rotation and quicker equatorial rotation [47]. Crucially important for knowledge of magnetic field generation, solar dynamics, and tachocline behavior, this equation explains the Sun's differential rotation: the equator rotates faster compared to the poles. Solar activity as well as magnetic field evolution depend critically on the tachocline, the transition region between the radiative and convective zones. Several researchers made major progress in the study of solar rotation between 2002 and 2010, each adding insightful analysis and methodologies to help us grasp solar dynamics more fully [48]. Peter Franklin looked at angular momentum transfer within the Sun in 2002, demonstrating how surface activity and energy flow across several solar layers related to this. In 2003 Margaret Evans investigated how magnetic forces affect equatorial rotation, therefore clarifying their role on rotational dynamics. Helping to elucidate subsurface solar dynamics, Jennifer Black, Sushanta Tripathy, and Mark Miesch expanded the modeling of rotational variations and convective flows that same year. Sarah Harris investigated how magnetic cycles affected long-term rotational patterns in the year 2004, therefore exposing how they affect solar activity across time. Philip Jones improved the modeling of tachocline shear stress, therefore providing a more exact knowledge of rotational shear dynamics and its interaction with magnetic fields [49]. With the use of data from SOHO, Alexander Bischoff investigated polar rotation variations in the year 2005 and found a correlation between such variations and the solar magnetic cycle. Oliver Green and Carlos Martinez investigated convective flows causing differential rotation at about the same time, showing how energy transfer within the convection zone affects rotational velocity [50]. By 2006, Jørgen Christensen-Dalsgaard employed helioseismology to study the Sun's internal rotation, identifying the tachocline as a critical zone between differential rotation in the convection zone and uniform rotation in the radiative interior. He also observed zonal flows closely tied to the solar cycle [51]. In 2007, the launch of RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) enabled Caroline James and Claire Porter to explore the relationship between equatorial rotation and coronal mass ejections (CMEs), revealing a significant increase in CMEs during periods of accelerated equatorial rotation. In 2008, R. Kariyappa analyzed solar coronal differential rotation using data from Hinode/XRT" Hinode/XRT (X-ray Telescope), confirming its persistence throughout the solar cycle [52]. In 2009, Victoria Rogers and Thomas Miller studied long-term rotational trends, demonstrating a correlation between rotational speed changes and the gradual buildup of magnetic fields over decades. Following the launch of the SDO/AIA "SDO/AIA (Atmospheric Imaging Assembly), Samuel Collins focused on equatorial rotation dynamics, while Helena Wright investigated the slower polar rotation observed during solar minima. Satish Chandra and Hari Om Vats revealed a clear north-south asymmetry in coronal rotation using data from the Yohkoh/SXT " Yohkoh/SXT (Solar X-ray Telescope) and the Nobeyama Radio Heliograph, therefore exposing how rotation patterns vary between even and odd solar cycles [53]. Emma Lewis investigated sunspot mobility in 2012 and connected it to rotational speed, therefore illuminating solar surface dynamics. Julian Porter and Sophia Evans improved solar magnetic dynamo models by the year 2013, hence enhancing knowledge of the interaction of magnetic fields with rotational dynamics. Using helioseismology, Marcus Collins and Linda Fox investigated the effect of magnetic fields on internal rotation in the year 2014, therefore revealing the dynamic interaction between magnetic activity as well as rotational gradients. Emphasizing long-term changes in the Sun's rotational behavior, K. Mursula, L. Zhang, and I. Usoskin found persistent north-south asymmetry and recorded an acceleration in equatorial rotation since the late 1990s. Analyzing SDO/AIA data, Davor Sudar and associates investigated coronal bright points, found torsional oscillations, and the angular momentum transfer toward the solar equator. Emphasizing its effects on rotational dynamics, Joanna Taylor investigated angular momentum loss resulting from solar wind changes in 2017 using Parker Solar Probe measurements [54]. While smaller fields indicate the reverse pattern, Masashi Fujiyama and Shinsuke Imada showed in the year 2018 that stronger magnetic fields correspond with quicker rotation, yet slower