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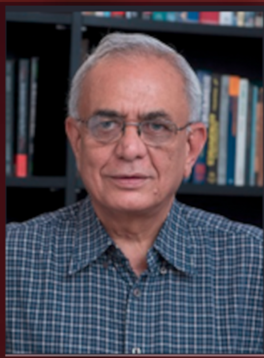
airis4D

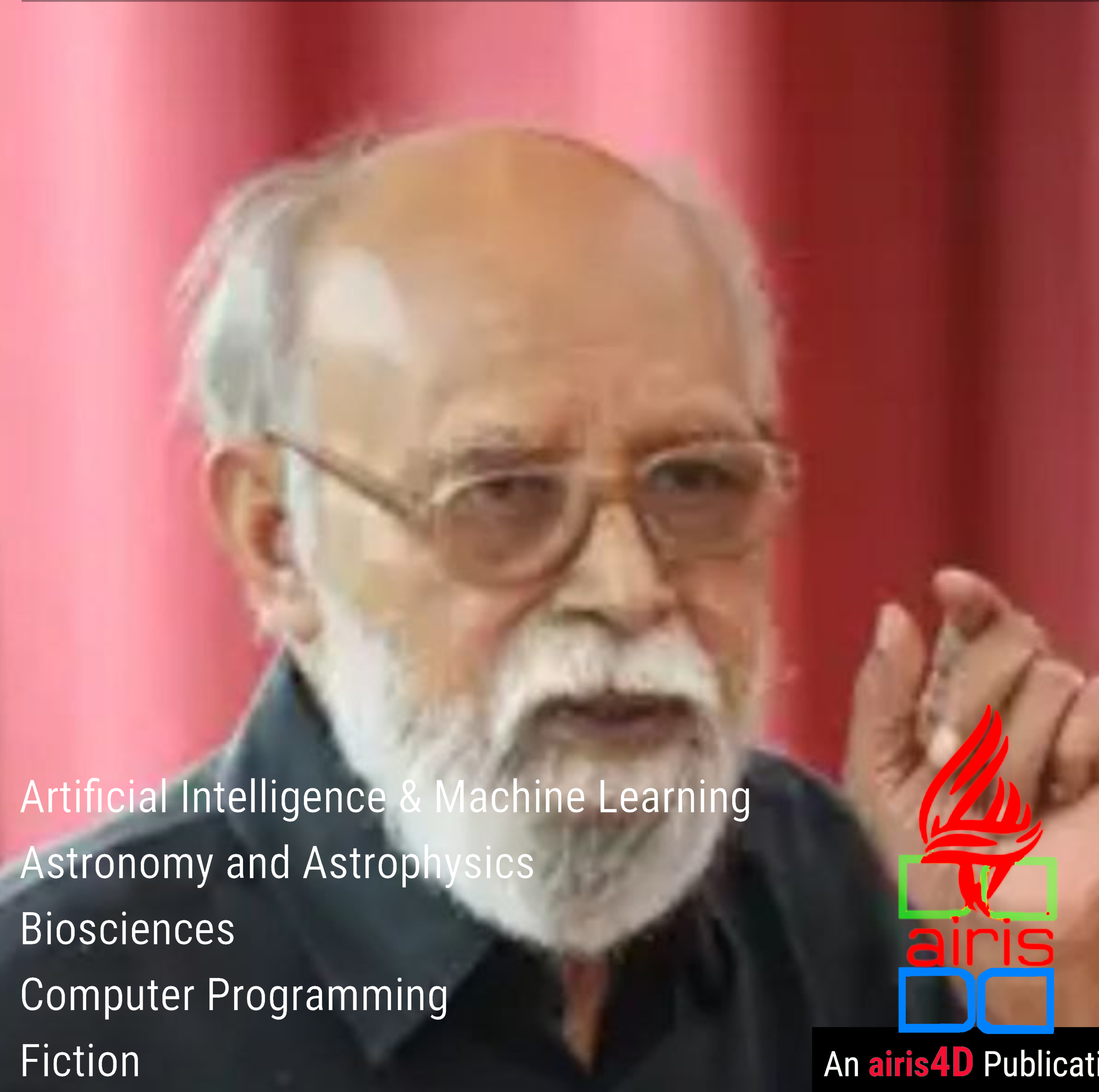
We Dream, Design, Develop and Deploy the Future

Professor Ajit Kembhavi

writes on the latest advances in astronomy and astrophysics.

He will answer questions about his article, and selected readers can participate in an online interactive session with him.





Artificial Intelligence Research and Intelligent Systems

Artificial Intelligence & Machine Learning

Astronomy and Astrophysics

Biosciences

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Fiction

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Cover page

Image: *Prof Dr P P Divakaran : Scientist, Historian, Truth-Seeker* says MG Radhakrishnan in his article that appeared in Mathrubhumi. The photograph is from the same article. The article was written remembering Prof Divakaran (1936–2025) who was a a respected physicist and the finest multi-talented humane personalities one may come across. "He was an authority everybody sort of looked up to. A person who actually had the domain knowledge, and he was able to shed the correct light on the historical part," Kaushal Verma, Dean, Physical & Mathematical Sciences Division, Indian Institute of Science (IISc), quoted The Print. Above all, he was a good friend, a well-wisher of airis4D at all times. We are deeply moved by his passing away. This edition of airis4D pays homage to his memory. Photo: adopted from Mathrubhumi

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Editorial

by Fr Dr Abraham Mulamoottil

airis4D, Vol.3, No.9, 2025

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This edition of Journal airis4D is an obituary for Prof. Dr. P. P. Divakaran, a renowned physicist, historian, and truth-seeker, who passed away on 23rd August 2025, leaving behind a legacy of scholarship and humanity. He was admired not only for his authority in physics but also for his clarity in illuminating history. Beyond his brilliance, Prof. Divakaran was a good friend and a constant well-wisher of airis4D. His passing deeply moves us, and with this edition, we pay homage to his enduring memory.

Jinsu Ann Mathew's article Entropy in Networks: Order, Uncertainty, and the Dynamics of Connection explores how entropy—a concept from physics and information theory—helps us understand the complexity of networks. It introduces three key structural measures (degree distribution entropy, spectral entropy, and topological entropy) to quantify connectivity and organisation, and extends to dynamic entropy, which captures how information, resources, or diseases flow through networks. Across domains like communication, biology, epidemiology, and social systems, entropy reveals the balance between order and unpredictability, efficiency and resilience, showing networks as dynamic systems where stability and adaptability must coexist.

Abishek P. S.'s article Plasma Physics Solar Physics highlights how plasma—making up over 99% of visible matter—governs the Sun's dynamics through ionisation, magnetohydrodynamics, the solar dynamo, and wave–particle interactions. Using tools like helioseismology, spectroscopy, and space missions (Parker Solar Probe, SDO), scientists study solar flares, CMEs, and the solar wind that shape space weather and affect Earth. Beyond astrophysics, this research informs fusion energy, satellite protection, and advances our understanding of both cosmic processes and practical technologies.

Ajit Kembhavi's Black Hole Stories–21 recounts the historic first detection of gravitational waves by LIGO on 14 September 2015. The signal, GW150914, came from the merger of two black holes—36 and 29 solar masses—1.3 billion light-years away, forming a 62-solar-mass Kerr black hole. In less than a second, energy equivalent to three solar masses was radiated as gravitational waves, confirming Einstein's century-old prediction and opening a new window to the Universe.

Aromal P's article X-ray Astronomy: Through Missions surveys major X-ray space observatories of the late 2010s. It highlights NASA's NICER (pioneering precise neutron star measurements), China's Insight-HXMT (advancing black hole and pulsar studies), and the Russian–German Spektr-RG mission (mapping the X-ray universe and discovering thousands of new galaxy clusters). Together, these missions mark a transformative era in high-energy astrophysics.

Sindhu G's Isochrones in Astronomy explains how isochrones—curves on the Hertzsprung–Russell diagram representing stars of the same age—are constructed from stellar evolution models and applied to date star clusters, measure distances, study galactic history, and characterise exoplanet hosts. Despite challenges from stellar physics uncertainties, binaries, and dust effects, advances from Gaia, improved models, and machine learning promise more precise isochrone applications in future astrophysics.

Geetha Paul's The Symphony of Signal explores neurotransmission—the precise electrical and chemical dialogue between neurons that underlies thought, movement, emotion, and memory. The article explains how neurotransmitters like dopamine, serotonin, and acetylcholine are synthesised, released, and inactivated, highlighting their roles in health, disease, and therapy.

Contents

Part I

Artificial Intelligence and Machine Learning

Entropy in Networks: Order, Uncertainty, and the Dynamics of Connection

by Jinsu Ann Mathew

AIRIS4D, VOL.3, NO.9, 2025

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In earlier articles, we explored how entropy, first rooted in physics and information theory, provides a measure of uncertainty and disorder in physical systems. We then followed entropy into the world of natural language processing, where it reveals the hidden structure of texts through lexical diversity, n-gram entropy, and cross-entropy in language models. Extending this journey, we examined human language itself, showing how ambiguity, redundancy, and predictability can all be understood as manifestations of entropy in communication.

This article continues that exploration by moving from individual systems—whether physical states, sentences, or utterances—to collective systems. These collective systems take the form of networks, which are everywhere: in the neurons of the brain, the ties of social media, the nodes of the internet, and the interactions of ecosystems and economies. Networks represent the fabric of relationships that define complexity in nature and technology. By applying entropy to networks, we gain a powerful lens to measure structural complexity, dynamic uncertainty, and resilience.

