Vol. 4, No.4, 2026

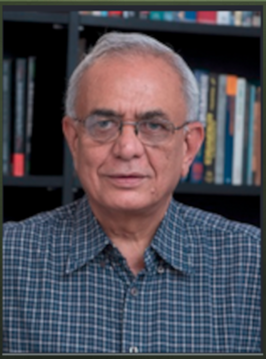
airis4D

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
Computer Programming
Fiction

An airis4D Publication

Cover page

Chitaura indica is a species of grasshopper in the family Acrididae, subfamily Oxyinae, and is endemic to the Indian subcontinent, particularly South India. It was first described by Boris Uvarov in 1929 from specimens collected from Siddapura in the Karnataka (Mysore Plateau) region of the Western Ghats, with the holotype deposited at the Natural History Museum of Geneva. The species is characteristic of tropical grassland and scrub–forest habitats, likely feeding on grasses and herbaceous vegetation as a typical herbivorous orthopteran, and appears to be a relatively robust, medium-sized grasshopper with colouration and markings that may aid in camouflage within its native vegetation.
Photo Credit: Vidyamol M .V, DCII Zoology, project student at airis4D from Christian College, Chenganoor

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Editorial

by Fr Dr Abraham Mulamoottil

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This edition's cover page is a photograph by Vidyamol M .V, DCII Zoology, project student at airis4D from Christian College, Chenganoor. Vidya is an inborn, talented photographer with keen observation. This photograph was captured on her mobile phone near her home premises at Kuttoor, Thiruvalla.

The journal starts with Blesson George's article, "Towards Efficient Learning in Neuromorphic Computing: A Hybrid Probabilistic–Spike Approach". The author proposes a hybrid learning framework that integrates probabilistic reasoning with spike-based neural computation to address key limitations in training spiking neural networks (SNNs). The model combines the efficiency of event-driven, spike-based processing with the mathematical robustness of probabilistic inference by introducing feature-aware connections, adaptive prior updating, and local learning rules. This approach overcomes challenges such as non-differentiability and temporal dynamics in SNNs, offering computational advantages including event-driven efficiency, reduced complexity, parallel processing capability, and hardware compatibility for scalable, low-power neuromorphic systems.

In "From Shannon to ChatGPT: Information Theory in Modern NLP," Jinsu Ann Mathew traces the conceptual continuity from Claude Shannon's foundational information theory to contemporary large language models such as ChatGPT. The article argues that the core principle underlying modern natural language processing—viewing language as a probabilistic system governed by uncertainty—has remained unchanged since Shannon introduced concepts like entropy to quantify unpredictability. Early language models evolved from simple n-gram frequency counters to today's neural networks that leverage massive context windows and cross-entropy optimization to make increasingly accurate predictions. Mathew suggests that what appears as linguistic understanding in systems like ChatGPT may actually emerge from sophisticated prediction and compression capabilities, reframing the question of machine understanding in terms of how effectively a system can reduce uncertainty about language.

Abishek P S examines in "Plasma Physics- Plasma Collisions & Transport," the fundamental differences between collisions in plasmas and those in neutral gases, emphasizing the complexity introduced by long-range Coulomb forces and collective effects. Unlike neutral gas collisions that involve short-range, localized encounters, plasma collisions are shaped by Debye shielding, which confines the influence of charged particles within a characteristic length, and by a rich spectrum of collisional processes including electron-ion, electron-neutral, ion-ion, and photon interactions—that govern transport properties such as conductivity, viscosity, and diffusion. The article highlights how binary collision models provide a foundational framework for analysis, but must be considered alongside collective phenomena like plasma oscillations and wave-particle interactions to fully understand energy exchange, heating, and stability in both natural plasmas (such as those in stars) and engineered systems (such as fusion devices). Ultimately, the author underscores that mastering collision physics is crucial for controlling plasma behavior and advancing applications like sustainable fusion energy.

Ajit Kembhavi's article "Black Hole Stories-25: Some Black Hole Mergers From LIGO-Virgo-KAGRA Observing Run O3," examines significant gravitational wave detections from the third observing run, highlighting how these mergers challenge existing astrophysical theories about black hole formation and mass distributions. The article explains key concepts such as the black hole mass gap—ranging from approximately 60 to 130 solar masses predicted by pair instability supernova theory, and intermediate mass black holes (IMBHs) ranging from 10^2 to 10^5 solar masses. Notable events discussed include GW190412, with its highly unequal mass ratio that required accounting for higher-order gravitational wave multipoles; GW190425, a binary neutron star merger with total mass exceeding known electromagnetic binaries; GW190521, which placed a remnant black hole firmly in the IMBH range while its primary component fell within the pair instability mass gap; and GW190814, whose secondary component at 2.59 solar masses sits in the neutron star–black hole mass gap, raising questions about its true nature. These detections collectively demonstrate how gravitational wave observations are reshaping our understanding of stellar evolution, binary formation mechanisms, and the boundaries between neutron stars and black holes.

