Auroras as Habitability - Indicators Exploring the Conditions for Life on Exoplanets

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Abstract

For thousands of years, humans have marveled at auroras – lights from solar winds interacting with Earth's magnetic field. Although we know a lot about auroras in our solar system, we are just starting to study them on exoplanets. Studying these lights on other planets helps us learn about their magnetic fields, winds, and atmospheres. This review dived into emerging exoplanetary aurora research, studying how we detect them from far away. We discussed what these auroras can tell us about magnetism, habitability, and possible life beyond our solar system. The Aurora borealis indicates planet habitability by indicating a magnetic field, which is crucial for life as it helps to maintain water on the surface of the planet and protects it from harmful radiation from its parent star. The study of auroras in exoplanets is essential to our understanding of the universe and its diverse phenomena. We also explored the challenges of observing exoplanetary auroras, shedding light on future discoveries about these radiant displays. Delving more into potential biosignatures, it can be stated that the magnetic fields of the exoplanets can be one of the leading signals of their habitability. According to our analysis of various works such as those of Ramirez and Lazio, who considered magnetic fields to be of great importance in protecting habitable zones, we concluded that auroras are reliable indicators of any form of life on exoplanets.

I. Introduction

Auroras, also known as polar lights, are natural light displays that occur in the polar regions of planets. They are instigated by solar ionized particles plummeting into the Earth's upper atmospheric layer at velocities of up to 45 million mph. The magnetic field of the Earth afterward guides the particles toward the Arctic and Antarctic regions. The charged particles enter Earth's atmosphere, exciting gas atoms to generate auroras. The color of auroras is determined by the gas mixture present in the atmosphere. The aurora's green color comes from oxygen, while nitrogen creates purples, blues, and pinks. There are several places around the world where auroras often appear. Some of the popular destinations include Iceland, Norway, Finland, Sweden, Canada, and Alaska.

While auroras have been extensively studied in our solar system, little is known about auroras in exoplanets. Observations and potential findings about auroras in exoplanets have been limited because of the difficulty in identifying them from Earth. However, new advancements in satellite telescope technology such as the Low-Frequency-ARray (LOFAR), an SKA predecessor that has exceptional sensitivity at 150 MHz, opened the possibility of detecting radio waves from neighboring exoplanets and their host stars, enabling us to make more exact observations. For instance, in research [1], auroral emissions in the atmosphere of a hot Jupiter exoplanet were discovered. The research discovered that the planet's magnetic field and its host star's stellar wind interacted to produce the auroras. Other scientists predicted that Proxima b, the exoplanet closest to us orbiting an M dwarf star, could be a likely candidate for producing detectable radio emissions from Earth due to its proximity [2]. The prediction was announced in 2017 and was confirmed in 2019 by A Vidotto and others. They concluded that GJ 876 b in the constellation of Aquarius, YZ Cet b in the constellation of Cetus, and GJ 674 b in the constellation of Ara could also present good prospects for radio detection [3]. In the same year, scientists discovered that planetary magnetic fields could be one of the key ingredients for determining planetary habitability [4].

Exploring auroras in exoplanets is critical in our quest to understand the universe and the various phenomena that occur within it. Auroras are a beautiful and awe-inspiring sight, but they also provide valuable information about the magnetic fields of planets and the processes that drive them. By studying auroras in exoplanets, we can gain insight into the conditions and environments of these distant worlds, which can ultimately help us better understand our planet and its place in the cosmos. Additionally, studying auroras in exoplanets can help us identify potentially habitable worlds since the presence of auroras may indicate the presence of protective magnetic fields that can shield the planet's surface from harmful cosmic rays. Overall, exploring auroras in exoplanets is a crucial step to our ongoing exploration of the universe and the search for life beyond our planet.

Our research focuses on investigating auroras as a potential biosignature for detecting life on exoplanets since they can reveal magnetic fields generated by the planet's core, which are critical for life's development and sustenance. The presence of planetary magnetism could significantly impact the long-term survival of the atmosphere and liquid water on rocky exoplanets. The discovery of habitable exoplanets would have profound implications on our understanding of the universe and our place in it. It would also raise new questions about the nature of life and its ability to thrive in a variety of environments.

The outline of the paper is as follows. The next section details the early studies on the presence of exoplanetary auroras, both pre-2000 and post-2000. Section 3 is entirely devoted to auroras and their formation. It also covers the many varieties of auroras and their occurrence on other planets. Section 4 provides a comprehensive explanation of the magnetic field, its properties, and the general concepts of the Magnetic Dynamo Theory. This section also contains a mass of information about magnetic fields in other planets and their presence in Earth-like exoplanets. The influence of the auroras on the habitability of exoplanets is discussed in Section 5 of the paper. Section 6 presents an instance of a habitable exoplanet that also experiences aurora on its surface. Section 7 reviews previous research on the indication of habitability through auroras and magnetic fields. The discussion section discusses firm facts and evidence as well as our view while the concluding section summarizes our review.

II. Early studies

i. Pre-2000 studies on the presence of exoplanetary auroras

In this part of the section, we provide a short overview of 'historical' (pre-2000) works on auroras in exoplanets. The exploration of auroras in exoplanets prior to the year 2000 was limited due to technological constraints. Hence, studies on auroras in exoplanets were primarily theoretical and conceptual. However, it laid the foundation for understanding the potential presence and characteristics of these fascinating phenomena beyond our solar system. Researchers laid the groundwork by adapting our understanding of magnetospheric physics to potential exoplanetary scenarios and set the stage for future advancements.