1.1 Entropy in Network Structure

The structure of a network is determined by how its nodes and edges are arranged. While we can often "see" a network's complexity when drawn, entropy provides a way to quantify that complexity mathematically. By treating different aspects of the network as probability distributions, we can measure how much uncertainty or unpredictability is embedded in its structure. Three of the most widely discussed notions are degree distribution entropy, spectral entropy, and topological entropy.

Degree Distribution Entropy

Degree distribution entropy is perhaps the most intuitive. Every node in a network has a degree, meaning the number of connections it maintains. If we look at all nodes together, we obtain a degree distribution: the probability that a randomly chosen node has a certain degree. The entropy of this distribution tells us how diverse and unpredictable the network's connectivity is. Consider a star-shaped network, like an airline hub system where one airport connects to every other but all other airports only connect to the hub. Such a system is extremely predictable: the hub is always the center of traffic. The entropy here is low because the degree distribution is sharply uneven. Contrast this with a friendship network in a classroom, where some students are very social, others less so, and many fall in between. This diversity of connections increases uncertainty about which degree a randomly chosen node might have, leading to higher entropy. In short, degree distribution entropy reflects how egalitarian or concentrated a network's connections are.

Spectral Entropy

Another way to capture the complexity of a network is by looking at its spectral properties. A network can be represented by an adjacency matrix, which records which nodes are connected to which. From this matrix, we can calculate eigenvalues, which reflect the overall connectivity patterns of the network. The distribution of these eigenvalues can then be treated like a probability distribution, allowing us to compute entropy. This measure, called spectral entropy, quantifies how ordered or disordered the network's structure is.

Imagine a perfectly regular crystal lattice in physics, where each atom connects to its neighbors in a fixed and repeating pattern. The eigenvalues of such a highly regular network are very structured and predictable, and thus the spectral entropy is low. Now compare this to a biological neural network, where the connections between neurons are far more irregular and variable. The eigenvalue spectrum here is more spread out and less predictable, leading to higher spectral entropy.

In other words, spectral entropy gives us a global view of how "organized" or "messy" the overall network is. Where degree distribution focuses only on how evenly connections are spread across nodes, spectral entropy reflects whether the entire system behaves like a predictable lattice or a disordered web.

Topological Entropy

The third perspective is topological entropy, which considers how complexity unfolds as one moves through a network. If you imagine walking along the nodes of a chain, like beads on a string, the path is entirely predictable—you can only move forward or backward. The growth of possible paths is minimal, and so the entropy is low. By contrast, imagine browsing the internet through hyperlinks, or exploring a dense web of acquaintances in a social network. At each step, the number of possible next moves grows explosively, creating unpredictability about where you might end up. This rapid expansion of possibilities is reflected in a high topological entropy. Topological entropy therefore measures the richness of navigational or dynamical complexity within the network.

Taken together, these three notions—degree distribution entropy, spectral entropy, and topological entropy—paint a comprehensive picture of network structure. Degree distribution captures the fairness of connectivity, spectral entropy reveals global structural regularities or irregularities, and topological entropy measures the branching richness of possible paths. By applying these measures, researchers can move beyond visual impressions of networks and develop a rigorous language for describing and comparing the complexity of systems as diverse as airline routes, neural circuits, city layouts, and online social platforms.

1.2 Entropy in Network Dynamics

While structural entropy focuses on how a network is built, dynamic entropy captures how processes unfold on top of that structure. Networks are not static: they carry information, resources, or signals across their nodes. Entropy provides a natural way to measure the uncertainty, unpredictability, and diversity of these flows. By studying entropy in network dynamics, we can better understand how robust, efficient, or fragile a system is in motion.

Information Flow Entropy

One of the most important ideas is information flow entropy. In many networks—whether it be messages traveling across the internet, rumors spreading through social media, or impulses moving between neurons—information can follow multiple routes. If there is only a single, predictable path for transmission, the entropy is low. For example, in a centralized communication network, all messages may pass through one central server, so the flow is highly constrained and predictable. By contrast, in a peer-to-peer file-sharing network, there may be dozens of possible routes for a message to reach its destination. This diversity of possible paths increases uncertainty, giving the system higher entropy. High flow entropy can make communication more resilient—if one path fails, others remain—but it also makes the flow less predictable.

Robustness and Vulnerability

Entropy in network dynamics is also closely tied to robustness and vulnerability. Networks that are too orderly may function efficiently under normal conditions but are fragile when disrupted. For instance, in a power grid designed around a small number of central hubs, failure of a single hub can trigger cascading breakdowns. Such a system has low entropy because its dynamics are highly concentrated around predictable routes. On the other hand, a system with very high entropy—where signals or resources disperse unpredictably—may lack stability and coherence. Interestingly, many natural and human-made networks seem to operate in a balance, maintaining a moderate level of entropy that allows both resilience and efficiency. This balance helps explain why the internet, biological ecosystems, and social networks often survive shocks yet remain functional.

Predictability of Spreading Processes

Another dimension of dynamic entropy involves the predictability of spreading processes. Consider the example of an epidemic spreading through a community. If the social network is highly clustered, the disease may spread along a few well-defined routes, resulting in low entropy of infection pathways. If the network is more loosely structured, the disease may jump across many unpredictable links, leading to high entropy. Similarly, in online environments, a viral meme might follow either a few predictable influencers (low entropy spread) or leap across the network through diverse routes (high entropy spread). In both cases, entropy serves as a measure of how predictable or surprising the spread is.

In summary, entropy in network dynamics captures the uncertainty of motion and flow within a system. It tells us whether communication is centralized or distributed, whether processes are robust or fragile, and whether spreading events are predictable or chaotic. Just as structural entropy gives us a snapshot of the network's architecture, dynamic entropy provides a moving picture of how that architecture is used. Together, they form a comprehensive framework for understanding the complexity of networks in action.

1.3 Applications Across Domains

The idea of using entropy to study networks is not just abstract mathematics—it has powerful applications across many fields of science and society. By measuring uncertainty and unpredictability in how networks are structured and how processes flow through them, researchers can uncover hidden patterns, assess stability, and even predict failures.

Communication Networks

In communication networks, entropy helps describe how information spreads across the internet or through social media platforms. A centralized system, where most traffic flows through a handful of servers, exhibits low entropy: the paths are predictable but also vulnerable to attack or overload. In contrast, decentralized peer-to-peer networks have higher entropy, as messages can take many different routes. This diversity makes them harder to shut down and more resilient, but it also introduces unpredictability in delivery times. Studying entropy in these systems gives engineers a way to balance efficiency and robustness.

Biology and Neuroscience

In biology and neuroscience, entropy provides a lens for understanding complex living systems. Neural networks in the brain, for instance, display rich dynamics that can be studied with entropy. Low-entropy states often correspond to deep sleep, where brain activity is highly synchronized and predictable. High-entropy states, in contrast, are linked to wakefulness and consciousness, when neural signals are diverse and less predictable. Similar approaches have been used in genetics and systems biology, where entropy measures help describe how robust a metabolic or protein-interaction network is against perturbations.

Epidemiology

In epidemiology, entropy in network dynamics offers a way to study how diseases spread. A community where most people interact within tight, predictable clusters has low entropy: infections move along narrow, well-defined routes. But when connections are more varied and unpredictable—such as in large, highly mobile urban populations—the entropy of disease spread increases, making outbreaks harder to trace and control. Public health models often rely on entropy-based measures to evaluate the effectiveness of interventions like travel restrictions or vaccination strategies.

Social Systems

Finally, in social systems, entropy sheds light on how ideas, rumors, or cultural trends spread. A tightly controlled flow of information, such as in a hierarchical organization, has low entropy—messages follow predictable paths, but innovation is limited. In open social networks, where anyone can connect with anyone else, entropy is higher, leading to more diverse and unpredictable exchanges. This can foster creativity but also allows misinformation to spread rapidly.

1.4 Conclusion

In our earlier explorations, entropy appeared first as a bridge between physics and information theory, then as a measure of uncertainty in language and meaning. With networks, we encounter a new dimension: entropy no longer measures just the randomness of states or symbols, but the unpredictability of connections and flows. Whether in the structure of a network—captured by degree distributions or spectral measures—or in the dynamics of how processes evolve across it, entropy provides a unifying lens for complexity.

This perspective shows that networks are not merely collections of nodes and edges, but dynamic systems where predictability and uncertainty coexist. Low entropy can signal stability but also fragility, while high entropy may reflect adaptability at the cost of control. By quantifying these trade-offs, entropy allows us to compare systems as diverse as the brain, the internet, economies, and cities within a single conceptual framework.

Perhaps the most striking lesson is the universality of entropy. From particles to words to networks, the same principle recurs: uncertainty is not noise to be discarded, but a feature to be measured, understood, and even harnessed. Each domain reveals new faces of entropy, and together they point toward a broader philosophy of complexity—one in which randomness and order are deeply intertwined.

As we continue this journey, the study of entropy in networks stands as a reminder that complexity is not chaos, but structured unpredictability. In embracing this view, we open the door to deeper insights into the systems that shape both nature and society.

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Jinsu Ann Mathew is a research scholar in Natural Language Processing and Chemical Informatics. Her interests include applying basic scientific research on computational linguistics, practical applications of human language technology, and interdisciplinary work in computational physics.

Part II

Astronomy and Astrophysics

Plasma Physics & Solar Physics

by Abishek P S

AIRIS4D, VOL.3, NO.9, 2025

www.airis4d.com

1.1 Introduction

The study of plasma physics and solar physics offers a profound gateway into understanding the fundamental processes that govern not only our Sun but much of the observable universe. Plasma physics, which deals with the behaviour of ionized gases, is essential because over 99% of the visible matter in the cosmos exists in this state[1]. In the context of solar physics, plasma becomes the medium through which energy, momentum, and magnetic fields interact in complex and often turbulent ways. The Sun, our closest star, serves as a natural laboratory for plasma phenomena, exhibiting dynamic behaviours such as solar flares, coronal mass ejections, and the solar wind-all driven by the interplay of magnetic fields and charged particles. Through the lens of magnetohydrodynamics (MHD), scientists model the Sun's interior and atmosphere, exploring how fluid-like plasma flows are shaped by electromagnetic forces. Observational tools like helioseismology, spectropolarimetry, and space-based missions such as the Parker Solar Probe and Solar Orbiter provide critical data that help validate theoretical models[2,3]and uncover new layers of complexity.