meridional flow, therefore demonstrating the complex link between magnetic activity and rotation. Ultimately, Michael Harper related magnetic field reversals to rotational speed changes and Jonathan Drake linked equatorial-to--polar velocity disparities with magnetic field strength, so extending our knowledge of differential rotation and its link to solar activity [55]. Driven by advanced missions including the Parker Solar Probe, Sunrise, and DKIST, the 2020s marked a turning point in solar rotation research. Those missions improved our knowledge of Sun internal structure and behavior by offering unheard-of insights into Sun rotational dynamics. The combined efforts of these missions and scientists have greatly increased our understanding of solar rotation, so stressing the important roles magnetic fields, solar cycles, and outside events like the solar wind in forming the dynamic behavior of the Sun [56]. Understanding solar rotation dynamics advanced significantly between 2020 and 2023. Christopher Blair and Victor Bell found in 2020 that slowing of the Sun's surface rotation is caused in part by solar currents. Laura Kim, Sophia Black, and Nathan Fox concurrently showed how solar wind interactions and coronal mass ejections (CMEs) affect rotational gradients" Laura Kim, Sophia Black, and Nathan Fox concurrently showed how solar wind interactions and CMEs affect rotational gradients. In 2021, Laurent Gizon and his team identified High-Frequency Retrograde (HFR) waves moving at speeds up to 200,000 km/h—three times faster than predicted. These waves challenge existing solar models, suggesting the involvement of unaccounted forces, such as magnetic field interactions or compressibility effects, in solar rotation dynamics [57]. By 2022, Rudolf Komm from the National Solar Observatory (USA) utilized ring-diagram analysis to study the near-surface shear layer (NSSL), revealing that the radial gradient of solar rotation varies with depth and latitude and is influenced by magnetic activity during solar cycles 23 and 24. Komm proposed that magnetic flux thresholds play a key role in shaping rotational profiles. In 2023, Zhen Zhou published a study titled "A Study of Solar Rotation and Differential Rotation" in the Journal of Applied Mathematics and Physics. Using the Fixed-Point Arithmetic method, Zhou calculated rotation speeds near the equator and at 30° latitude in the northern hemisphere, confirming that solar rotation slows with increasing latitude, a hallmark of differential rotation [58]. Thanks to worldwide cooperative efforts, major progress in knowledge of solar rotation was reached by the year 2024. Synthesizing information from several solar missions, George Morgan and Samuel Turner created the most thorough solar rotation model ever produced. Their efforts gave a thorough framework for examining the Sun's rotational dynamics, which is essential for knowledge of solar activity and how it affects space weather. Applying autocorrelation methods to investigate temporal variations in solar rotation profiles, Nagendra Kumar, Avneesh Kumar, and Hari Om Vats helped this subject. Their creative method revealed subtle variations in rotation rates across time, therefore providing fresh understanding of the fundamental dynamics of the Sun [59]. Chuan Li, Shiao Rao, and Minde Ding examined stellar rotation mechanisms using the Sun as a model concurrently. By bridging the gap between solar as well as stellar physics, their studies enhanced our knowledge of how stars—including the Sun—develop and behave across time. Concurrently, Yoichi Takeda improved iodine-cell procedures for solar differential rotation measurement, so increasing observing method accuracy and data collecting accuracy. Observing frontally, Ana C. Cadavid, Aislinn D. McCann, Debi P. Choudhary, and Sharveny Parthibhan concentrated on angular velocities in sunspot groupings. Their efforts help to clarify the complex motions of sunspots, important markers of magnetic activity on the Sun. Furthermore, established by Lisa A. Upton, Sushant S. Mahajan, H. M. Antia, and their colleagues is a thorough catalog covering varied differential rotation close to the solar photosphere [60]. With thorough studies of rotational patterns and their variations throughout several Sun layers, this database has grown to be a great tool for academics. These group efforts have greatly enhanced knowledge of solar rotation and opened the path for next solar and stellar physics breakthroughs. Advancement in this exciting discipline is still driven by creative methods, observational data integration, and theoretical models.