The work of Donahue and colleagues in the late 1970s was instrumental in shaping early discussions on exoplanetary auroras [5]. They speculated on the possibility of auroral emissions resulting from interactions between a planet's magnetic field and the solar wind, suggesting that such emissions could be detected through spectroscopic analysis.

Building upon this foundational concept, P. Zarka's study further expanded our understanding [6]. Published in the Journal of Geophysical Research in 1998, this seminal work delves into the correlation between auroras and radio emissions in the outer planets of our solar system. By examining these radio emissions associated with auroras, the study offers insights into the complex interactions between planetary magnetic fields, charged particles, and atmospheric gases. Zarka's research contributes to our knowledge of auroras and paves the way for studying similar phenomena in exoplanetary systems.

Another important advancement was the development of the Magnetospheric Imaging Instrument (MIMI) on the Cassini spacecraft, which was launched in 1997. MIMI was designed to observe the magnetospheres of Saturn and its moons, but it also provided valuable data on the auroras on Saturn. This data helped scientists better understand the processes that drive auroras in exoplanets.

ii. Post-2000 studies on the presence of exoplanetary auroras

Over the past few years, there has been an upturn in the study of auroras in extrasolar planets, highlighted by noteworthy improvements in observational methods and theoretical models. In this part of the section, we dive into the post-2000 era of research on this engaging phenomenon, marking the significance of this period. Focusing on work after the year 2000 is crucial because of the accelerated speed of technological advancements and the coming breadth of our understanding of planets beyond our solar system. Ongoing progress in space-based telescopes, spectrographic techniques, and computer simulations have granted scientists the opportunity to gain new insights into the proportions of atmospheres and magnetospheres in exoplanets.

Extending this line of reasoning, the study by W. M. Farrell et al theorized that magnetized exoplanets may emit radio frequencies, similar to the planets in the Solar system with emissions reoccurring during the planetary rotation period [7].

Expanding on this premise, the study authored by Helmut Lammer et al. in 2007, revealed that extreme ultraviolet (XUV) radiation from active M stars leads to atmospheric expansion and extended exospheres [8]. It suggested that Earth-like exoplanets with weakened magnetic spin orientations might suffer a decrement of dozens to hundreds of bars of atmospheric pressure due to coronal mass ejections (CME) -induced O ion pickup. Atmospheres with CO_2/N_2 mixing ratios below 96% experience increased exospheric temperatures and expanded environments, leading to stronger atmospheric erosion. Magnetic moments are crucial for protecting exoplanets' expanded upper atmospheres and for the detectivity of habitability. This study also revealed that Earth-like exoplanets orbiting around low-mass M stars with high CO_2 mixing ratios and strong magnetic dynamos can preserve their atmospheres if exposed to XUV fluxes less than 50 times the Sun's current flux [8]. However, stars emitting XUV radiation higher than 70-100 times the solar flux may pose problems for atmospheric stability due to CME ion pickup. The combination of intense XUV radiation and CME plasma interaction can result in high non-thermal atmospheric loss rates of 10-100%. CO_2-rich exoplanets exposed to lower XUV radiation should have strong magnetic moments to preserve their atmospheres [8].

The work by J. F. Kasting et al. states that exoplanets orbiting M dwarfs are believed to be the most possible for detecting habitable zones since they are able to maintain liquid water on their surfaces [9].

Developing this core idea, the research of A. West in 2008 suggested that the habitability of M dwarf planets is influenced by their active host stars and high flare and coronal mass ejection rates, which remain active for a significant portion of their lives [10].

However, another study called “Effects of M dwarf magnetic fields on potentially habitable planets” by A. A. Vidotto proved that intense activity could pose a threat to habitable zone planets due to high-energy radiation and intense stellar wind/CME, potentially causing the loss of their atmospheres [11]. They found that hypothetical Earth-like planets with similar terrestrial magnetization would have magnetospheres that extend up to 6 planetary radii. To sustain an Earth-sized magnetosphere, the planet would need to orbit farther out or require a magnetic field ranging from a few Gauss (G) to a few thousand Gauss (G). The study also found that the required rotation rate for early- and mid-dM stars are slower than solar ones.

Exoplanetary radio emission, powered by intense winds and CMEs, can be used to probe magnetism in exoplanets, despite potential dangers to planetary atmospheres.

B. Burkhart and A. Loeb predicted Proxima b, our closest exoplanet, could emit radio emissions as high as 10^{-26} $W \cdot m^{-2} \cdot Hz^{-1}$ (1 Jy) at 0.02 MHz frequency [12].

Now returning to M dwarfs, previous works of A. A. Vidotto suggested that rocky planets are more likely to have magnetic moments similar to or smaller than Earth's, so lower magnetic field values are preferred [13]. However, the study found a weak dependence of the planet's radio flux density on its magnetic field strength. The study reveals that K2-45b has the largest radio power due to its size, but its estimated flux density is small. Other planets, like YZ Cet b, GJ 1214 b, GJ 674 b, GJ 436 b, and Proxima b possess the highest magnetic induction levels.

III. Auroras

i. Auroral formation mechanisms

Auroras occur as a result of interaction between charged particles from the Sun and the magnetic field of the Earth. Specifically, the heat from the Sun’s outermost layer of atmosphere, the corona, makes its hydrogen and helium atoms vibrate and shake off protons and electrons. These particles are then too fast to be contained by the Sun’s gravity after which they group as plasma. It travels away from the sun and that is called the solar wind. When this electrically charged gas collides with atoms and molecules in the Earth’s atmosphere, it emits energy in the form of light. This mechanism is, therefore, called “Solar Wind and Magnetosphere Interaction” (Figure 1) [14].