In "X-ray Astronomy: Theory," Aromal P examines thermonuclear X-ray bursts in neutron star low-mass X-ray binaries, a phenomenon that forms the core of his observational research. The article explains how accreted material accumulating on a neutron star's surface can undergo a thermonuclear runaway driven by thin-shell instability, where degenerate electron pressure prevents cooling and leads to explosive burning of hydrogen and helium via processes such as the CNO cycle, triple-alpha reactions, and the rapid-proton process. These bursts, which temporarily outshine the persistent accretion luminosity by an order of magnitude or more, produce thermal blackbody spectra peaking in the soft X-ray band and can trigger photospheric radius expansion when the Eddington limit is exceeded. Beyond their intrinsic brightness, these events interact with the surrounding accretion environment by cooling the corona, distorting the accretion disk, and producing reprocessed emission at longer wavelengths. The author emphasizes that studying these bursts provides a unique laboratory for constraining the equation of state of supranuclear matter in neutron star cores, probing accretion physics, and testing nuclear reaction networks under extreme conditions.

Geetha Paul explores in "The Genetic Whisper: Unlocking Biodiversity with eDNA," environmental DNA (eDNA) as a transformative biomonitoring tool that enables scientists to detect organisms by analyzing genetic material shed into water, soil, or air, bypassing the limitations of traditional visual surveys. The article details how eDNA metabarcoding uses universal primers and next-generation sequencing to identify entire communities from a single sample, with applications ranging from detecting invasive species during their lag phase for early intervention to assessing ecosystem health through indicator groups like odonates. Paul highlights cutting-edge extensions of the technology, including airborne eDNA for surveying elusive canopy-dwelling species in tropical rainforests, deep-sea eDNA for mapping biodiversity in the midnight zone, and ancient DNA extracted from permafrost and cave sediments to reconstruct extinct ecosystems. By transforming environmental samples into high-resolution genetic maps, eDNA serves as a non-invasive, sensitive early warning system for biodiversity monitoring, bridging traditional zoology with genomic science to address the global biodiversity crisis.

News Desk

Vijnanam by Prof Babu Joseph, former VC, CUSAT

airis4D has the pleasure of announcing a monthly column, titled Vijnanam, which in Sanskrit, means knowledge. It will be handled by Prof. K. Babu Joseph, formerly of CUSAT, and currently, an advisor to this journal. He is a physicist and a writer of popular science, philosophy and poetry in English and Malayalam.The series will be focussed on science, but occasionally, address other disciplines as well. The first contribution will appear in the May 2026 issue.

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Part I

Artificial Intelligence and Machine Learning

Towards Efficient Learning in Neuromorphic Computing:
A Hybrid Probabilistic–Spike Approach

by Blesson George

airis4D, Vol.4, No.4, 2026

www.airis4d.com

1.1 Introduction

Neuromorphic computing has emerged as a powerful paradigm aimed at replicating the efficiency and adaptability of the human brain. Unlike traditional computing systems, which rely on sequential processing and separate memory and computation units, neuromorphic systems operate using distributed, event-driven architectures.

Spiking neural networks (SNNs) form the computational backbone of neuromorphic systems. These networks process information through discrete spike events, enabling low-power and real-time computation. However, despite their advantages, training SNNs remains a challenging problem due to their non-differentiable nature and temporal dynamics.

Existing approaches to learning in SNNs often rely on biologically inspired rules such as Hebbian learning and spike-timing dependent plasticity (STDP). While these methods provide local learning capabilities, they lack the flexibility and efficiency of modern machine learning techniques.

In this paper, we propose a hybrid probabilistic–spike learning framework that integrates probabilistic reasoning with spike-based neural computation. The proposed model overcomes key limitations of existing approaches by introducing feature-aware connections, adaptive prior updating, and efficient learning dynamics.

1.2 Background and Motivation

Biological neural systems learn through synaptic plasticity, where connections between neurons are strengthened or weakened based on activity. Hebbian learning captures this principle through correlation-based updates, while STDP introduces temporal sensitivity by considering the timing of spikes.

Although these mechanisms are biologically plausible, they are not sufficient for solving complex computational tasks efficiently. On the other hand, probabilistic models such as Bayesian learning provide a strong mathematical framework for inference and uncertainty handling but are not directly compatible with spike-based computation.

This gap motivates the development of hybrid approaches that combine the strengths of probabilistic modeling and neuromorphic computation.

1.3 Proposed Hybrid Learning Framework

1.3.1 Model Representation

Let the input feature vector be defined as:

$$X = \{x_1, x_2, \dots, x_n\} \tag{1.1}$$

Each feature is connected to the output neuron through a synaptic weight interpreted probabilistically:

$$w_i = P(y|x_i) \tag{1.2}$$

Unlike naive probabilistic models, the proposed framework accounts for feature interactions by introducing adaptive importance factors.