Describing the Sun as a plasma laboratory is not merely metaphorical-it reflects the reality that our star offers a naturally occurring, high-energy environment where the principles of plasma physics can be observed and tested at scales unattainable on Earth. The Sun is composed almost entirely of plasma, allowing it to conduct electricity and interact strongly with magnetic fields. This plasma is not static; it is governed by a complex interplay of electromagnetic forces, fluid dynamics, and nuclear reactions. At its core, nuclear fusion converts hydrogen into helium, releasing vast amounts of energy that propagate outward through radiative and convective zones. As this energy reaches the outer layers-the photosphere, chromosphere, and corona-it drives dynamic phenomena such as solar flares, coronal mass ejections, and the solar wind. These events are shaped by magnetic field lines that twist, reconnect, and evolve due to the Sun's differential rotation and turbulent convection, processes best described by magnetohydrodynamics (MHD) [4]. Plasma physics provides the theoretical and computational tools to model these behaviours, while observational instruments like spectrometers, helioseismology arrays, and space-based probes offer empirical data to validate and refine our understanding. In essence, the Sun serves as a vast, self-sustaining plasma experiment, enabling researchers to study fundamental processes that influence not only stellar evolution but also planetary environments and space weather throughout the solar system..

1.2 Plasma State and Ionization

In the solar context, the plasma state and ionization represent the most fundamental aspects of solar physics. At the extreme temperatures found within the Sun-ranging from approximately 6,000 K at the photosphere to over 15 million K in the core-thermal energy is sufficient to strip electrons from atoms, resulting in a fully ionized gas composed of free electrons and atomic nuclei. This ionized state, known as plasma, dominates the Sun's composition and behaviour. Unlike neutral gases, plasma is electrically conductive and highly responsive to magnetic and electric fields, which makes it a dynamic medium for energy transport and magnetic interactions. To quantify the degree of ionization under varying solar conditions, we apply the Saha ionization equation, a thermodynamic relation that links ionization levels to temperature and particle density[5]. This equation is particularly useful in modelling the transition zones of the Sun, such as the chromosphere and photosphere, where partial ionization occurs and radiative processes are complex. The prevalence of plasma throughout the Sun-from its core to the outer corona-forms the basis for understanding solar phenomena like flares, prominences, and the solar wind. Thus, the plasma state is not just a descriptive label but a critical framework for interpreting the Sun's structure, dynamics, and its influence on the heliosphere

1.3 Magnetohydrodynamics (MHD)

Magnetohydrodynamics (MHD) is a cornerstone of solar physics, offering a powerful theoretical framework to understand the behaviour of the Sun's plasma[6]. MHD merges the principles of fluid dynamics with Maxwell's equations of electromagnetism to describe how electrically conductive fluids-like the ionized plasma in the Sun-interact with magnetic fields. One of the most critical features of solar plasma is its high electrical conductivity, which leads to the phenomenon known as the "frozen-in" condition: magnetic field lines are effectively locked into the plasma and move along with it. This coupling between plasma motion and magnetic field evolution is central to many solar phenomena.

MHD equations allow modelling and prediction of dynamic solar events such as solar flares and coronal mass ejections (CMEs), which are sudden releases of magnetic energy that accelerate particles and eject massive amounts of plasma into space[7]. These events are often triggered by magnetic reconnection, a process where oppositely directed magnetic field lines break and reconnect, releasing stored magnetic energy explosively. MHD also explains the formation and evolution of sunspots, which are regions of intense magnetic activity

Figure 1: Parker Solar Probe

Image courtesy: https://science.nasa.gov/mission/parker-solar-probe/

on the solar surface, and their role in the 11-year solar cycle, during which the Sun's magnetic field reverses polarity and solar activity waxes and wanes.

Through numerical simulations and observational data from missions like the Solar Dynamics Observatory (SDO) and Parker Solar Probe, scientists refine MHD models to better understand the Sun's magnetic architecture and its influence on the heliosphere[2]. In essence, MHD is not just a theoretical tool-it is the language through which scientists decode the Sun's most energetic and enigmatic behaviours

1.4 Solar dynamo theory

The solar dynamo theory is central to understanding the origin and evolution of the Sun's magnetic field[8,9]. This theory posits that the magnetic field is generated and sustained by a dynamo mechanism operating within the Sun's convective zone, where hot plasma rises and cooler plasma sinks in a turbulent, churning motion. Crucially, the Sun exhibits differential rotation-its equator rotates faster than its poles-which stretches and twists magnetic field lines over time. Combined with helical turbulence from convective motions, this differential rotation amplifies and reorganizes magnetic fields through a process known as the α–Ω dynamo. The result is a self-sustaining cycle of magnetic field generation that manifests in the 11-year solar cycle, during which the Sun's magnetic polarity reverses and solar activity fluctuates.

This dynamo action explains the periodic emergence of sunspots, regions of intense magnetic concentration, and the occurrence of solar flares and coronal mass ejections (CMEs)-all of which are surface expressions of deeper magnetic processes. These magnetic phenomena have profound implications for space weather, influencing the solar wind and impacting Earth's magnetosphere, satellites, and communication systems. Researchers use a combination of numerical simulations, helioseismic data, and observations from solar missions to refine dynamo models and better predict solar behaviour. In essence, the solar dynamo is not just a theoretical construct-it is a dynamic engine driving the Sun's magnetic heartbeat and shaping the space environment throughout the solar system.

1.5 Wave-Particle Interactions

In the realm of solar and space plasma physics, wave-particle interactions are fundamental to understanding energy transfer and particle dynamics in the Sun's atmosphere. Plasma, being a magnetized and ionized medium, supports a variety of wave modes, notably Alfvén waves and magnetosonic waves, which arise from the coupling between magnetic fields and charged particles. Alfvén waves propagate along magnetic field lines and are driven by magnetic tension, while magnetosonic waves combine pressure and magnetic effects, allowing them to travel across field lines. These waves play a critical role in transporting energy and momentum from the lower solar atmosphere into the corona. One of the most compelling applications of this mechanism is in explaining the coronal heating problem-why the solar corona reaches temperatures exceeding one million Kelvin, far hotter than the underlying photosphere. As these waves travel upward, they undergo dissipation through resonant absorption, phase mixing, and turbulent cascade, effectively heating the coronal plasma. Moreover, during dynamic solar events such as flares and coronal mass ejections (CMEs), wave-particle interactions become even more pronounced[7]. Particles can gain energy through resonant interactions with plasma waves, where their velocities match the wave phase speed, leading to efficient energy transfer. Additionally, magnetic reconnection-a process where magnetic field lines break and reconnect-releases vast amounts of stored magnetic energy, accelerating particles to high energies. These mechanisms collectively contribute to the generation of high-energy electrons and ions observed during solar eruptions, which in turn produce X-ray and radio emissions and influence space weather conditions throughout the heliosphere.

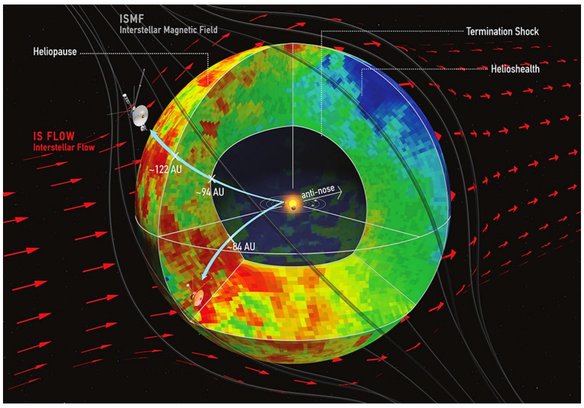

Figure 2: Heliosphere

Image courtesy :Heliosphere.jpg (1600×1103)

1.6 Solar Wind and Heliosphere

The solar wind is a continuous outflow of charged particles-primarily electrons and protons-from the Sun's upper atmosphere, driven by the immense thermal and magnetic energy of the corona. This stream of plasma expands outward, carving out a vast region in space known as the heliosphere, which acts as a protective bubble enveloping the entire solar system. The heliosphere is shaped by the interplay between the solar wind and the interstellar medium, with its boundary-the heliopause-marking the point where solar influence wanes and galactic forces dominate.

The behaviour of the solar wind is governed by the principles of plasma physics, particularly magnetohydrodynamics (MHD), which describes how magnetic fields and ionized gases interact. As the solar wind travels through space, it encounters planetary magnetic fields, leading to complex interactions that form magnetospheres-regions where a planet's magnetic field deflects and channels the incoming plasma. These interactions can compress, stretch, and energize the magnetosphere, triggering phenomena

Figure 3: Solar Dynamics Observatory

Image courtesy :NASA's Solar Dynamics Observatory Celebrates Decade of Watching Sun | Sci.News

such as geomagnetic storms, auroras, and radiation belt enhancements.

For Earth, such disturbances have tangible consequences: they can disrupt satellite operations, interfere with GPS and radio communications, and even pose risks to astronauts and power grids. Understanding the dynamics of the solar wind and its coupling with planetary environments is thus critical for both fundamental science and practical applications in space weather forecasting. Missions like Voyager, Parker Solar Probe, and Solar Orbiter continue to provide invaluable data, helping researchers refine models of heliospheric structure and solar-terrestrial interactions.