The Earth nevertheless creates a detour, the magnetosphere, to stop the solar wind from entering the Earth directly. When the magnetosphere is overwhelmed by a fresh wave of visitors, the wind has the chance to resume its journey to the atmosphere. This phenomenon, known as a coronal mass ejection, happens when the Sun launches a huge ball of plasma into the solar wind. A magnetic storm is produced when one of these coronal mass ejections strikes Earth and overpowers the magnetosphere. The magnetosphere is put under extreme strain by the powerful storm until it abruptly snaps back, hurling some of the detoured particles toward Earth. They are pulled down to the aurora ovals by the magnetic field's retracting band. Hence, “Magnetic Field Alignment” takes place in regions closer to polar circles [15].

With the assistance of oxygen and nitrogen atoms 20 to 200 miles above the surface, the Sun's particles ultimately generate their stunning light display after traveling 93 million miles across the galaxy. The atomic constituents get activated and radiate light when they make contact with the atmospheric composition at the atomic level. Hence, this process is known to be the “Excitation of Atmospheric Gases” [16].

“Relaxation and Emission of Light” occurs when the hues of the sky are influenced by the photon's wavelength from an atom. The tones of sapphire and scarlet are a byproduct of the excitation of nitrogen atoms, while the shades of lime and crimson are yielded through the excitation of oxygen atoms [17].

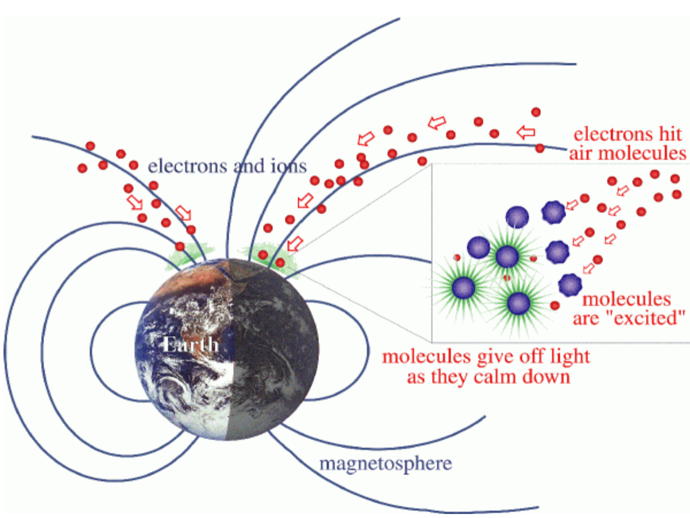

Figure 1: Process of formation of auroras [18].

A magnetic field significantly impacts the interaction between a planet and the solar wind, affecting the global distribution of energy dissipated into atmospheric gases. A planet without an intrinsic magnetic field may appear more exposed to atmospheric ablation, but the net loss may be comparable with or without a magnetic field. The presence of a magnetic field concentrates electro-mechanical energy dissipation at the planetary end of flux tubes, which link with the boundary layer between the solar wind and its magnetic field and the planetary magnetic field and its enclosed plasma. This region accelerates charged particles, generating the aurora [19].

The high-latitude ionosphere-magnetosphere region is a rich and interesting area in the space plasma universe, accessible for direct measurements. Its energetic processes contribute to the expansion and escape of the ionosphere beyond geospace's outer regions. Figure 2 illustrates the range of processes driving these outflows upward and outward [19].

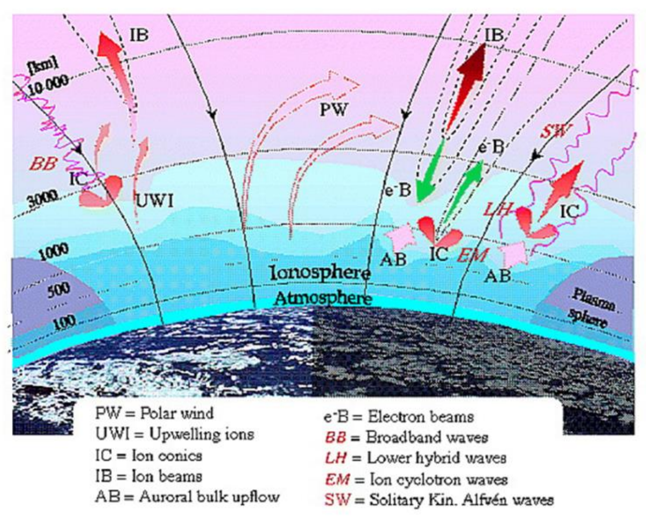

Figure 2: Noon-midnight cross-section of ionosphere−lower magnetosphere summarizing phenomena involved in the heating and escape of ionospheric plasmas [19].

Ionospheric outflows from high-latitude ionosphere-lower magnetosphere generation regions flow on magnetic field lines into magnetospheric regions like the tail lobes and plasma sheet. If these outflows remained on polar lobe field lines, they would be lost from the magnetosphere. However, they join the convective circulation of plasma in the magnetosphere as they expand out of the ionosphere. These emerging ionospheric plasmas flow across the magnetic field into the closed field line region of the plasma sheet, carrying the current responsible for the stretched magnetotail. Ionospheric flows from nightside auroral regions are injected directly into the plasma sheet, which is the primary source of plasmas for the quasi-trapped hot plasmas of the inner magnetosphere. These ionospheric plasmas populate the ring current in considerable quantities. (Figure 3) [19].