1.3.2 Feature Interaction Modeling

The conditional probability of the output is expressed as:

$$P(y|X) \propto \prod_{i=1}^{n} P(y|x_i)^{\alpha_i} \tag{1.3}$$

where α_i represents the importance of each feature and is learned dynamically.

This formulation relaxes the independence assumption and enables more expressive representations.

1.3.3 Spike-Based Computation

The membrane potential of a neuron is computed as:

$$V(t) = \sum_i w_i x_i(t) \tag{1.4}$$

A spike is generated when:

$$V(t) \geq V_{th} \tag{1.5}$$

This event-driven mechanism ensures efficient computation.

1.3.4 Adaptive Prior Updating

The prior probability is updated incrementally as:

$$P_{t+1}(y) = (1-\eta)P_t(y) + \eta \cdot \hat{P}(y|X) \tag{1.6}$$

where η is the learning rate.

This allows the system to adapt continuously to new data.

1.3.5 Weight Learning Rule

The synaptic weights are updated using a probabilistic learning rule:

$$w_i^{new} = w_i^{old} + \eta \cdot (x_i y - w_i^{old}) \tag{1.7}$$

This update balances stability and adaptability.

1.4 Proposed Algorithm

The complete training procedure is outlined below:

Algorithm 1: Hybrid Probabilistic–Spike Learning

```
1. Initialize weights $w_i$ and prior probabilities $P(y)$
2. For each input sample $X$:
    (a). Compute membrane potential:
             $V = \sum_i w_i x_i$
    (b). Generate spike if $V \geq V_{th}$
    (c). Estimate posterior probability $P(y|X)$
    (d). Update weights:
             $w_i \leftarrow w_i + \eta(x_i y - w_i)$
    (e). Update prior:
             $P(y) \leftarrow (1-\eta)P(y) + \eta P(y|X)$
3. Repeat until convergence
```

1.5 Computational Advantages

The proposed hybrid probabilistic–spike learning framework offers several computational advantages that make it well suited for efficient and scalable intelligent systems. By combining probabilistic reasoning with event-driven neural computation, the framework achieves a balance between expressiveness and efficiency.

1.5.1 Event-Driven Efficiency

Unlike conventional neural networks that perform continuous computations, neuromorphic systems operate in an event-driven manner. Computation occurs only when spikes are generated. This significantly reduces unnecessary processing when inputs are inactive, leading to lower energy consumption and improved efficiency. Such behavior is particularly advantageous for sparse and real-time data streams.

1.5.2 Reduced Computational Complexity

Traditional probabilistic models often require either strong independence assumptions or computationally expensive joint probability estimation. The proposed framework avoids both extremes by introducing feature-weighted probabilistic contributions. By assigning adaptive importance factors to features, the model captures relevant interactions without requiring full joint distributions. This results in a substantial reduction in computational complexity while maintaining expressive power.

1.5.3 Parallel Processing Capability

Neuromorphic systems naturally support parallel computation, as neurons operate independently and simultaneously. In the proposed model, each feature contributes independently to the neuron's activation, and weight updates are performed locally. This eliminates the need for centralized computation and makes the framework highly compatible with parallel architectures such as GPUs and neuromorphic hardware.

1.5.4 Incremental and Online Learning

The framework supports continuous and incremental learning through adaptive updates of both synaptic weights and prior probabilities. Instead of requiring batch training over large datasets, the system updates its parameters on a per-sample basis. This reduces memory requirements, shortens training time, and enables real-time learning in dynamic environments.

1.5.5 Avoidance of Backpropagation Bottleneck

Conventional deep learning methods rely on backpropagation, which requires global error propagation and high computational cost. In contrast, the proposed approach employs local update rules based on spike activity and probabilistic adjustments. This eliminates the need for global gradient computation, making the model more efficient and suitable for hardware implementation.

1.5.6 Sparse Computation

Spike-based processing inherently leads to sparse activity, as only a subset of neurons is active at any given time. This sparsity reduces the number of computations required and improves overall efficiency. Sparse representations also contribute to better scalability in large networks.

1.5.7 Hardware Compatibility

The proposed framework is well aligned with the constraints of neuromorphic hardware. It supports local memory usage, low-precision computation, and event-driven processing. These characteristics make it suitable for deployment in low-power devices, embedded systems, and edge computing environments.

1.5.8 Scalability

Due to its reliance on local learning rules, parallel processing, and reduced dependence on global information, the framework scales efficiently to larger systems. As network size increases, computational cost grows in a manageable manner, making the approach practical for real-world applications.

These applications benefit from low power consumption and efficient learning.

1.6 Conclusion

This paper presented a hybrid probabilistic–spike learning framework for neuromorphic computing systems. By integrating probabilistic inference with spike-based neural dynamics, the proposed model addresses key limitations of existing learning approaches. The framework introduces feature-aware connections, adaptive priors, and efficient learning rules, enabling scalable and energy-efficient computation.