1.7 Observational and experimental tools in Solar Physics

In solar and space plasma research, observational and experimental tools are indispensable for bridging theory and reality. The Solar Dynamics Observatory (SDO) and Parker Solar Probe are at the forefront of high-resolution plasma imaging. SDO continuously monitors the Sun in multiple wavelengths of extreme ultraviolet light, capturing dynamic phenomena such as flares, coronal loops, and magnetic field evolution. Its data provide critical insight into the structure and behaviour of the solar atmosphere[10]. Meanwhile, Parker Solar Probe ventures closer to the Sun than any spacecraft before, directly sampling the solar wind and magnetic fields in the corona. This proximity allows researchers to study plasma conditions in situ, offering unprecedented views of solar particle acceleration and wave-particle interactions.

Complementing these imaging missions is helioseismology, a technique akin to terrestrial seismology but applied to the Sun. By analysing oscillations-primarily pressure modes (p-modes)-on the solar surface, scientists can infer the internal structure of the Sun, including temperature gradients, flow patterns, and rotational dynamics. These oscillations are driven by turbulent convection and provide a window into otherwise inaccessible regions like the radiative zone and the tachocline, a key layer for magnetic field generation.

Spectroscopy adds another layer of diagnostic power. By examining the spectral lines emitted by solar plasma, researchers can determine key parameters such as temperature, density, and magnetic field strength. Spectral line broadening, Doppler shifts, and Zeeman splitting are used to quantify these properties, enabling detailed mapping of plasma conditions across different solar regions. These measurements are crucial for understanding energy transport, magnetic reconnection, and coronal heating mechanisms.

Together, these tools not only validate theoretical models but also refine our understanding of plasma behaviour under extreme conditions-where temperatures soar into the millions of Kelvin and magnetic fields shape the dynamics of the solar system. They form the backbone of modern heliophysics, allowing researchers to decode the Sun's influence on space weather and planetary environments.

1.8 Relevance of Solar Plasma Physics

Studying solar plasma physics is not merely an academic pursuit, it's a gateway to solving some of the most pressing scientific and technological challenges of our time. At its core, solar plasma physics deepens our understanding of stellar evolution, shedding light on how stars are born, live, and die. The Sun serves as a natural laboratory, allowing researchers to observe plasma behaviour in real time, which in turn informs models of more distant and exotic astrophysical objects like pulsars, magnetars, and accretion disks around black holes. This knowledge helps refine theories of energy transport, magnetic field generation, and particle acceleration across the universe.

On a more immediate scale, solar plasma research is vital for space weather forecasting. The Sun's activity-flares, coronal mass ejections, and solar wind variations-can have dramatic effects on Earth's magnetosphere. These disturbances can disrupt satellite operations, GPS systems, aviation routes, and even electrical power grids. By understanding the plasma processes that drive solar eruptions, scientists can develop predictive models that help mitigate risks to critical infrastructure and human safety.

Finally, solar plasma physics offers profound insights into fusion energy, a potential cornerstone of future clean energy solutions. The conditions in the Sun's core-extreme temperatures, magnetic confinement, and turbulent plasma dynamics-mirror those in experimental fusion reactors like tokamaks and stellarators. By studying how the Sun naturally sustains nuclear fusion, researchers gain valuable clues for optimizing confinement, reducing instabilities, and achieving energy-positive fusion on Earth. In essence, solar plasma physics connects the cosmic with the practical, advancing both our cosmic understanding and our technological future.

1.9 Conclusion

Together, plasma physics and solar physics not only deepen our understanding of stellar dynamics and space weather but also inform terrestrial technologies, from fusion energy research to satellite protection. This interdisciplinary field continues to evolve, bridging theory and observation in the quest to unravel the mysteries of our star and its influence on the solar system.

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Black Hole Stories-21

The First LIGO Detection – A Binary Black Hole

by Ajit Kembhavi

airis4D, Vol.3, No.9, 2025

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In this story we will describe the first detection of a gravitational wave source, a binary black hole, by the LIGO detectors. The detection opened a completely new window to the Universe. It is sobering to realise that the binary could not have been detected by any other means now available to us.

2.1 The First Detection

We have described in BHS-20 the Advance LIGO detector (aLIGO), which were installed in the LIGO observatories at Livingston, Louisiana and Hanford, Washington State in the USA. By 2015, the engineering runs, during which the systems were being validated, had begun. During these runs, a signal, which could be a burst of gravitational waves, was observed by the detectors in the morning of September 14, 2015. The signal was first detected at the Livingston observatory, and 7 milliseconds later in the detector at Hanford. The delay in detection between the two detectors provides a constraint on the direction in which the gravitational wave could have approached the Earth and reached the two detectors. This provides a broad region in the sky where the source of the gravitational waves could be located.

But is the signal really a burst of gravitational waves? There are many other effects which could lead to spurious signals which mimic gravitational waves, and these have to be carefully eliminated if the signal is to be accepted as a real gravitational wave. The fact that the signal was detected in both observatories within a time span which was consistent with the distance between them was very encouraging. Careful analysis of the data led to the conclusion that the chance that the signal is spurious is less than one in a million such cases. The gravitational wave detection was therefore taken to be genuine and was labelled as GW150914, with the numbers indicating the date in the order year, month, day.

2.2 The Nature of GW150914

The signal detected from GW150914 is shown in Figure 1. The event as detected at Hanford is shown in the upper panel of the figure, while in the lower panel the event as detected by the two detectors are shown, for comparison. The start of the signal was at 09:50:45 UTC (UTC is Coordinated Universal Time, which for practical purposes coincides with the more familiar GMT, which is Greenwich Mean Time). The time measured from the start is shown on the horizontal axis of the figure. The vertical axis shows the strain, which is the change in length of the detector arm divided by its steady length in the absence of the wave. As explained in BHS-20, as the wave passes the detector, the arms periodically becomes longer and shorter than their steady length, so the strain goes from being positive to negative to positive again and so on. Each such

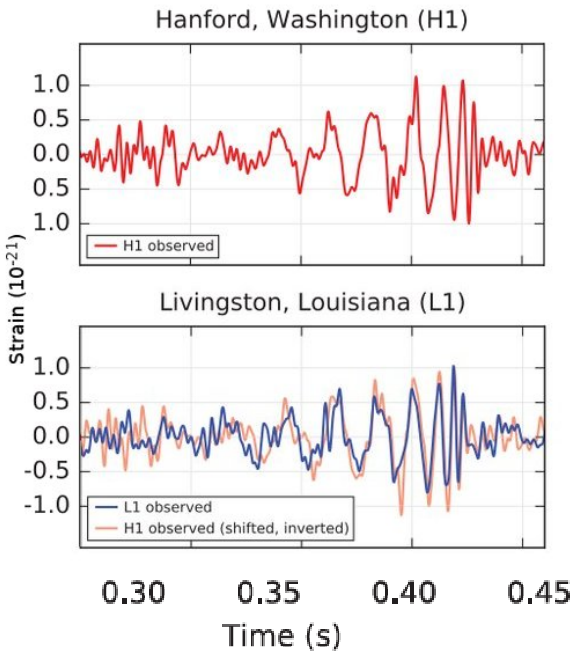


Figure 1: The event GW150914. The upper panel shows the signal detected at Hanford, while the lower panel shows the detection at both the detectors, for comparison. The axes are described in the text.

oscillation is known as a cycle.

The total time covered by the signal is about 0.2 seconds, during which the strain goes through about 8 cycles, with increasing height of the peak at each cycle. The time interval between successive peaks in the signal is shorter, which means that the frequency of the signal increases for each cycle. Such a signal is known as a *chirp*. The amplitude of the signal, i.e., the height reached by the peaks, is maximum at a frequency of about 150 Hertz. Beyond that, the amplitude decreases over successive cycles, which is known as the *ringdown*.

The periodic nature of the signal shows that the source was a binary system, with the two components rapidly going round each other. The observed increasing frequency of the gravitational waves meant that the rate at which the two components go round each other, which is the period of rotation, was increasing. It follows from Kepler's law the distance between the components must be decreasing, i.e. , the components were spiralling towards each other. The spiralling in is due to the emission of gravitational waves, which leads to loss of energy, making the total energy of the binary more negative, which requires the size to shrink (see BHS-4, BHS-6). The highest frequency the observed signal reached was about 150 Hertz (cycles per second). It can be shown from the theory of gravitational waves that the frequency of the emitted gravitational wave is twice the rotation rate. The two components of the binary were therefore going round each other at about 75 times a second at peak amplitude.

From the observed frequency of the gravitational waves at some point of the orbit, and the rate at which the frequency increases, it is possible to estimate the total mass of the binary. This turns out to be greater than 70 Solar masses. The sum of the Schwarzschild radius of the two components must then be greater than about 210 km, since one Solar mass corresponds to a Schwarzschild radius of 3 km. The two components are going round each other 75 times per second when the maximum strain is reached. Assuming that the masses are equal, the distance between them can be calculated to be only 350 km. The components therefore have to be very compact. If they were extended, they would have smashed into each other long before the distance between them reduced to 350 km, and in that case the peak frequency of 150 Hz would not have been observed.

Neutron stars are very compact, with a radius of about 10 km. Could the observed binary have consisted of two neutron stars? That is simply not possible, since a neutron star can have a maximum mass about three Solar masses, which is not enough to make up the estimated mass of the binary. Another plausible configuration is a neutron star in orbit around a massive black hole. But here again the binary would be disrupted before the frequency of 150 Hertz is reached, because of the tidal forces exerted by the black hole on the neutron star. So a binary consisting of two massive black holes is the best case for explaining the observations. We will see below what happens to the binary after the two components merge together.