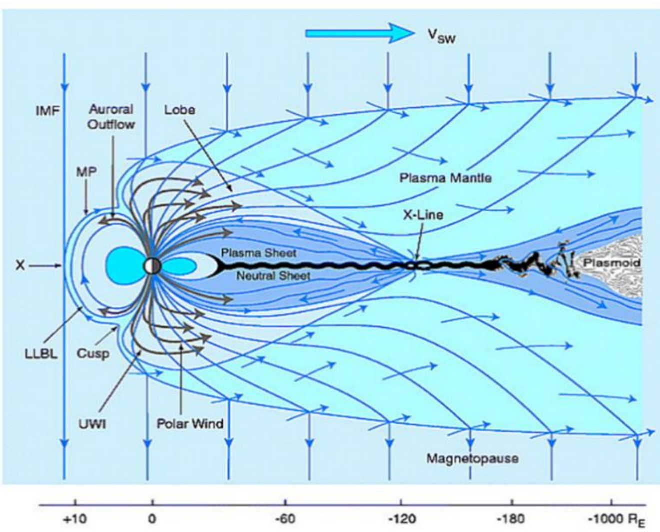

Figure 3: The global circulation of plasmas in Earth's magnetosphere occurs during the noon-midnight meridian [19].

ii. Types of Auroras

•A diffuse aurora is a widespread and faint type of auroral display resulting from the scattering of charged particles along the Earth's magnetic field lines, creating a gentle and uniform glow in the night sky. They lack distinct shapes and patterns. Typically, they are seen during periods of low geomagnetic activity. The term "diffuse" describes the spread-out nature of the light emitted by this type of aurora [20].

•Discrete auroras are well-defined and localized bright regions within the auroral display, and they are characterized by distinct arcs or bands of concentrated light in the sky. Some researchers even reported occasional mysterious sounds. Unlike other types of auroras, discrete ones have ribbon-like structure which shapes them into intricate shapes. This term describes the specific, clearly visible features of auroras that stand out from the overall auroral glow [20].

•An "Alfvén Aurora" occurs when Alfvén waves, which are plasma waves with a component parallel to the magnetic field, interact with charged particles, particularly electrons. This interaction leads to the acceleration of electrons and contributes to the formation of auroral emissions. Alfvén auroras were first proposed as a theoretical concept in the late 20^{th} century and were several years later observed and confirmed through satellite and ground-based observations. They have unique features such as vertical stripes and dynamic movements. The term "Alfvénic" is derived from Hannes Alfvén, a Swedish physicist who made a significant contribution to the studying the formation of auroral emissions [20].

iii. Aurora properties

Shape, altitude of emission, solar activity influence, and sounds are all various characteristics of auroras.

•Shape: Auroras often appear as waves with smooth arcs or chaotic patterns due to three factors which are convergence of magnetic field lines towards magnetic poles, collision of charged particles with gas molecules, and atmospheric density [21].

•Wavelength color relation: The different colors of aurora are produced when different atoms and molecules are excited to various energy levels.

For instance, the most common color pale green can be seen at the wavelength of approximately 5500 nm as a result of oxygen having been excited to the Singlet S state, whereas another less common color deep red is visible at the wavelength of around 6250 nm as a result of oxygen having been excited to the Single D state [22].

• Activity: During periods of high solar activity, such as solar flares and coronal mass ejections, auroras can become more vivid and occur at lower latitudes than usual [23] [24].

•Sounds: People have occasionally described hearing tremulous sounds or crackling noises connected to auroras. These noises are thought to be caused by electromagnetic waves from the auroras interacting with the magnetic field and atmosphere of the Earth. Further, the experiments should be repeated to make sure the sounds come from auroras [18].

iv. Aurora simulations

The Japanese satellite Hinode conducted an experiment to establish initial and boundary conditions for solar flare onset and CME propagation from the sun to Earth. The large-scale structure of the quiet auroral arc is believed to be formed due to the interaction between magnetosphere and ionosphere, with ionospheric feedback instability being a candidate. Auroral energetic electrons, which excite emission lines in aurora, need to be accelerated by an electrostatic double layer created by kinetic processes in micro-scale instability (Figure 4).

The results of the interlocked space weather simulations of the solar active region model (top-left), the solar coronal model (top-right), and the heliospheric model (bottom) are shown in Fig.4 [25].

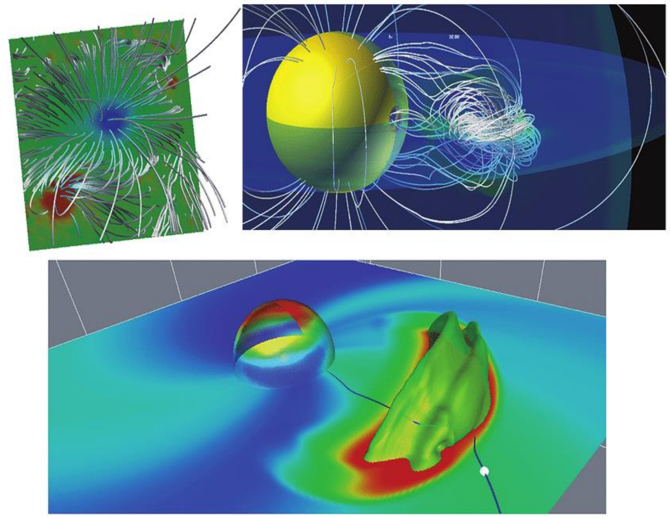

Figure 4: The structure of magnetic field lines in the flaring region and CME was computed using data from the Hinode satellite observed between December 12 and 13, 2006 [25].