Future work may focus on experimental validation, hardware implementation, and integration with deep learning systems to further enhance performance.

About the Author

Dr. Blesson George presently serves as an Assistant Professor of Physics at CMS College Kottayam, Kerala. His research pursuits encompass the development of machine learning algorithms, along with the utilization of machine learning techniques across diverse domains.

From Shannon to ChatGPT: Information Theory in Modern NLP

by Jinsu Ann Mathew

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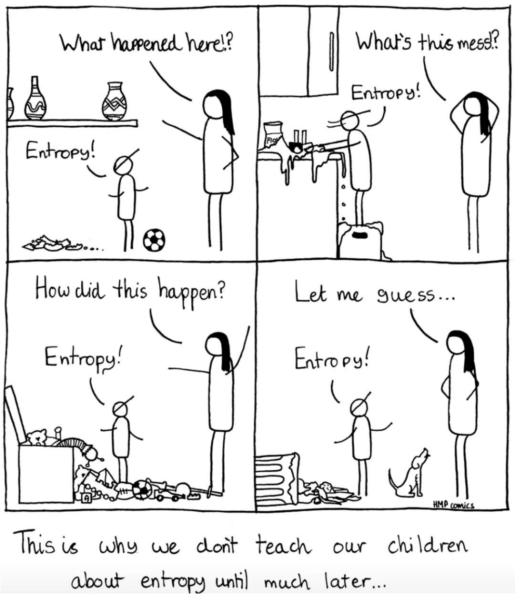
In the late 1940s, long before machines could generate essays or answer complex questions, Claude Shannon was working on a seemingly unrelated problem: how to transmit messages efficiently over imperfect communication channels. His goal was not to understand language, but to ensure that information could be sent accurately despite noise and interference. In doing so, he introduced a mathematical framework—information theory—that would later reshape how we think about language itself.

Today, systems like ChatGPT can generate coherent paragraphs, solve problems, and assist in research. While these systems appear fundamentally different from Shannon's early work, they are deeply connected. The apparent intelligence of modern NLP systems is built upon a principle Shannon introduced decades ago: information can be measured, and uncertainty can be reduced.

The journey from Shannon to modern language models is not about replacing ideas, but about extending them. It is a story of how a theory of communication gradually became a theory of language.



(image courtesy: HMP Comics)

Figure 1: A humorous illustration of entropy by HMP Comics, depicting how systems tend to move from order to disorder, often leading to the oversimplified explanation that "entropy causes everything."

2.1 When Language Became a Problem of Uncertainty

Shannon's most influential idea was that information is fundamentally tied to uncertainty. If the outcome of a message is already known, it carries little new information. On the other hand, if it is surprising or unpredictable, it carries more. To quantify this, Claude Shannon introduced the concept of entropy, a measure of how uncertain or unpredictable a system is.

At first glance, this idea may seem abstract. However, its intuition is surprisingly familiar in everyday life. We often observe that systems tend to move from order to disorder: a neatly arranged room gradually becomes messy, objects get misplaced, and structured arrangements break down over time. This common intuition is humorously captured in figure 1. In the comic, a child explains every instance of disorder—whether it is a messy room or a chaotic situation—by simply saying "entropy." While this explanation is not entirely incorrect, it reflects a common misunderstanding. Entropy does not actively cause disorder in a physical sense. Rather, it describes a statistical tendency: there are far more ways for a system to be disordered than ordered.

To understand this more clearly, consider a simple example. Imagine a set of objects arranged neatly on a shelf. There are only a limited number of ways in which this ordered arrangement can exist. In contrast, there are countless ways for those same objects to be scattered randomly. Because disordered configurations are vastly more numerous, a system that evolves randomly is far more likely to move toward disorder than toward order. What we perceive as the "increase of disorder" is therefore a reflection of probability, not a directed force.

When this idea is applied to language, it leads to a powerful insight. Language is neither completely predictable nor entirely random. If every sentence were perfectly predictable, communication would carry no new information. If it were completely random, it would be meaningless. Instead, language operates in a balance between structure and variability. Certain word sequences are highly likely because they follow familiar patterns, while others are rare or unexpected.

This balance is precisely what makes language both expressive and analyzable. From Shannon's perspective, understanding language is not just about interpreting meaning, but about recognizing and modeling these underlying probabilities. In this way, language itself becomes a system governed by uncertainty—one that can be studied, measured, and ultimately modeled using the principles of information theory.

2.2 From Words to Probabilities: The Birth of Language Models

Once language was viewed as a system governed by uncertainty, the next logical step was to model it using probability. If certain word sequences occur more frequently than others, then these patterns can be captured and quantified.