2.3 A Model for the Black Hole Binary GW150914

In the above, we have used simple Newtonian dynamics of binary systems to argue that the source of the observed gravitational waves was a binary system of two black holes with a total mass of about 70 Solar masses. But the gravitational forces involved are very strong and detailed modelling of the system requires the use of the general theory of relativity. The analysis involves mathematical calculations as well as the use of numerical methods. Such analysis is used to predict the shape of the signal which would be observed from black hole binaries with a wide range of properties. By comparing the predicted shape with the observed signal, the parameters which lead to the best agreement can be determined.

The result is that the binary system, which emitted the gravitational wave signal, was at a distance of about 1.34 billion light years from us. The mass of the two black holes was 36 Solar masses and 29 Solar masses respectively, so that the combined mass before the merger was 65 Solar masses (the estimate above from Newtonian dynamics was $>$ 70 Solar masses). As described above, the binary contracts in size as the two black holes rapidly spiral in. The eventual merger leads to the formation of a rapidly spinning black hole with a mass of 62 Solar masses. The mass of the final black hole is therefore less than the combined mass of the two black holes in the binary by three Solar masses.

What happened to the difference of about 3 Solar masses? According the special theory of relativity, mass and energy are equivalent, so the missing mass must have been emitted from the system as energy. Since the components of the binary are black holes, no electromagnetic energy can be emitted, and the only form of emission possible is gravitational waves. It is this emission which leads to the contraction of the binary. It can be shown, from the theory of gravitational wave emission from binary sources, that the total amount of gravitational wave energy emitted by the system is equal to the energy corresponding to three Solar masses. This is exactly equal to the mass missing after the formation of the single black hole. The gravitational energy was emitted in a fraction of a second, and at its peak the rate of emission was equivalent to converting 200 times the mass of the Sun to energy in a second.

After the peak frequency is reached, the two black holes merge together and the waveform enters what is known as the ringdown phase through which the merged object settles down to a black hole which has only two properties. These are the mass, which for GW150914 is 62 Solar masses, and spin, which is equivalent to about 100 rotations per second. Such an object is known as a Kerr black hole (see BHS-9). The irregularities present in the object soon after the merger are all radiated away as gravitational waves, leaving behind a pristine black hole described by just the mass and spin.

The observed ringdown phase agrees perfectly with the form predicted from a theoretical calculation by C. V. Vishveshwara in 1970. The calculated waveform emitted by the binary is shown in the upper panel of Figure 2, along with a sketch of the merging binary. The shape of the single black hole soon after the merger, and after the ringdown, are also shown. These have been obtained using numerical calculations. The decreasing separation of the two components, and the increasing velocity are shown in the lower panel of the figure. The waveform shows the increasing frequency as the black holes approach each other, the peak amplitude reached, and the ringdown after the merger. At their closest distance before merger, the black holes are moving relative to each other with a very high velocity of 0.6 times the velocity of light.

The binary black hole emits absolutely no electromagnetic waves, so it could not have been observed by any means other than the gravitational waves detected by aLIGO. The discovery established the existence of black holes, binary black holes, gravitational waves and the correctness of Einstein's theory in describing the system. It therefore ranks as one of the great discoveries in the history of physics and astronomy, which yet again demonstrates how the building of novel, large telescopes and detectors always leads to startling new discoveries. The discovery is of such great importance that the 2017 Noble prize in physics was awarded jointly to the American physicists Reiner Weiss, Barry C. Barish and Kip S. Thorne for their decisive contribution to the LIGO detector and the observation of gravitational waves''.

It is interesting that the detection was made a century after the formulation of the general theory of relativity by Albert Einstein in 1915, and the announcement was made a century after Einstein first predicted the existence of gravitational waves in 1916!

In the following stories we will describe other black hole binaries detected as gravitational wave sources, and possible formation mechanisms for these objects.

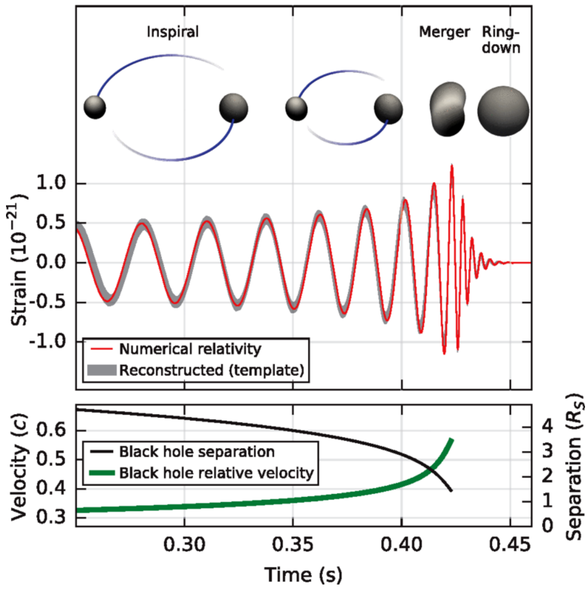
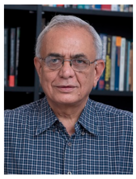


Figure 2: The horizontal axis shows the time elapsed after the start of the detection of gravitational waves. The observations are limited to just 0.2 seconds, at the end of which the merger is completed. In the upper panel a sketch of the binary and the shapes soon after the merger and after the ringdown are shown. In the middle panel, the vertical axis corresponds to the strain, which is the fractional change in length of the arms of the detector due to passage of the gravitational wave. The theoretically and numerically calculated waveform, consistent with the observations, is shown in the panel. In the lower panel, the vertical axis on the left indicates the velocity with which the black holes are moving in the orbit, as a fraction of the velocity of light. The vertical axis on the right shows the separation of the black holes in units of the Schwarzschild radius. The highest velocity reached at peak amplitude is about 0.6 times the velocity of light. The separation reduces to zero at the merger.

Figure courtesy B. P. Abbot et. al., Phys. Rev. Letts **116,** 06112, 2016.

About the Author



Professor Ajit Kembhavi is an emeritus Professor at Inter University Centre for Astronomy and Astrophysics and is also the Principal Investigator of the Pune Knowledge Cluster. He was the former director of Inter University Centre for Astronomy and Astrophysics (IUCAA), Pune, and the International Astronomical Union vice president. In collaboration with IUCAA, he pioneered astronomy outreach activities from the late 80s to promote astronomy research in Indian universities.

X-ray Astronomy: Through Missions

by Aromal P

airis4D, Vol.3, No.9, 2025

www.airis4d.com

3.1 Satellites in 2015s

The second half of the 2010s marked the emergence of a new space power: China. As with many fields of science and astronomy, China invested in X-ray astronomy as well. They began their journey into the X-ray sky with the launch of small satellites, including the X-ray Pulsar Navigation (XPNAV-1) and several CubeSats. Additionally, China launched the Insight-HXMT during this decade. This period also witnessed the launch of some of the most sophisticated instruments in the field, including NASA's NICER and the SRG project developed by Russia and the Max Planck Institute (MPE). We will discuss these observatories in more detail in this article.

3.2 NICER

The Neutron star Interior Composition Explore(NICER) is an externally attached Payload to the ExPRESS Logistics Carrier-2 (ELC-2) of International Space Station(ISS). NICER was launched on June, 2017 in SpaceX's falcon 9 rocket in the Dragon cargo spacecraft as a supply to the ISS. It was later fixed in the mentioned position using robotic arms and astronauts onboard of the ISS. NICER follow orbiter parameters as same as that of ISS. The mission's primary scientific objectives include measuring neutron star radii with unprecedented precision (better than 10% uncertainty), constraining the equation of state of matter at supranuclear densities, and exploring the dynamics of matter under extreme gravitational fields. NICER was originally designed for an 18-month baseline mission, but has far exceeded expectations, now operating in its eighth year. NICER has encountered light leak issues while operating and it is resolved by another special mission.

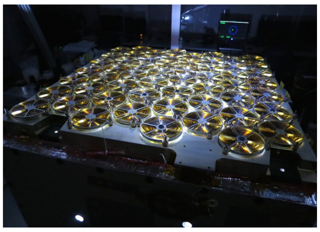


Figure 1: NICER's 56 X-ray Concentrator optics integrated onto the Concentrator Plate in NICER's dedicated coalign- ment facility Credits:[1].

NICER's primary scientific instrument is the X-ray Timing Instrument (XTI), which consists of an aligned collection of 56 X-ray concentrator optics (XRC) and silicon drift detector (SDD) pairs. NICER did not have imaging capabilities. SDDs are fast-response silicon devices that enable high throughput and rapid temporal response while maintaining excellent spectral resolution. Each X-ray concentrator consists of 24 nested parabolic gold-coated thin foil mirrors designed to concentrate (rather than focus) X-ray photons from cosmic sources onto the detectors. NICER XTI operates in an energy range of 0.2-12 keV, has a timing resolution of 300 nanoseconds and a field of View of 30 arcminutes for each concentrator [1]

NICER's most celebrated achievement came in December 2019 with the first accurate measurement of both the mass and radius of a neutron star, PSR J0030+0451. This groundbreaking observation revealed a pulsar with a mass of 1.44 ± 0.15 solar masses and a radius of 13.02 km (with uncertainties of

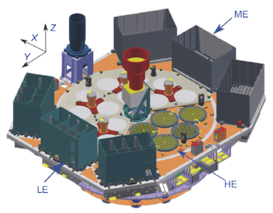


Figure 2: Orientations for all telescopes in insight-HXMT. Creadits:[3]

+1.24/-1.06 km)[2]. Remarkably, NICER also produced the first-ever map of a pulsar's surface, revealing hot spots with temperatures exceeding one million degrees arranged in unexpected configurations on the pulsar's southern hemisphere.