In the same year, Macro-Micro Interlocked (MMI) examined the impact of microscopic instability on quiet auroral arc formation. The left panel of Figure 5 displays the distribution of ionospheric plasma density from 18:30 to 19:00 local time, with a large peak located around 70.5˚ latitude. The increase in plasma density is attributed to the ionization of accelerated electrons produced by microscopic instability, which is triggered by the linear growth of field-aligned current. The growth of plasma density reduces the absolute value of the latitudinal electric field at ionosphere height, as shown in the middle panel of Fig. 5. The right panel of Fig. 5 illustrates how the distribution of field-aligned current is influenced by the variation of the ionospheric electric field [25].

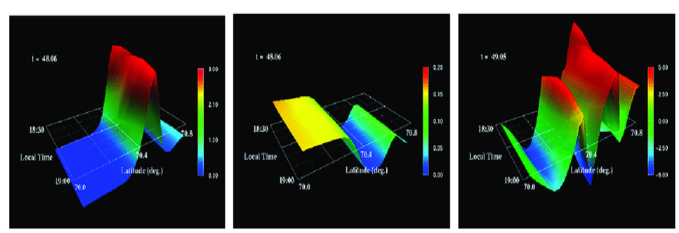

Figure 5: MMI aurora simulation's result [25].

v. Auroras on other planets and moons

Recent developments in the exploration of planets have discovered auroral phenomena on different planets and moons in our solar system. This part of the section explores noteworthy examples of auroras out of Earth's confines, contributing to a deeper understanding of space weather phenomena.

Jupiter, a gas planet known for its enormous magnetic field, provides a good example of auroras on a planetary scale. Driven by the interaction between Jupiter's magnetic field and charged particles, these auroras exceed Earth's in size and intensity [26].

Auroral phenomena appear on Saturn and its moon Enceladus too. The latter one contributes charged particles to Saturn's magnetic field. This interaction results in auroral-like emissions, also referred to as "atmospheric jets". Atmospheric jets share some similarities in appearance with auroras but they are different in their origin and characteristics. Atmospheric jets tend to occur at lower latitudes and may involve different physical processes not yet understood by scientists [27].

Uranus and Neptune, located on the outer fringes of our solar system, produce faint yet intriguing auroral emissions. They showcase highly tilted magnetic fields and their auroras can occur far from the poles. These emissions provide insights into the complexities of auroral formation in solar wind interactions and unique magnetospheres [28].

On Mars, aurora-like phenomena have the form of "discrete auroras" or "nightglow". They contribute to the mosaic of space weather dynamics in our solar system [29].

IV. Magnetic field

Magnetic fields are a crucial phenomenon not only in our solar system but also beyond it. This is an important tool for observing, studying, and analyzing planets and giving them characteristics. It causes various phenomena such as sunspots, coronal heating, solar areas, and coronal mass ejections. Understanding the nature of matter in the Solar System is essential for understanding the mechanism generating Earth's geomagnetic field and other planets' magnetic fields. The magnetic field provides information about a body's internal structure and thermal evolution, as well as their histories. The presence and behavior of these fields are often triggered by electrical currents deep within the planet, providing insight into its physical state and dynamics [30] [31].

All planets in the solar system have or have had internal magnetic fields, except Venus, the Moon, and Jupiter's satellite Ganymede. Other bodies in the solar system may have generated magnetic fields in the past [32].

Mercury: Mercury, a billion-year-old planet, has a 100 times weaker magnetic field than Earth, which was once as strong as Earth's, and is the only planet in our system including Earth whose magnetic fields are generated by liquid metal movement [30].

Venus: With a slow rotation rate of 243 Earth days, Venus uses a unique form of magnetism to protect itself from solar winds. Its upper atmosphere, the ionosphere, interacts with solar particles, creating a magneto tail shaped like a jellyfish tentacle, facing away from the sun [30].

Earth: Earth's magnetic field is generated by liquid metal at its core and its 24-hour rotation. Other planets, except Venus and Mars, have magnetic fields or traces of magnetism that differ from Earth's [30].

Mars: Mars does not have a conventional magnetic field but instead has powerful magnetic crustal fields that create magnetism if located correctly on the surface. These protective bubbles help maintain Mars' vulnerable atmosphere [30].

Jupiter: Jupiter, the largest planet in the solar system, generates the largest magnetic field even larger than the Sun. This happens due to its fast rotation and interactions in its outer core, likely made of dense, molten liquid metallic hydrogen [30].

Saturn: Saturn's magnetic field aligns with its axis of rotation, generated by liquid metallic hydrogen and heated by gravity and rapid rotation of its rocky core [30].

Uranus: Uranus' magnetic field is complex, tilting 59 degrees and running off center. It has two poles in some places and four elsewhere. It meets the usual requirements for a magnetic field with a rotation period of 18 Earth hours and electrically charged convection currents near the core. Scientists believe this unusual magnetic field could be caused by electrical currents in the planet's salty ocean [30].