Early language models did exactly this. They estimated the probability of a word based on its context. In the simplest case, a unigram model treated each word independently, assigning probabilities based on frequency. More advanced models, such as bigrams and trigrams, considered short sequences of words, capturing local dependencies. For example, after the phrase "I am going to," a model might assign high probability to words like "school," "work," or "sleep," and very low probability to unrelated words like "banana." These probabilities are not based on understanding in a human sense, but on observed patterns in data.

What is important here is not the complexity of the model, but the conceptual shift. Language was no longer treated as a purely symbolic system governed by rules. Instead, it became a probabilistic system, where structure emerges from patterns of usage. Even without explicit knowledge of meaning, these models could generate plausible sequences by following statistical regularities.

This idea—that meaning can emerge from probability—would become central to all future developments in NLP.

2.3 Scaling the Same Idea: From Simple Models to ChatGPT

By this point, one thing becomes clear: the core idea of language modeling—predicting what comes next—has not changed. What has changed is how much context a model can use and how well it can capture patterns across that context.

Early models were extremely limited. They could only look at a few words at a time. This meant they often failed when meaning depended on information that appeared earlier in the sentence or even in previous sentences.

To see this limitation, consider the sentence:

"Ravi dropped the glass. It shattered because it was fragile."

A simple model that only looks at the last few words might struggle to understand what “it” refers to. Is it the glass, or something else? Humans easily resolve this because we use the broader context of the sentence. Early models, however, often could not.

Modern systems like ChatGPT overcome this limitation by considering much larger context. They can connect words across an entire sentence—or even multiple sentences—and identify relationships between them. In the example above, such a model correctly associates “it” with “the glass,” allowing it to generate or interpret the sentence coherently.

Another important difference is how these models learn. Instead of relying on simple frequency counts, they learn from massive amounts of text and adjust their internal parameters to improve predictions over time. When the model makes an incorrect prediction, it updates itself to reduce that error. This learning process is guided by a measure called cross-entropy, which essentially tells the model how far its predictions are from the actual text.

What emerges from this process is not just better prediction, but the ability to capture deeper patterns in language—such as relationships between words, sentence structure, and even subtle contextual cues.

So while modern NLP systems may appear fundamentally different, they are still following the same principle introduced by Claude Shannon. The goal remains unchanged: ’Reduce uncertainty by making better predictions’.

The difference is that today’s models can do this across much larger contexts, making their predictions appear far more intelligent.

2.4 Prediction, Compression, and the Question of Understanding

As language models become more accurate in their predictions, an interesting connection emerges between prediction and compression. If a model can predict text with high accuracy, it can also represent that text more efficiently by exploiting its regularities. This is because predictable elements require fewer bits to encode, while unpredictable elements require more.

This idea leads to a powerful insight: a good language model is also a good compression system. By learning the statistical structure of language, the model reduces redundancy and captures essential patterns. In doing so, it mirrors the goals of information theory—efficient representation and transmission of information.

However, this raises a deeper question. When a system like ChatGPT generates coherent and contextually appropriate responses, is it truly understanding language, or is it simply performing highly sophisticated prediction?

From Shannon’s perspective, understanding may not be a separate process at all. It may emerge naturally from the ability to model and predict language effectively. If a system can consistently reduce uncertainty and capture patterns, it begins to exhibit behaviour that resembles understanding.

This does not fully resolve the debate, but it reframes it. Instead of asking whether machines understand language in a human sense, we can ask how far prediction and compression can go in approximating what we call understanding.

2.5 Conclusion

The evolution from Claude Shannon to ChatGPT is not a story of conceptual revolution, but of continuity and expansion. The central idea—that language can be described in terms of probability and uncertainty—has remained unchanged.

What has changed is our ability to apply this idea. From simple probabilistic models to large-scale neural networks, each step has brought us closer to capturing the complexity of human language.

At its core, modern NLP still reflects Shannon’s original insight:

To understand language is to reduce uncertainty about it.

And in that sense, every prediction made by a language model is part of a journey that began not with language itself, but with a fundamental question about information.

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About the Author

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- Plasma Collisions & Transport

by Abishek P S

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1.1 Introduction

Plasma collisions are far more complex than the simple, short-range encounters we see in neutral gases. In a plasma, the charged particles, electrons and ions interact through long-range Coulomb forces, meaning that each particle can influence many others over significant distances. This makes collisions in plasma not just isolated events but part of a collective, interconnected system. Energy exchange and scattering occur, but they are strongly shaped by the surrounding environment, particularly through phenomena like Debye shielding, where a cloud of opposite charges forms around a particle and effectively reduces the strength of its electric field beyond a certain distance. This shielding alters how particles see each other, softening the long-range interactions and giving plasma its distinctive behaviour. Moreover, collisions in plasma are tied to collective effects such as waves, instabilities, and transport processes, which can redistribute energy and momentum across the entire system. As a result, plasma collisions are not merely about two particles bumping into each other, they are about how countless particles, through their electric fields, continuously reshape the dynamics of the medium. This makes understanding plasma collisions essential for explaining conductivity, diffusion, heating, and the stability of both natural plasmas, like those in stars, and engineered ones, such as in fusion devices.