3.3 Insight-HXMT

The Insight-HXMT (Hard X-ray Modulation Telescope) is China's first X-ray astronomy satellite. It was launched on June, 2017, from Jiuquan Satellite Launch Center aboard a Long March 4B rocket. The satellite was placed in a low earth orbit of 550 km radius with an inclination of ~ 43° which gives an orbital period of 96 minutes. Initially proposed lifespan of 4 years, the satellite is still operational. This satellite has three scientific payloads that work in an energy band between 1.0-250 keV [3].

The Low Energy X-ray telescope (LE): LE contains three detector boxes with a sun buffer each. One LE detector box contains two modules and each module contains 16 Swept Charge Device (SCD) chips, and every four SCD detectors share one collimator. SCD's are a special kind of CCD which can offer pile-up free observations. The total detection area of each module is 64 cm^2. It works in an energy range of 1.0-15 keV. LE offers a timing resolution of 0.98 ms and have Multiple configurations FOVs of 1.6°×6°, 4°×6°, 50°-60°×2°-6° for different detector boxes. The LE telescope excels in studying the spectral and temporal properties of soft X-ray sources, with extremely low pileup rates

The Medium Energy X-ray telescope (ME): consisted of three individual Si-PIN detector boxes. It works in an energy range of 5-30 keV. The effective area of the instrument is ~ 952 cm^2. It offers a spectral resolution of ~ 3 keV at 17.8 keV and a Time Resolution of 255 μs

High Energy X-ray Telescope (HE): HE consists of 18 NaI(Tl)/CsI(Na) phoswich detectors with a total geometrical area of about 5100 cm^2. It has an energy resolution of ~ 15% at 60 keV and a timing resolution of $< 10\mu s$. HE has a combined FOV od 5.7°5.7°. The CsI(Na) component serves dual purposes as active shielding for NaI(Tl) and as an omnidirectional gamma-ray monitor for GRB detection in the 0.2-3 MeV range.

Insight-HXMT has been instrumental in studying newly discovered black hole X-ray binaries, providing unprecedented insights into their fundamental properties. The telescope measured precise spin parameters for several black hole systems[4]. The mission has provided detailed phase-resolved spectroscopy of numerous X-ray pulsars, revealing complex relationships between cyclotron line energies, pulse phases, and luminosity. Insight-HXMT conducted extensive monitoring of SGR J1935+2154 during its active episodes, detecting over 300 bursts during a 20-day observation in October 2022. The mission characterized burst spectral properties, phase distributions, and statistical behaviors, finding evidence for self-organizing criticality in magnetar burst processes[5].

3.4 Spektr-RG

Spektr-RG (Spectrum-Röntgen-Gamma), also known as SRG, is a joint Russian-German high-energy astrophysics space observatory launched on July, 2019. The mission represents the most significant Russian space science project in the post-Soviet era and serves as the second observatory in the Spektr series of space telescopes. The primary scientific goal of Spektr-RG is to create an unprecedented X-ray map of the Universe, identifying all large galaxy clusters in the observable cosmos. SRG is located at the L2 Legrangian point, which gives continuous unprecedented observation of the sky away from the sun throughout the year. SRG consists of mainly two scientific payloads that covers a total energy band of 0.2-30 keV.

eROSITA (Extended Roentgen Survey with an Imaging Telescope Array): eROSITA is the primary

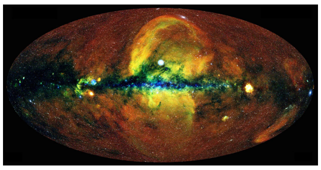


Figure 3: The full view of the X-ray sky monitored by the eRosita mission. Credits:Public Domain

German-built instrument developed by the Max Planck Institute for Extraterrestrial Physics (MPE). The telescope features seven identical mirror modules arranged in a hexagonal configuration. Each module contains 54 nested mirror shells in Wolter-I geometry. It works in the energy range of 0.2-8 keV and offers a FOV of 1 degree. The eROSITA telescope structure measures approximately 1.9 m in diameter by 3.2 m in height. Each camera assembly includes a pn-CCD detector with 384 × 384 pixels, providing excellent spectral resolution. It also has an effective area of 2400 cm^2 at 1 keV[6].

ART-XC (Astronomical Roentgen Telescope - X-ray Concentrator): ART-XC is the Russian-built instrument developed by the Space Research Institute (IKI) and the All-Russian Scientific Research Institute for Experimental Physics (VNIIEF). It consists of seven identical mirror modules with nested mirror shells. Each module contains 28 nested conical mirror shells in Wolter-I geometry. The ART-XC detectors are Double-sided Silicon Strip Detectors (DSSDs) made of cadmium telluride (CdTe). It operates in the energy range of 4-30 keV with an effective area of 385 cm^2at 8.1 keV[7]

One of Spektr-RG's most remarkable achievements is its discovery and cataloging of galaxy clusters on an unprecedented scale. The first eROSITA All-Sky Survey (eRASS1) resulted in the identification of 12,247 optically confirmed galaxy clusters and groups, with 68% (8,361) being entirely new discoveries previously unknown to science[9]. Spektr-RG has dramatically expanded our catalog of supermassive black holes throughout the universe. This mission is expected to detect approximately 3 million supermassive black holes in active galactic nuclei (AGN) during its operational lifetime. Recent achievements include the discovery of 11 new active galactic nuclei at relatively nearby distances (redshifts 0.028-0.258), and the identification of 13 tidal disruption events (TDEs)[8]

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Isochrones in Astronomy

by Sindhu G

AIRIS4D, VOL.3, NO.9, 2025

www.airis4d.com

4.1 Introduction

In stellar astrophysics, one of the most powerful tools to study the properties, structure, and evolution of stars is the isochrone. Derived from the Greek words for "equal" (iso) and "time" (chronos), isochrones are curves on the Hertzsprung–Russell (HR) diagram or the color–magnitude diagram (CMD) that represent the theoretical positions of stars of different masses but the same age and chemical composition. These curves allow astronomers to compare observed stellar populations with theoretical models of stellar evolution.

Isochrones are essential for a wide range of astronomical studies, including determining the ages of star clusters, tracing the history of star formation in galaxies, and understanding stellar structure and nucleosynthesis. This article discusses the theoretical basis of isochrones, their construction, applications in astronomy, and the challenges associated with their use.

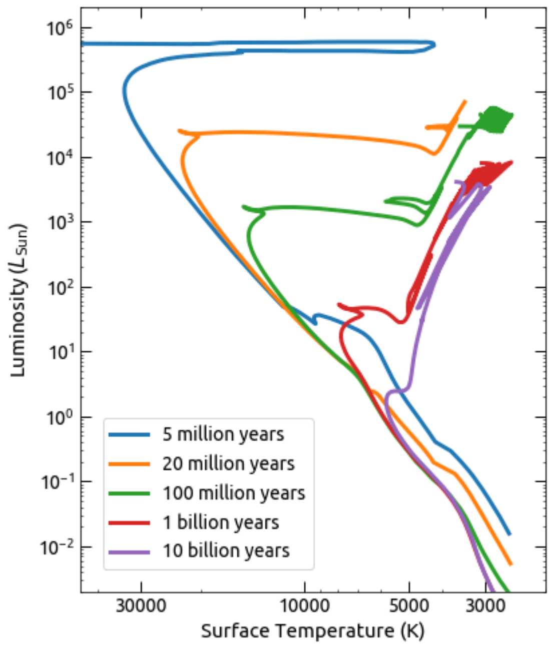

Figure 1: Theoretical isochrones from the stellar models by Leo Girardi and collaborators (Padova) for near-solar metallicity and a range of ages. Image Credit: Ivan Ramirez.

4.2 Theoretical Basis of Isochrones

Isochrones are derived from stellar evolution models, which track the changes in a star's luminosity, effective temperature, and internal structure over time as it burns nuclear fuel. The position of a star on the HR diagram at a given time depends primarily on three parameters:

- **Initial Mass** – Determines the rate of stellar evolution. High-mass stars evolve rapidly and end their lives as supernovae, while low-mass stars evolve more slowly and may live for billions of years.
- **Chemical Composition (Metallicity)** – Heavier element abundance affects stellar opacity, energy transport, and nuclear burning rates.
- **Age** – Stars of the same age but different masses occupy different positions on the HR diagram.

By computing stellar evolutionary tracks for stars of different masses, astrophysicists can construct a set of points corresponding to stars of a given age and metallicity. Connecting these points results in an isochrone.

Figure 1 shows theoretical isochrones of different ages (5 Myr, 20 Myr, 100 Myr, 1 Gyr, and 10 Gyr). The x-axis represents the stellar surface temperature (decreasing to the right), while the y-axis shows luminosity in units of solar luminosity ($L/L_{\odot}$). Each colored curve corresponds to stars of the same age but different masses. The diagonal band represents the main sequence, where stars burn hydrogen in their cores. The "turnoff point" (where the curve bends away from the main sequence) shifts downward with increasing age and provides a direct estimate of the stellar population's age. Stars moving upward and rightward are evolving into red giants after exhausting core hydrogen. Isochrone fitting to observed cluster stars allows astronomers to estimate the cluster's age.

4.3 Construction of Isochrones

The construction of isochrones requires sophisticated numerical modeling of stellar structure and evolution. The key steps include:

1. **Stellar Evolutionary Tracks:** Compute evolutionary tracks for a grid of stellar masses over time using stellar structure equations and input physics such as nuclear reaction rates, opacities, and equations of state.
2. **Isochrone Interpolation:** For a given age, extract points from each stellar track where the star has reached that age. Interpolate between tracks of different masses to create a continuous curve.
3. **Transformation to Observables:** Convert theoretical parameters (luminosity, effective temperature) into observational quantities (magnitudes and colors) using bolometric corrections and stellar atmosphere models.
4. **Extinction and Distance Corrections:** Apply corrections for interstellar dust extinction and distance modulus to compare with observational data.