Neptune: Neptune's magnetic field is off-center and tilted away from its axis of rotation, similar to Uranus. Scientists believe magnetic or electrical interactions occur closer to the planet's surface, similar to Earth [30].

The existence of magnetic fields is an important aspect of the habitability of the planet. The magnetic field protects us from harmful radiation from the Sun and helps keep our atmosphere from leaking into space (Figure 6) [33].

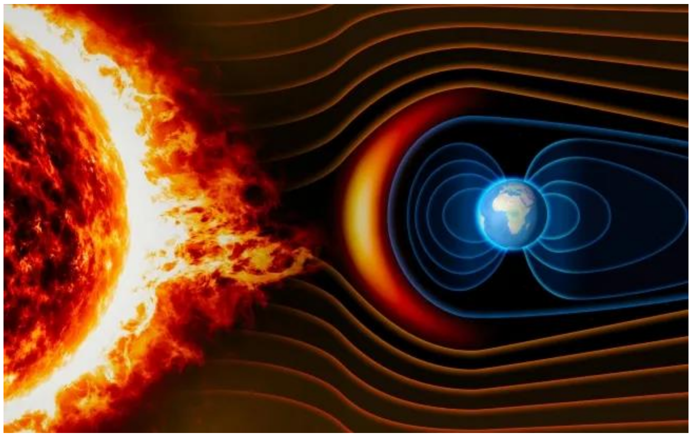

Figure 6: Earth's normal magnetic field [34].

vi. Planetary Magnetism Development

All discoveries in planetary Magnetic fields were made by observing magnetized objects such as the Earth or the Sun. It can be noticed that since ancient times people have known the existence of certain forces inherent in the Earth and the first recordings about it were written in 11th century by the Chinese. Willian Gilbert made the first attempt to explain the mysterious phenomenon in 1600 presenting that the Earth was magnetic because it was rotating. However, another explanation was proposed by Heinrich Schwabe in 1826-1843 where he discovered the 11-year sunspot cycle and noted that geomagnetic storms corresponded to sunspot maximums [35] [36] [30].

In 1907, Carl Stormer and Hale discovered that charged particles could be trapped in a dipole or magnetized sphere, and in 1908, Hale observed that sunspots were intensely magnetic [37]. Joseph Larmor introduced the fluid dynamo model in 1919, proposing that sunspots and the Sun's magnetic field were the result of a self-sustaining dynamo in the plasma interior [38]. Blackett's magnetic theory, which did not explain Earth's pole reversals, was replaced by Parker's fluid dynamo model in 1955, which is still used today, despite other proposed mechanisms [39] [40].

vii. Magnetic dynamo theory's general concepts

The dynamo theory explains Earth's main magnetic field as a self-sustaining dynamo. Fluid motion in Earth's outer core generates an electric current, which interacts with fluid motion to create a secondary magnetic field. This secondary magnetic field is stronger than the original and lies along Earth's rotation axis. The heat from radioactive decay in the core is thought to induce convective motion (Figure 7) [30].

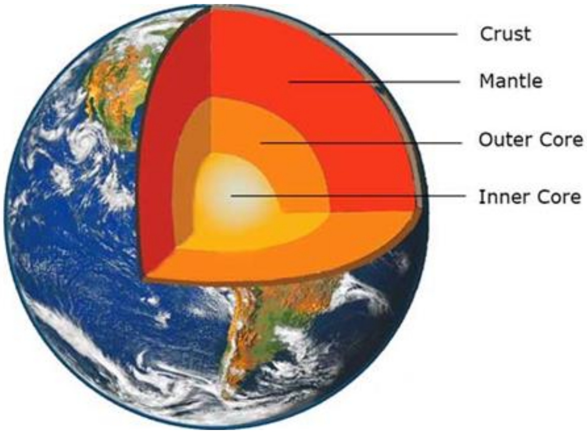

Figure 7: Composition of the Earth [41].

Electrons move through a liquid, creating electric currents and converting energy into a magnetic field. Planetary bodies like Earth, Moon, Mars, and asteroids have magnetic fields, which reveal the formation of a metallic core. This field is unique in remotely sensing a core buried deep beneath a body's surface. This process can tell a lot about the origin of the planetary body and even the history of climate change for that body. To fully grasp planetary magnetism, it is important to comprehend the physics of dynamos and how they affect the body in which they are found [42] [43] [30].

viii. What then generates the magnetic field?

The magnetic dynamo theory suggests that a magnetic field is created by swirling motions of liquid conducting material in planet interiors. Metallic materials, such as hydrogen in Jupiter and Saturn, have free electrons that can move around, forming a magnetic field. To sum up, a planet's magnetic field is generated by a moving charge and a liquid conducting material in its interior. Rapid rotation increases the stirred material, making the magnetic field stronger. However, if the liquid interior becomes solid or rotation slows, the magnetic field weakens [44] [45] [30].

ix. Properties of Planetary Magnetic Fields

There are two types of magnetic fields, namely remanent and intrinsic fields with an intermediate form induced by external forces. Remanent fields indicate an object that was once magnetized and still retains magnetism, while intrinsic fields are active phenomena resulting from an object's property. Most planetary magnetic fields are self-sustaining intrinsic fields generated by an internal dynamo, following the model proposed by Parker (1955) and later modified to become Kinematic Dynamo Theory (Fortes 1997). This model requires a planet to have a molten outer core of a conducting material, convective motion within the core, and an energy source to power the convective motion. Remanent fields are stable and not suitable for fields with changing polarity [46] [47].