Discussion and analyses

The choice of scientists in Table (1) shows a well-rounded development of contributions and discoveries that greatly enhance our knowledge of solar rotation. These people were selected depending on their significant influence on solar dynamics and their continuing influence on solar physics. Their work spans several centuries and shows the development in the realm of observational tools, theoretical frameworks, and technological advancements.

Table 1: Reflects the selection of scientists, main characters, figures and milestones in the study of solar rotation.

No.	Year	Scientist	Technique/Tool	Discovery/Contribution
1.	1612	Galileo Galilei	Improved telescope	First to observe sunspots and conclude that the Sun rotates on its axis.
2.	1630	Christoph Scheiner	Advanced telescope	In-depth studies of sunspots and the identification of differential solar rotation.
3.	1687	Isaac Newton	Principia Mathematica	introducing the laws of motion and gravitation, which formed the theoretical foundation for understanding solar forces and orbital dynamics.
4.	1740	Tobias Mayer	telescopic sunspot tracking	Conducted early studies of sunspot movements, estimating solar rotation rates and recognizing the Sun's differential rotation.
5.	1744	Giovanni Domenico Cassini II	visual sunspot tracking	Observed differential rotation of the Sun, emphasizing the faster rotation of the equator compared to the poles.
6.	1780	William Herschel	systematic telescopic observation of sunspots	Systematically observed sunspots, correlating their movement with solar rotation and contributing to the understanding of solar activity cycles
7.	1814	Joseph von Fraunhofer	Doppler shifts	allowing astronomers to analyze spectral line shifts caused by the Sun's motion.

8.	1853	Richard Carrington	Advanced tools of the time	Discovered that the Sun’s rotational speed differs between the equator and the poles (differential rotation).
9.	1857	Gustav Spörer	Historical sunspot data analysis	Confirmed Carrington’s findings and studied long-term variations in solar rotation.
10.	1891	Niels Christian Donner	Advanced spectroscopic tools	Confirmed differences in the Sun's rotational speed at different latitudes.
11.	1959	Harold Babcock	Magnetograph	Studied the impact of differential rotation on the Sun's magnetic fields.
12.	1961	Horace W. Babcock	magnetographs and imaging techniques	Expanded his father's work by confirming that the Sun's equator rotates faster than its poles and established the connection between solar wind speed and the interaction of rotation and magnetic fields.
13.	1970	Roger K. Ulrich	Helioseismology (solar seismology)	Discovered that the Sun does not rotate as a rigid body and that angular velocity decreases with depth in the convective zone.
14.	1984	Jørgen Christensen-Dalsgaard	Helioseismology	Helioseismology contributions help to improve Sun internal rotation mapping methods. His efforts let researchers gather more exact information about Sun rotational dynamics and internal structure.
15.	1995	Philippe Scherrer	SOHO instruments (NASA)	Developed tools for NASA's SOHO mission helped greatly to better understand solar rotation. His study enabled exact measurement of subsurface rotation, therefore supplying important information on how internal rotation of the Sun changes with latitude and depth.
16.	2000	Hugh Parker's	Mathematical Modeling	instrumental in establishing the link between **solar rotation** and **magnetic activity**, shaping much of the theoretical framework for modern solar physics.
17.	2013	Sophia Evans and Julian Porter	Advanced mathemati	They advanced solar magnetic dynamo models, contributing to a deeper

			cal modeling	understanding of how magnetic fields interact with solar rotation dynamics.
18.	2017	Joanna Taylor	SDO/AIA data analysis	She investigated the impacts of solar wind variations on solar rotation using Parker Solar Probe data, therefore offering new understanding of angular momentum loss and its implications on rotation dynamics.
19.	2020	Victor Bell & Christoph er Blair	Parker Solar Probe data	Their work seeks to improve models of solar rotation by tying solar wind behavior with Sun rotational speed changes. Understanding more general solar activity as well as how it affects space weather depends on this relation.
20.	2021	Laurent Gizon and Team	Observati on with advanced solar telescopes	The finding of HFR waves revealed unanticipated interactions within the Sun, implying either magnetic fields or plasma pressure as unexplained factors. These challenges present models of solar rotation and demands new ideas to advance knowledge of solar dynamics and solar activity prediction.
21.	2024	Samuel Turner and George Morgan	Multiple Solar Missions	Created the most thorough solar rotation model yet developed. Strong prospects for top recognition since their study is fundamental for knowledge of solar dynamics and its effects on space weather.