Many public databases, such as the Padova isochrones and MESA Isochrones and Stellar Tracks (MIST), provide pre-computed isochrones for a wide range of ages and metallicities, which are widely used in stellar population studies.

4.4 Applications of Isochrones

Isochrones are indispensable in many fields of astronomy:

4.4.1 Age Dating of Star Clusters

Star clusters are nearly coeval stellar populations. By fitting isochrones to the observed CMD of a cluster, astronomers can estimate its age. The position of the main-sequence turnoff point, where stars begin to leave the main sequence, is particularly sensitive to age.

4.4.2 Determining Distances

If the metallicity and age are known, fitting an isochrone to the observed CMD provides the distance modulus of the cluster or stellar population. This technique is often used in combination with parallax measurements.

4.4.3 Chemical Evolution Studies

Isochrones for different metallicities allow astronomers to trace the chemical enrichment history of galaxies. Comparing isochrones with observed stellar populations helps determine the distribution of metallicities and ages.

4.4.4 Exoplanet Host Stars

The properties of exoplanetary systems depend strongly on their host stars. Isochrone fitting helps determine stellar radii, masses, and ages, which in turn constrain planetary properties.

4.4.5 Galactic Archaeology

Large surveys such as *Gaia* provide photometric and astrometric data for millions of stars. Isochrone fitting across these datasets helps reconstruct the star formation history and assembly of the Milky Way.

4.5 Challenges and Limitations

Despite their usefulness, isochrones face several challenges:

- **Uncertainties in Stellar Physics:** Processes such as convection, rotation, mass loss, and magnetic fields are difficult to model accurately, leading to uncertainties in isochrone predictions.
- **Binary Stars:** Many stars exist in binary or multiple systems. Interactions between stars can alter their evolution, making single-star isochrones inadequate.
- **Extinction and Reddening:** Dust obscuration complicates the comparison of isochrones with observed CMDs, especially in star-forming regions.
- **Degeneracies:** Similar CMD features can result from different combinations of age, metallicity, and distance, making unique solutions challenging.

4.6 Future Prospects

The future of isochrone applications in astronomy is bright, with improvements in both observational data and theoretical models:

- **Gaia Mission:** The unprecedented precision of *Gaia* parallaxes and photometry allows more accurate CMDs, enabling refined isochrone fitting for millions of stars.
- **Advanced Stellar Models:** Incorporation of rotation, asteroseismic constraints, and 3D stellar atmosphere models will lead to more realistic isochrones.
- **Machine Learning Techniques:** Automated fitting of isochrones to large datasets is becoming possible through artificial intelligence and Bayesian inference methods.

4.7 Conclusion

Isochrones are fundamental tools in stellar astrophysics, bridging theoretical stellar evolution models with observational data. They provide insights into the ages, distances, and chemical compositions of stars and stellar systems, and are essential in fields ranging from star cluster studies to galactic archaeology and exoplanet science. While uncertainties remain, continued advances in both theory and observations promise to refine isochrones and expand their role in understanding the universe.

In summary, isochrones serve as a cosmic clock, allowing astronomers to piece together the life stories of stars and galaxies across cosmic time.

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Sindhu G is a research scholar in the Department of Physics at St. Thomas College, Kozhencherry. She is doing research in Astronomy & Astrophysics, with her work primarily focusing on the classification of variable stars using different machine learning algorithms. She is also involved in period prediction for various types of variable stars—especially eclipsing binaries—and in the study of optical counterparts of X-ray binaries.

Part III

Biosciences

The Symphony of Signal: A Deep Dive into Neurotransmission

by Geetha Paul

AIRIS4D, VOL.3, NO.9, 2025

www.airis4d.com

1.1 Introduction

Neurotransmission, the fundamental language of the nervous system, is the process by which neurons transmit signals to each other or to other cells. Neurons have a specialised anatomy consisting of dendrites (signal receivers), a cell body, and a long axon (signal transmitter). Signals are initiated by an action potential, an electrical impulse travelling down the axon. A process by which neurons communicate through chemical and electrical signals, analogous to a symphony with various players contributing to a harmonious outcome. Neurotransmission involves multiple components such as neurotransmitters, receptors, ion channels, and signal propagation, all working in concert to enable brain functions like thought, emotion, sensation, and movement.

Neurons (also called neurones or nerve cells) are the fundamental units of the brain and nervous system, the cells responsible for receiving sensory input from the external world, for sending motor commands to our muscles, and for transforming and relaying the electrical signals at every step in between. More than that, their interactions define who we are as people. Having said that, our roughly 100 billion neurons do interact closely with other cell types, broadly classified as glia (these may actually outnumber neurons, although it's not really known).

There are billions of neurons and thousands of varieties of neurons; they can be classified into three basic groups based on function. These are motor neurons, sensory neurons, and interneurons.

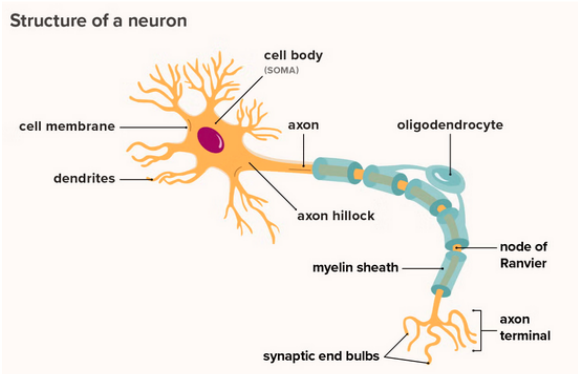

Figure 1: Structure of a typical neuron. Nervous system cells are called neurons. They have three distinct parts, including a *cell body, axon, and dendrites.* These parts help them to send and receive chemical and electrical signals.

Image courtesy: https://www.healthline.com/health/neurons

This network operates through a process called **neurotransmission**, an elegant game of chemistry and electricity that allows billions of neurons to converse, creating everything from the spark of a thought to the surge of fear, from a deliberate movement to a subconscious heartbeat. Two of the most potent messengers in this system are **dopamine** and **adrenaline (epinephrine)**. Dopamine, the currency of reward, motivation, and fine motor control, and adrenaline, the architect of the primal 'fight-or-flight' response, exemplify how chemical molecules can produce profound physical and psychological effects. While their outcomes differ dramatically, their journey from one cell to the next follows a precise and universal sequence of events, a testament to the elegant design of biological signalling.

1.2 Steps involved in the process of Neurotransmission

1.2.1 Synthesis and Storage - Crafting the Message

The process begins not with a signal, but with preparation. Within the cytoplasm of the presynaptic neuron (the sending cell), the raw materials for communication are gathered. Using enzymes and precursors derived from our diet, like the amino acid tyrosine, the neuron meticulously manufactures its neurotransmitter cargo. For a dopamine neuron, this means converting tyrosine through a series of steps into dopamine itself. For a cell producing adrenaline, the process is more complex, involving the conversion of dopamine first into noradrenaline and then into adrenaline within the adrenal medulla. Once synthesised, these powerful chemical messages are not left to drift freely. They are immediately packaged and sealed into tiny, spherical membranes called **synaptic vesicles**. These vesicles act as protective storage units, safeguarding the neurotransmitters from degradation and concentrating them in the axon terminal, poised for immediate release the moment the command arrives.

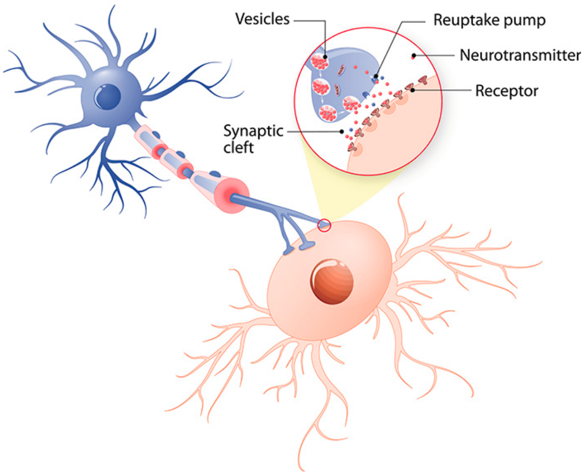

Figure 2: Communication between twoneurons happens in the synaptic cleft (the small gap between the synapses of neurons). Here, electrical signals that have travelled along the axon are briefly converted into chemical ones through the release of neurotransmitters, causing a specific response in the receiving neuron.

Image courtesy: https://qbi.uq.edu.au/brain/brain-functions/what-are-neurotransmitters

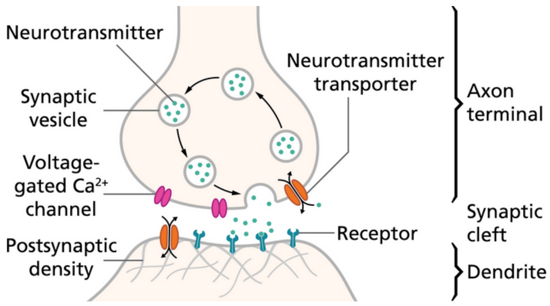

Figure 3: An action potential, or spike, causes neurotransmitters to be released across the synaptic cleft, causing an electrical signal in the postsynaptic neuron.