A dynamo can function even if it's embedded in a time-varying magnetic field, such as a parent planet or the passing solar wind. This interaction between the solar wind and a planetary magnetosphere is equivalent to a dynamo, modulated by changes in the solar wind's plasma flow. Planets like Earth, Mercury, Jupiter, and Saturn generate magnetic fields in their interiors, surrounded by invisible magnetospheres. These magnetospheres deflect charged particles of the solar wind, creating a protective bubble around the planet, ending in an elongated magneto tail on the lee side. Solar ultraviolet radiation creates an ionosphere in the upper atmosphere, which interacts with the solar wind and magnetic field. This creates a magnetosphere on the left side of a planet, causing particle flow to slow and divert. The importance of magnetospheres is crucial for planets [46] [47].

Celestial bodies that have weak magnetic fields rotate very slowly. This relates to the Moon and Venus, but there can be exceptions where the planet rotates quickly but still does not have an appreciable magnetic field (e.g. Mars). The very logical reason for this is that the core is no longer liquid. Larger gas planets have magnetic fields comparable to or larger than Earth's due to their rapid rate of rotation [46] [47].

x. Earth-like exoplanets' magnetic fields

The study presents magnetic dipolar moment estimations for terrestrial planets with masses and radii up to 12 M_E and 2.8 R_E, and different rotation rates [47]. The results show that the pure iron core, minerals perovskite, and ferropericlase ((Mg, Fe) SiO_3) mantle composition models provide the most conservative dipolar magnetic moment estimates for assumed planetary interior conditions. The study also includes the locations of transiting low-mass planets GJ 1214b, CoRoT-7b, Kepler-10b, and 55 Cnc e, and estimated locations of non-transiting planets Gl 581 d and Gl 581g. In the fast-rotating regime, strong enough dipolar magnetic moments can be generated for all planets, with the surface of those planets potentially shielded. However, in the slow rotation regime, not all planets will have dipolar magnetic moments strong enough to shield their surfaces. Planets with masses below ~2M_E will have dipolar magnetic moments less than Earth's, even for very fast rotation rates [48].

V. Influence of auroras on the habitability

Modern Earth is exposed to XUV and particle emissions from the quiescent and active Sun, including solar-wind plasma with embedded magnetic fields. Extremes of these external influences occur in the form of solar flares, CME-driven plasma, magnetic-field enhancements, shocks, and related solar-energetic particles (SEPs). Galactic cosmic rays (GCRs) diffuse into the inner heliosphere and the planetary atmospheres, with specific atmospheric and surface influences potentially consequential for our technological society and the biosphere [49].

The Earth's current ion outflowing at high latitudes consists of a light ion-dominated polar wind and heavier ion outflows, primarily composed of oxygen ions associated with auroral activity [50]. The combined oxygen ion outflows are estimated to be 10^{24} ions per second for low geomagnetic activity and 10^{26} ions per second for high activity. The solar wind does not directly interact with the ionosphere due to a planetary-scale magnetic field. However, it does interact with the Earth's magnetosphere through magnetic-field reconnection, allowing solar-wind momentum and energy to be coupled into the magnetosphere and affects the high latitude ionosphere, mainly in the auroral zone and cusp region [51]. This connection was explored by a study using data from the Fast Auroral Snapshot (FAST) Small Explorer in 2005 and was extended in 2011 by analysis to include the effects of Alfvén waves [52] [53].

VI. Impact on Proxima b's habitability

Proxima Centauri is the third and smallest member of the triple star system Alpha Centauri, the closest star to our Solar System. Proxima Centauri has two known exoplanets and one candidate exoplanet: Proxima Centauri b, Proxima Centauri d, and the disputed Proxima Centauri c.

Proxima Centauri b, with a minimum mass of 1.27 $M_\odot$ and an orbital period of 11.2 days, is clearly located in the circumstellar habitable zone (CHZ). This information is supported by various studies and research [54] [55]. The planet's upper mass limit is unknown, but it could be rocky based on planetary population statistics from the Kepler mission [56]. It is also unclear whether there could be more planets around this M5.5V red dwarf star with its effective temperature T_{eff} of 3050 K [57] [58]. The habitability of Proxima Centauri is influenced by factors such as planetary mass, orbital evolution, and atmospheric properties. Since Proxima Centauri is non-transiting, the key parameter ranges determining the state of

Proxima b's atmosphere are large [59]. For both cases, there are parameter ranges for which it could still possess a significant amount of water. Numerous model studies have shown scenarios for which Proxima b could support periods of liquid water, depending on the H_2, O_2, and CO_2 evolution of its atmosphere [60]. The study found the possibility of an even broader region of liquid water with their 3D-general circulation model (GCM) studies including a dynamic ocean [61]. The environments of close-in terrestrial-type planets within the CHZ from their parent stars can be hospitable to life. This answer requires the conditions of atmospheric space weather (SW) around red dwarf stars including quiescent and flare-driven XUV fluxes and their properties of stellar winds. Discovery presented XUV emission from Proxima Centauri, using reconstructed XUV fluxes that appear to be over 2 orders of magnitude greater at the planet location than that received by the Earth to evaluate the associated ion escape. The calculated escaping O^+ mass flux from Proxima Centauri appears to be high, consistent with the results of the study. The study also discussed the impact of thermospheric temperature and polar cap area on the escape fluxes. A hotter thermosphere is expected to result in stronger outflows, but a larger polar cap area also results in more net mass flux of ionized particles lost to space [62] [63].