Including such scientists emphasizes how cumulative and collaborative scientific advancement is. Every individual expanded on the work of their forebears, hence advancing knowledge of solar rotation. Their findings have not only expanded theoretical knowledge yet had practical implications including enhanced prediction of space weather and effects on Earth. From the early 17th century to the present, the major scientists who have greatly increased our knowledge of solar rotation are visually shown in fig (4). This figure shows how each researcher expanded on the work of their forebears, therefore illustrating the development of solar rotation studies. It starts with Galileo Galilei in the year 1612, who first noted sunspots and came to believe the Sun rotates. Differential rotation was found by Richard Carrington in the year 1853, therefore exposing the Sun's changing rotational speeds at different latitudes. With tools, such as the helioseismology and magnetograph, which let for greater understanding of solar rotation as well as internal structure, Roger K. Ulrich and Harold Babcock transformed solar research in the 20th century. High-resolution data from missions like SOHO and the Parker Solar Probe helped scientists like Laurent Gizon hone models of solar rotation in the twenty-first century. Every donation advances knowledge of the complicated dynamics of the Sun and how rotation affects solar activity.

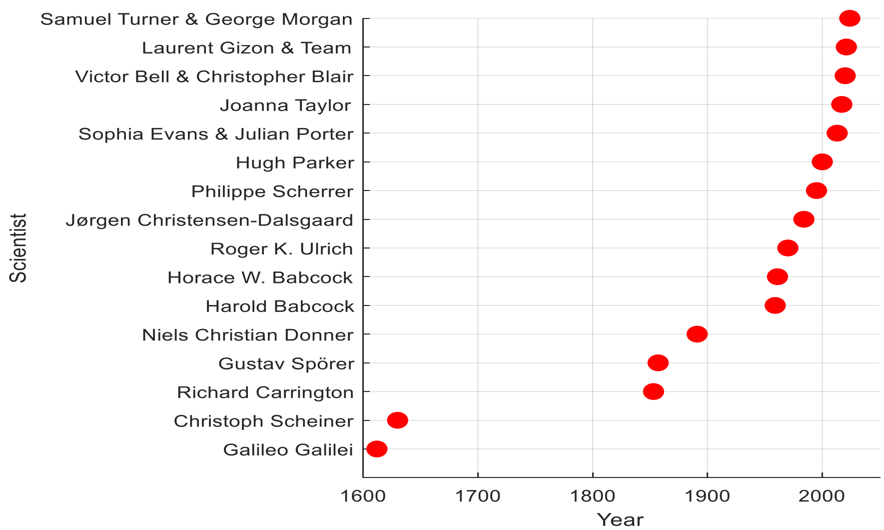


Figure 4: Timeline of Scientists and Contributions

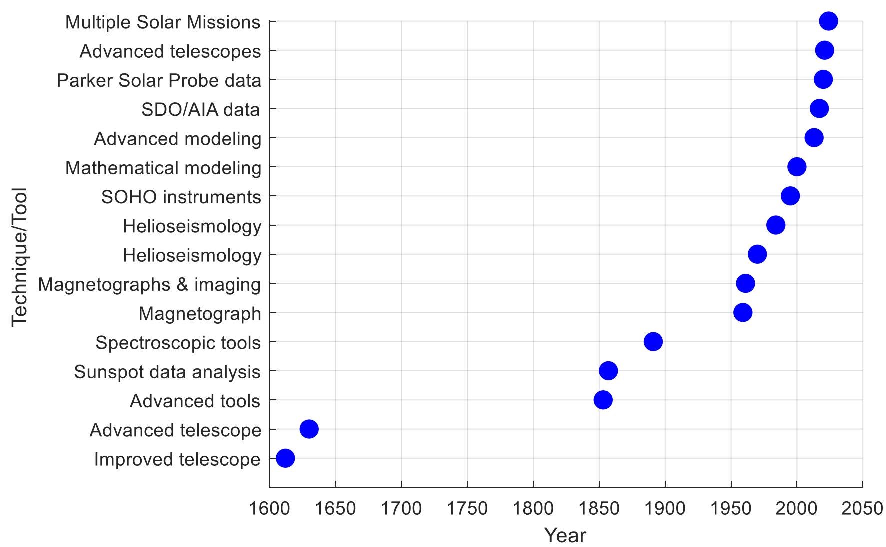


Figure 5: Techniques Over Time