1.2 Nature of Collisions

In plasmas, the nature of collisions is profoundly different from those in neutral gases, and this difference stems from the fundamental forces at play. In a neutral gas, collisions occur when molecules physically bump into each other due to short-range forces like van der Waals interactions. These encounters are localized, meaning that only particles in close proximity exchange momentum and energy. By contrast, plasmas are composed of charged particles such as electrons and ions that interact through the Coulomb force, which is long-range and does not require direct contact. This means that even particles separated by significant distances can influence each other's trajectories, creating a web of interactions that is inherently collective. The presence of many charged particles also leads to phenomena such as Debye shielding, where the effective range of the Coulomb force is modified by the surrounding cloud of charges, ensuring that collisions are shaped by the plasma environment rather than being isolated events [1].

Another layer of complexity arises when we distinguish between elastic and inelastic collisions in plasmas. Elastic collisions conserve kinetic energy, redistributing momentum among particles without changing the total energy of the system. These are important for processes like thermalization, where particles gradually reach a common temperature through repeated scattering. Inelastic collisions, however, involve energy transfer into other processes such as ionization, excitation of atomic states, or radiation emission. For instance, when a fast electron collides with an ion, it may excite the ion to a higher energy state or even strip away another electron, leading to ionization. These inelastic processes are crucial in determining plasma radiation, energy loss mechanisms, and the overall balance of energy within the system. The coexistence of both elastic and inelastic collisions makes plasma behaviour far richer and more varied than that of neutral gases, since collisions can simultaneously redistribute momentum and alter the internal energy states of particles.

Taken together, the long-range nature of Coulomb interactions and the duality of elastic versus inelastic collisions highlight why plasma collisions are central to plasma physics. They govern transport properties like conductivity and diffusion, influence heating and cooling processes, and play a decisive role in the stability of both natural plasmas such as those in stars and interstellar space and engineered plasmas in fusion devices. Unlike the relatively straightforward collisions in neutral gases, plasma collisions are embedded in a dynamic, collective environment where every particle's motion is shaped by the fields of many others, making them a fascinating and complex subject of study.

1.3 Binary Collisions

The study of plasma collisions often begins with the simplification of a many-body system into binary collisions. Although a plasma is inherently a collective medium where countless particles interact simultaneously, modelling collisions as two-body encounters provides a tractable framework for analysis. This approach relies on the concept of reduced mass, which allows the motion of two interacting particles to be described relative to their centre of mass. By treating collisions in this way, researchers can derive scattering angles, cross sections, and energy transfer rates without being overwhelmed by the complexity of the full many-body problem. While this simplification does not capture every collective effect, it serves as a foundational tool for understanding transport properties and for building more sophisticated kinetic and fluid models of plasma behaviour.

A particularly important case is electron-ion scattering, which illustrates the asymmetry inherent in plasma collisions. Electrons, being much lighter than ions, experience strong deflections when they encounter the Coulomb field of an ion [2]. Their trajectories can be significantly altered, leading to large-angle scattering events that influence how electrons move through the plasma. In contrast, ions, due to their much greater mass, barely change direction when colliding with electrons. This imbalance has profound consequences: it determines the plasma's electrical conductivity and resistivity, since electron motion largely governs current flow. Moreover, electron-ion collisions contribute to energy exchange between species, helping equilibrate temperatures and influencing how plasmas respond to external fields. Researchers pay close attention to these interactions because they directly affect confinement, heating, and stability in laboratory plasmas, as well as energy transport in astrophysical environments.

Thus, while the plasma is a many-body system, the binary collision model provides a powerful lens through which to analyse fundamental processes. By focusing on electron-ion scattering, researchers uncover the mechanisms that control macroscopic plasma properties, bridging the gap between microscopic interactions and large-scale phenomena. This dual perspective simplifying to two-body physics while acknowledging collective effects remains central to advancing both theoretical plasma physics and practical applications such as fusion energy research.

1.4 Collective Effects

Collective effects in plasmas are among the most fascinating and defining features of the field, because they highlight how the behaviour of individual particles is inseparably linked to the dynamics of the entire system. One of the most fundamental collective phenomena is Debye shielding. In a plasma, when a charged particle is introduced, the surrounding particles rearrange themselves in such a way that the particle's electric field is partially cancelled beyond a certain distance. This characteristic distance is known as the Debye length, and it sets the scale over which Coulomb interactions are effectively confined. Without shielding, the Coulomb force would extend infinitely, making collisions in plasma uncontrollably long-ranged[2]. Debye shielding ensures that interactions remain finite and manageable, allowing researchers to treat plasma as a quasi-neutral medium where local charge imbalances are quickly corrected by collective rearrangements[3]. This phenomenon is not just a mathematical convenience, it is a physical reality that governs how plasmas respond to perturbations, how waves propagate, and how instabilities develop.