Research characterized the effects of stellar wind from Proxima Centauri on Proxima Cen b, finding that the wind's dynamic and magnetic pressure is extremely large, up to 20,000 times that of the solar wind at 1 Astronomical Unit (AU which is about 93 million miles or 150 million kilometers) [64]. The planet experiences fast and large variations in ambient pressure, making the magnetosphere surrounding it vulnerable to strong atmospheric stripping and atmospheric escape. The simulations suggest Proxima Cen b may reside in the sub-Alfvenic stellar wind at least part of its orbit [64][65].

VII. Previous research on detecting habitability using the aurora and magnetic field

Within this specified part of the section, we present a concise summary of scholarly investigations that explore the influence of auroral activity on the potential habitability of exoplanets. These studies are of crucial importance in our quest to identify habitable worlds beyond our solar system [66].

Since auroras are caused by the collision of charged particles with a planet's atmosphere, this collision can affect the chemistry of the atmosphere by producing reactive species which could either enhance or deplete greenhouse gases essential for regulation of temperature. The changed chemistry can influence the planet's ability to retain heat and its overall habitability. While not directly referring to exoplanets, the studies on this statement such as of J. Maldonado et al. discuss how this concept can help us understand the potential role of auroras as biosignatures in exoplanets [66].

While auroras themselves may not be the primary focus, factors relating to stellar influence are considered when assessing habitability. A research paper by A. L. Shields suggests that the type and activity level of a host star, such as an M-dwarf star, can significantly impact the habitability of extrasolar planets [67]. Thus, active stars can produce more intense auroras and radiation, potentially impacting habitability.

Magnetic fields, another key factor, play a considerable role in protecting exoplanets within habitable zones. These zones around pre-main-sequence stars include young stars where exoplanets might form. So, the work of Ramirez elaborates on how magnetic activity, including auroras, can influence the habitability of such planets [68].

J. Lazio et al. would agree with the aforementioned author, clarifying that magnetic fields protect planets from solar and cosmic radiation which is exactly why their presence is considered to be a critical factor in exoplanet habitability [69].

Different energy sources support life on exoplanets which could include the energy emitted during auroras. While the study of Kopparapu and others does not directly address auroras, it still explores the habitable zones around main-sequence stars, considering various factors that influence planetary habitability [70].

VIII. Discussion

The main factors influencing the habitability of exoplanets include the evolutionary phase of bolometric luminosity and magnetic activity of host stars, their impact on a planet, and internal planetary dynamics. For some planets, the luminous pre-main sequence phase of the host star may have driven the planet into a runaway greenhouse state before it had a chance to become habitable. The composition of the planet, related to elemental abundances for its host star, may determine its interior structure and influence the tectonic history of the planet. Finally, due to the proximity of the planet to the star and the weakening of the magnetospheric field due to tidal locking, the stellar environment could lead to a strong bombardment of the atmosphere with high-energy particles and UV, either stripping the planet of its atmosphere or leaving its surface inhospitable to life. Conversely, auroras and magnetic fields can serve as valid signs of life-hospitable exoplanets, since they are interconnected with the factors mentioned earlier. Regarding the research of Ramirez and Lazio, magnetic fields play a crucial role in shielding a planet from harmful stellar radiation and charged particles. Thanks to an active magnetic field, the conditions necessary for life are maintained on the exoplanet. Similarly, the presence of auroras is often connected to a planetary atmosphere interacting with its magnetic field, creating colorful light displays. The detection of auroras on an exoplanet could suggest the presence of an atmosphere and an active magnetic field, which are vital for sustainable life as evident. Moreover, the observation of auroras and magnetic fields on exoplanets can be a key clue that life-supporting conditions may exist.

IX. Conclusion

To sum up, exoplanetary auroras are mysterious yet captivating phenomena that humankind has marveled at for centuries which opened a unique window into the understanding of space weather, atmospheric conditions, habitability assessment of exoplanets, and, most importantly, their magnetospheric interaction with their stars' environment. All this brought new insights for technological advances and testing theoretical models. Researching this subject enabled us to unravel new aspects in areas that were once thought to be settled and unchangeable, such as the presence of auroras beyond our solar system and their potential habitability.

Throughout our work, we explained the definition, characteristics, and formation mechanisms of auroras and the properties and concepts of planetary magnetic fields, highlighting the possibility of auroras being a sign of life on extrasolar planets. We decided to review this field because we wanted to identify gaps, such as the lack of research on the potential role of exoplanetary auroras as biosignatures and neglection of the diversity of exoplanetary environments across which auroras may vary.

The study of auroras on planets beyond our solar system is a demonstration of the power of interdisciplinary collaboration in broadening our understanding of space. This field has brought together scientists from different scientific disciplines like astrophysics, planetary science, atmospheric science, and magnetospheric physics. Astrophysics enhanced our understanding of the behavior of host stars and the impact of stellar activity on exoplanet environments; planetary science informs us of exoplanetary atmospheres; atmospheric science explains the interactions between exoplanetary atmospheres and incoming stellar radiation; lastly, magnetospheric physics helps unravel the intricate interplay between exoplanetary magnetospheres.

Exploring exoplanetary auroras is evidence of human curiosity and scientific ingenuity, driving us to delve more into the interactions between distant worlds and their host stars. The hunt for dancing lights in alien skies shows the complexity of exoplanetary systems, reminding us that our understanding of the universe is most vivid when we work together to decipher its most captivating mysteries.

X. References

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