Image courtesy: Thomas Splettstoesser

1.2.2 Release - Launching the Signal into the Void

The command for release is an electrical impulse known as an **action potential**. This wave of depolarisation rockets down the axon of the neuron like a fuse until it reaches the terminal button. Its arrival triggers the opening of voltage-gated calcium ($Ca^{[207A]}$) channels. The influx of calcium ions acts as the critical trigger, causing the synaptic vesicles to shudder, migrate toward the cell membrane, and fuse with it. In an explosive process called **exocytosis**, the vesicles empty their contents directly into the **synaptic cleft**, the minuscule, fluid-filled gap that separates the sending neuron from the receiving one. In an instant, the carefully crafted neurotransmitters, be it dopamine or adrenaline, are launched into the synaptic void, their fate now dependent on random diffusion.

1.2.3 Receptor Binding - The Lock and Key

The journey across the synaptic cleft is brief but random. On the other side, the postsynaptic membrane (of the receiving cell) is studded with specialised protein structures called **receptors**. Each receptor has a unique geometric shape, making it specific to a particular neurotransmitter, a classic lock and key mechanism. A dopamine molecule will only fit into a dopamine receptor, and adrenaline into an adrenergic receptor. The binding of the neurotransmitter to its receptor is a pivotal moment of recognition. It causes a conformational change in the receptor protein. For ionotropic receptors, this change opens a channel, allowing ions to flood in and alter the cell's electrical charge. For **G-protein-coupled receptors (GPCRs)**, common for dopamine and adrenaline, the binding activates an internal G-protein, initiating a powerful secondary messenger cascade within the cell that can amplify the signal and create diverse, widespread effects.

1.2.4 Postynaptic Effect - The Cellular Response

The binding event translates the chemical signal back to the postsynaptic cell. The receptor type and the cell itself determine the nature of this response. If the effect is **excitatory**, it depolarises the cell, making it more likely to generate its own action potential and propagate the signal. This is often adrenaline's effect on the heart. If the effect is **inhibitory**, it hyperpolarises the cell, suppressing its activity and quieting the neural circuit. Certain dopamine pathways provide this inhibitory effect. Beyond immediate electrical changes, the secondary messenger systems activated by GPCRs can unleash long-lasting biochemical alterations, such as activating enzymes, altering metabolism, or even triggering changes in gene expression, thereby forging long-term memories and adaptations.

1.2.5 Inactivation - Ending the Conversation

Precision in communication requires not just power, but also control. To prevent the signal from persisting indefinitely and causing erratic firing or damage, the neurotransmitter must be rapidly removed from the synaptic cleft. This critical process of inactivation occurs through three primary mechanisms. The most common is **reuptake**, where specialised transporter proteins on the presynaptic neuron act like molecular vacuum cleaners, actively pumping the neurotransmitter (e.g., dopamine) back into the terminal for recycling and reuse. Alternatively, enzymes in the cleft, such as **monoamine oxidase (MAO)** and **catechol-O-methyltransferase (COMT)**, can break down the molecules into inactive metabolites. Finally, simple **diffusion** can see some molecules drift away from the synapse entirely, diluting their concentration and ending their effect. This swift clearance resets the synapse, making it ready to receive the next message with clarity and precision.

1.3 Monoamine neurotransmitters

Monoamine neurotransmitters play a crucial part in regulating a wide range of functions in the nervous system, and their effects are especially prominent in the brain. They help manage consciousness, thinking, attention, and mood. Disorders of the nervous system often arise from imbalances in these chemicals, and many medications target these pathways to treat various conditions.

1.3.1 Serotonin

Serotonin is primarily an inhibitory neurotransmitter involved in stabilising mood, sleep cycles, appetite, sexual function, anxiety, and pain perception. Imbalances in serotonin levels have been linked to conditions such as seasonal affective disorder, anxiety disorders, depression, fibromyalgia, and chronic pain. Medications like SSRIs and SNRIs, which adjust serotonin activity, are widely prescribed for these issues.

1.3.2 Histamine

Histamine is important for maintaining wakefulness, regulating appetite, and motivating feeding behavior. It is implicated in responses linked to asthma, bronchospasm, mucosal swelling, and multiple sclerosis. This neurotransmitter helps modulate immune responses as well as brain activity.

1.3.3 Dopamine

Dopamine is central to the body's reward system, driving pleasure, arousal, and learning. It influences focus, memory, sleep, motivation, mood, and concentration. Disorders tied to dopamine irregularities include Parkinson's disease, schizophrenia, bipolar disorder, restless legs syndrome, and ADHD. Many addictive substances, such as cocaine and amphetamines, impact dopamine pathways directly.

1.3.4 Epinephrine

Also known as adrenaline, epinephrine is a key driver of the body's "fight-or-flight" reaction to stress or fear. It boosts heart rate, breathing, blood pressure, blood sugar, and muscle readiness, sharpening attention and enabling rapid responses to threats. Excess epinephrine is associated with high blood pressure, diabetes, and heart disease. As a drug, it is used for conditions such as severe allergic reactions, asthma attacks, cardiac arrest, and serious infections.

1.3.5 Norepinephrine

Norepinephrine, or noradrenaline, increases blood pressure and heart rate, and is well-known for boosting alertness, arousal, decision-making, and focus. Medications targeting norepinephrine can improve symptoms of ADHD and depression by enhancing concentration and mood.

These monoamine neurotransmitters not only underlie basic emotional and cognitive processes, but also represent central targets for many psychiatric and neurological therapies

1.4 Catechol-O-methyltransferase (COMT)

It is a crucial enzyme that plays a vital role in the metabolism and inactivation of catecholamines, a class of key neurotransmitters and hormones in the human body. Its primary function is to terminate the biological activity of these signalling molecules, ensuring that neural and hormonal messages are precise, brief, and controlled. **Parkinson's Disease** patients are often treated with L-DOPA (Levodopa), a dopamine precursor. COMT inhibitors (e.g., Entacapone, Tolcapone) are prescribed alongside L-DOPA to block its breakdown in the periphery, allowing more L-DOPA to reach the brain and become dopamine. This enhances the therapeutic effect and smooths out motor fluctuations.

1.5 Acetylcholine

Acetylcholine was the first neurotransmitter to be discovered, identified as a small but vital molecule in the nervous system. It was initially recognised for its key function in the peripheral nervous system, where it is secreted by motor neurons and by neurons of the autonomic nervous system to control numerous body processes. Within the central nervous system, acetylcholine is crucial for supporting cognitive abilities, and its deficiency, particularly from damage to cholinergic neurons, has been linked to **Alzheimer's disease.** This excitatory neurotransmitter serves essential roles in both the central nervous system (comprising the brain and spinal cord) and the peripheral nervous system (all nerves branching outside the CNS). Most neurons in the autonomic nervous system release acetylcholine, thereby influencing heart rate, the regulation of blood pressure, and intestinal movement. Additionally, acetylcholine is involved in muscle contraction, memory formation, motivation, sexual desire, sleep cycles, and learning. Variations in its levels are associated with health issues such as Alzheimer's disease, seizures, and muscle spasms.

1.6 Conclusion

Neurotransmission is the exquisitely precise process that forms the fundamental language of the nervous system, converting electrical impulses into chemical signals to orchestrate all brain and bodily functions. It begins with the synthesis and release of neurotransmitters like dopamine into the synaptic cleft, where they bind to specific receptors on the target cell, delivering commands that alter its activity through excitation or inhibition. Crucially, the signal is rapidly terminated via reuptake or enzymatic breakdown by molecules like COMT, ensuring communication remains brief and controlled. This elegant cycle from release to inactivation is the indispensable mechanism underlying every thought, memory, emotion, and action, highlighting the profound link between molecular biology and conscious experience.

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About the Author

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About airis4D

Artificial Intelligence Research and Intelligent Systems (airis4D) is an AI and Bio-sciences Research Centre. The Centre aims to create new knowledge in the field of Space Science, Astronomy, Robotics, Agri Science, Industry, and Biodiversity to bring Progress and Plenitude to the People and the Planet.

Vision

Humanity is in the 4th Industrial Revolution era, which operates on a cyber-physical production system. Cutting-edge research and development in science and technology to create new knowledge and skills become the key to the new world economy. Most of the resources for this goal can be harnessed by integrating biological systems with intelligent computing systems offered by AI. The future survival of humans, animals, and the ecosystem depends on how efficiently the realities and resources are responsibly used for abundance and wellness. Artificial intelligence Research and Intelligent Systems pursue this vision and look for the best actions that ensure an abundant environment and ecosystem for the planet and the people.

Mission Statement

The 4D in airis4D represents the mission to Dream, Design, Develop, and Deploy Knowledge with the fire of commitment and dedication towards humanity and the ecosystem.

Dream

To promote the unlimited human potential to dream the impossible.

Design

To nurture the human capacity to articulate a dream and logically realise it.

Develop

To assist the talents to materialise a design into a product, a service, a knowledge that benefits the community and the planet.

Deploy

To realise and educate humanity that a knowledge that is not deployed makes no difference by its absence.

Campus

Situated in a lush green village campus in Thelliyoor, Kerala, India, airis4D was established under the auspicious of SEED Foundation (Susthiratha, Environment, Education Development Foundation) a not-for-profit company for promoting Education, Research. Engineering, Biology, Development, etc.

The whole campus is powered by Solar power and has a rain harvesting facility to provide sufficient water supply for up to three months of drought. The computing facility in the campus is accessible from anywhere through a dedicated optical fibre internet connectivity 24×7.

There is a freshwater stream that originates from the nearby hills and flows through the middle of the campus. The campus is a noted habitat for the biodiversity of tropical Fauna and Flora. airis4D carry out periodic and systematic water quality and species diversity surveys in the region to ensure its richness. It is our pride that the site has consistently been environment-friendly and rich in biodiversity. airis4D is also growing fruit plants that can feed birds and provide water bodies to survive the drought.