Equally important is the concept of collision frequency, which determines how often particles interact and exchange energy. Unlike in neutral gases, where collision rates depend primarily on density and temperature, plasma collision frequencies are influenced by additional factors such as the charge states of ions and the degree of shielding. For example, highly charged ions exert stronger Coulomb forces, increasing the likelihood of deflecting electrons, while Debye shielding reduces the effective range of these interactions, modifying the overall collision rate. This sensitivity makes plasma transport properties such as electrical conductivity, viscosity, and diffusion highly dependent on environmental conditions. In astrophysical plasmas, variations in density and temperature across regions like the solar corona or interstellar medium lead to dramatic differences in collision frequencies, shaping energy transport and radiation processes. In laboratory plasmas, especially in fusion devices, controlling collision frequency is critical for achieving efficient confinement and minimizing energy losses.

Together, Debye shielding and collision frequency illustrate the collective nature of plasma physics. They show that collisions cannot be understood in isolation but must be analysed in the context of the plasma's self-organizing environment. For researchers, these effects are central to bridging the microscopic physics of particle interactions with the macroscopic behaviour of plasmas, whether in stars, space, or fusion reactors. By studying how shielding modifies forces and how collision rates respond to changing conditions, scientists gain insight into the fundamental mechanisms that govern plasma stability, transport, and energy balance knowledge that is indispensable for both theoretical advances and practical applications

1.5 Types of Collisional Processes

The types of collisional processes in plasmas represent a rich spectrum of interactions that connect microscopic particle dynamics with macroscopic plasma behaviour. Each type of collision contributes uniquely to transport, heating, radiation, and stability, making their study central to both theoretical and applied plasma physics.

Electron-ion collisions are among the most fundamental. Because electrons are much lighter than ions, they are strongly deflected when interacting with the Coulomb fields of ions [2]. These collisions lead to scattering, which redistributes electron trajectories, and to heating, as kinetic energy is exchanged between species. Importantly, electron-ion collisions are the primary mechanism behind plasma resistivity, since they impede the free flow of electrons that carry current. Understanding these collisions is crucial in fusion research, where resistivity affects confinement and energy losses.

Electron-neutral collisions introduce another layer of complexity, especially in partially ionized plasmas. When electrons collide with neutral atoms or molecules, they can cause ionization, stripping electrons from atoms and increasing plasma density. They can also lead to excitation, where electrons in atoms are promoted to higher energy levels, often followed by photon emission. Conversely, recombination occurs when free electrons reattach to ions, reducing ionization levels. These processes are vital in astrophysical plasmas, such as those in planetary atmospheres, and in laboratory discharges, where they determine plasma composition and radiation output[2].

Ion-ion collisions are heavier interactions that primarily govern momentum transfer. Because ions have comparable masses, their collisions are less about deflection and more about redistributing momentum across the plasma. This mechanism underpins plasma viscosity, influencing how plasmas flow and how energy is transported across magnetic fields. In fusion devices, ion-ion collisions help equilibrate ion temperatures, while in astrophysical plasmas they shape large-scale dynamics such as shock formation in supernova remnants.

Photon collisions highlight the coupling between electromagnetic radiation and plasma particles. Photons can ionize atoms (photoionization) or excite electrons to higher energy states, contributing to plasma heating and radiation balance. These interactions are especially significant in astrophysical contexts, where stellar radiation continuously ionizes interstellar gas, and in laser-plasma experiments, where intense photon beams drive ionization and heating.

We classify these processes into bound-bound, bound-free, free-bound, and free-free transitions, each describing a different energy exchange pathway. Bound-bound transitions involve excitation between discrete atomic energy levels, producing characteristic spectral lines that serve as diagnostic tools. Bound-free transitions correspond to ionization, where an electron escapes from a bound state into the continuum. Free-bound transitions describe recombination, where a free electron is captured into a bound state, often accompanied by photon emission. Finally, free-free transitions, also known as bremsstrahlung radiation, occur when free electrons are deflected by ions and emit photons, a key mechanism of energy loss in hot plasmas.

Taken together, these collisional processes form the backbone of plasma physics, linking microscopic interactions to macroscopic phenomena. For researchers, they are not just abstract categories but essential tools for diagnosing plasmas, predicting their behaviour, and designing systems from fusion reactors to astrophysical models that depend on a deep understanding of how particles and radiation interact.

1.6 Plasma Collisions and Neutral Gas Collisions

When comparing plasma collisions with neutral gas collisions, researchers emphasize the fundamental differences in the forces involved, the role of collective effects, the definition of collisions, the energy outcomes, and the dependence of collision frequency on environmental conditions. Each of these points highlights why plasma physics requires its own specialized framework, distinct from the kinetic theory of neutral gases.