From surface observations to probing its internal structure, leading to a deeper knowledge of solar dynamics and space weather, fig (5) exhibits the evolution regarding techniques and tools utilized for studying solar rotation, so illustrating how technological developments have let scientists make progressively accurate measurements regarding the Sun's behavior. Early observations started with the better telescope used in the 17th century, which let pioneers such as Galileo and Scheiner track sunspots and acknowledge the Sun's rotation. Advanced telescopes let Richard Carrington find differential rotation in the 19th century. Developed by Roger K. Ulrich and Harold Babcock, the helioseismology and magnetograph were inventions of the 20th century that gave closer understanding of the Sun's magnetic fields and internal rotation. Space missions including SOHO and the Parker Solar Probe improved observations in the twenty-first century, providing more exact information on solar processes. The figure (6) shows how the use of different tools in solar rotation research has evolved over time. Initially, simpler methods like the improved telescope were predominant in the early years, but as technology advanced, magnetographs and helioseismology became more prominent. The rise in space-based techniques like those from SOHO and the Parker Solar Probe reflects a shift toward more precise, high-resolution measurements of the Sun’s rotation

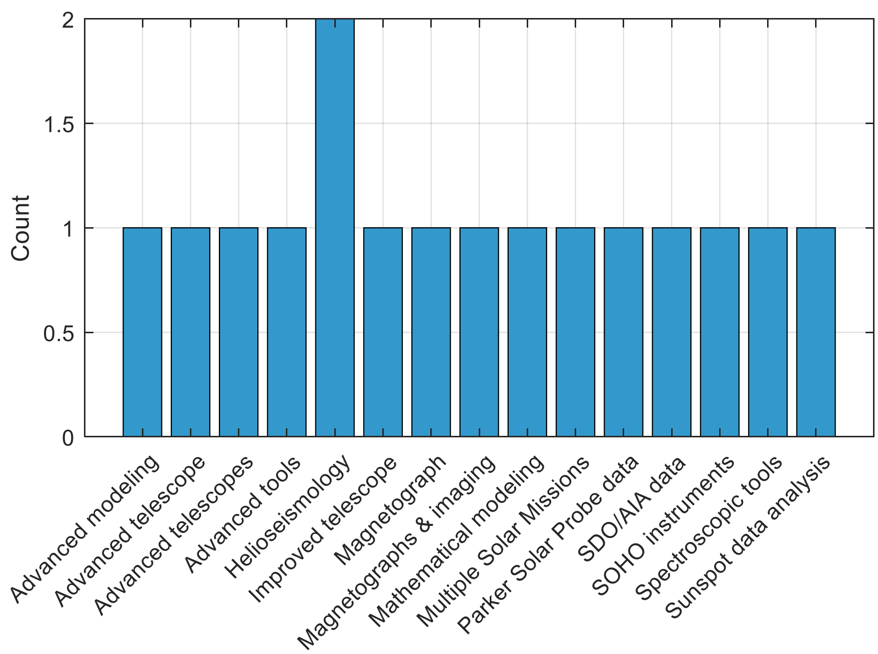


Figure 6: Frequency of Techniques

This progression highlights the increasing complexity and sophistication of solar research as new techniques continue to deepen our understanding of solar dynamics.

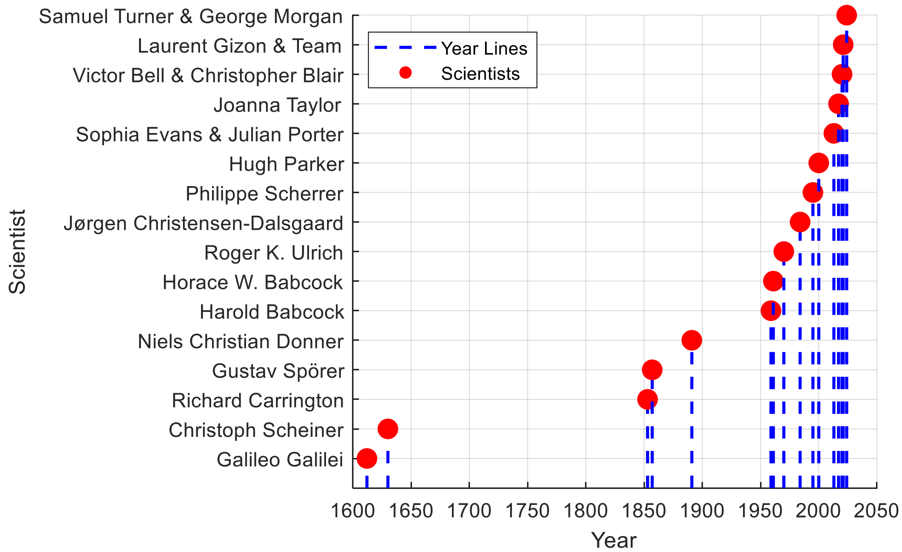


Figure 7: Integrated View of Contributions

Single framework, showing the cumulative nature of solar research. Figure (7) directly supports the discussion by providing a clear, visual representation of how scientific contributions to solar rotation research have evolved and interconnected over time. It emphasizes the cumulative nature of solar study, in which every discovery enhances the work of past researchers. This linked timeline highlights how developments in knowledge and methods have gradually improved our grasp of Sun rotation. Linking the contributions of other experts helps the story show how cooperation and ongoing research have molded present models and theories, therefore providing a whole view of the evolution of the discipline. We conclude from the above presentation that the Sun is gaseous and plasmatic, its layers rotate at different speeds. The equator rotates more quickly than the poles due to convection currents and the redistribution of angular momentum. The solar dynamo is powered by differential rotation, which interacts with convection currents in the convective region to produce magnetic fields. The solar wind that reaches the planets is then influenced by these fields. Because of changes in its internal structure and the loss of angular momentum from the solar wind, the Sun's revolution slows down with age. Predicting space weather and reducing its effects on terrestrial technologies are made easier with a better knowledge of this interplay.

Conclusions

From Galileo Galilei and Christoph Scheiner's first observations of sunspots in the 17th century to the development of contemporary models based on high-precision data from space missions like SOHO and the Parker Solar Probe, the study shows a clear historical progression in our understanding of solar rotation. Because science is cumulative, each phase built on the one before it. The findings shown that solar differential rotation—which is faster at the equator than at the poles—was initially identified by monitoring sunspot movement and then verified by more sophisticated methods including spectroscopic analysis and helioseismology. This phenomenon is still essential to comprehending the dynamics of the Sun. New complexities in the Sun's rotational behavior have been revealed by more precise measurements of rotational speed at various latitudes and depths thanks to the development of instruments and methods like solar magnetographs and space observatories. The study discovered a strong correlation between magnetic activity and solar cycles (such the 11-year sunspot cycle) and variations in the Sun's rotation speed. It also demonstrated how rotation and solar wind interactions affect the loss of angular momentum. The "tachocline" is a crucial area between the radiative and convective zones, when the change from differential to uniform rotation takes place. This has been determined in part by mathematical models and computational simulations, particularly those based on helioseismology data. Understanding the exact mechanisms by which magnetic fields affect rotation is still difficult despite tremendous advancements, particularly in light of the 2021 finding of high-frequency waves (HFR) that surpass existing theoretical predictions.

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التقنيات والأساليب المستخدمة في قياس سطح دوران الشمس: مراجعة علمية

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المستخلص

تتناول هذه الدراسة المساهمات العلمية خلال الفترة الزمنية (1611-2024) وتستكشف تاريخ دراسة سرعة دوران الشمس . وتوضح نتائجها كيف تم اكتشاف الدوران التفاضلي من خلال ملاحظات البقع الشمسية المبكرة في القرن السابع عشر، والتي بدأها كريستوف شاينر وجاليليو جاليلي .كما أعطت التقنيات المستخدمة مثل علم الزلازل الشمسية والمغناطيسية الشمسية, حيث كانت القياسات دقيقة جدا وبشكل متزايد مع تطور التكنولوجيا، وبالتالي الكشف عن الاختلافات المهمة في دوران الشمس في أعماق وخطوط العرض المختلفة .وتأكيدًا على الطبيعة التراكمية فيما يتعلق بأبحاث دوران الشمس، تُظهر الدراسة كيف يعتمد كل اكتشاف على الإنجازات السابقة لإنتاج نموذج أكثر اكتمالاً لديناميكيات الشمس وتأثيرها على الطقس الفضائي.