Force type is the most striking distinction. In neutral gases, collisions are governed by short-range forces such as van der Waals interactions or direct molecular contact. These forces act only when particles are very close, making collisions localized events. In plasmas, however, charged particles interact through long-range Coulomb forces, meaning that even particles separated by significant distances can influence each other's trajectories. This long-range nature makes plasma collisions inherently collective and far more complex to model.

Collective effects are another defining feature of plasma collisions. In neutral gases, collisions are essentially independent, with minimal collective behaviour beyond bulk pressure and flow. In plasmas, however, collective phenomena such as Debye shielding, plasma oscillations, and wave-particle interactions dominate. Debye shielding ensures that the Coulomb force is effectively confined within a characteristic Debye length, preventing infinite-range interactions. Waves and instabilities further couple particles across large distances, making plasma collisions inseparable from the collective dynamics of the medium.

The definition of collisions itself differs between the two systems. In neutral gases, collisions are always validly defined as discrete, short-range encounters between molecules. In plasmas, the concept of a collision is meaningful mainly in weakly coupled plasmas, where particle interactions can be approximated as binary events. In strongly coupled plasmas, where collective effects dominate, the notion of a simple collision breaks down, and researchers must rely on statistical or fluid descriptions instead.

Energy outcomes also diverge significantly. In neutral gases, collisions primarily redistribute kinetic energy among molecules, leading to thermalization. In plasmas, collisions can produce a much wider range of outcomes: ionization, where electrons are stripped from atoms; excitation, where electrons are promoted to higher energy states; and radiation emission, such as bremsstrahlung or recombination radiation. These processes not only redistribute energy but also change the plasma's composition and radiative properties, making collisions central to plasma heating and cooling.

Finally, collision frequency depends on different factors in plasmas compared to neutral gases. In neutral gases, collision rates are determined mainly by density and temperature, which set how often molecules encounter each other and how energetic those encounters are. In plasmas, collision frequency is more complex: it depends not only on density and temperature but also on charge states of ions and the degree of shielding. Highly charged ions increase collision likelihood, while Debye shielding reduces effective interaction ranges[1]. This sensitivity makes plasma transport properties such as conductivity, viscosity, and diffusion, highly dependent on environmental conditions, whether in astrophysical plasmas or laboratory fusion devices.

1.7 Challenges and Implications

The challenges and implications of modelling plasma collisions highlight why plasma physics is such a demanding yet rewarding field. The first major challenge lies in the complexity of modelling plasma collisions due to collective effects and long-range forces. Unlike neutral gases, where collisions are short-range and can be treated as isolated events, plasmas involve charged particles interacting through Coulomb forces that extend over significant distances. These interactions are further modified by collective phenomena such as Debye shielding, plasma oscillations, and wave-particle interactions. As a result, collisions cannot be understood simply as two-body encounters; they must be analysed within the context of the plasma's self-organizing environment. This makes theoretical modelling highly non-trivial, requiring advanced kinetic theory, statistical mechanics, and numerical simulations to capture the interplay between individual particle dynamics and collective behaviour.

The implications of these collisions are profound because they determine transport properties such as electrical conductivity, viscosity, and diffusion. Electrical conductivity in plasmas is largely governed by electron-ion collisions, which impede electron flow and introduce resistivity. Viscosity arises from ion-ion collisions, redistributing momentum and influencing how plasmas flow under external forces. Diffusion, meanwhile, is shaped by both electron-neutral and ion-neutral collisions, which determine how particles spread through the plasma. These transport properties are not fixed but vary dramatically with plasma density, temperature, and charge states, making them highly sensitive to environmental conditions. For researchers, this means that understanding collisions is essential for predicting how plasmas behave in both natural and laboratory settings.

In the context of fusion research, controlling collisions becomes absolutely crucial. Fusion plasmas must be confined at extremely high temperatures and densities to sustain reactions, but collisions can lead to energy losses through radiation, resistivity, and diffusion across magnetic fields. If collisions are not properly managed, they can degrade confinement, reduce efficiency, and destabilize the plasma[3]. On the other hand, collisions also play a beneficial role in equilibrating temperatures between electrons and ions, distributing energy, and maintaining quasi-neutrality. The challenge for researchers is to strike a balance, minimizing detrimental collisional effects while harnessing beneficial ones. This requires precise control of plasma parameters, advanced diagnostic tools, and sophisticated modelling to predict and optimize behaviour.

In summary, plasma collisions are not just a theoretical curiosity but a practical challenge with direct implications for transport properties and fusion energy development. Their complexity arises from long-range forces and collective effects, their importance lies in determining conductivity, viscosity, and diffusion, and their control is central to achieving stable, efficient plasma confinement in fusion devices. For researchers, mastering the physics of collisions is one of the keys to unlocking both the mysteries of astrophysical plasmas and the promise of clean, sustainable fusion energy.

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Black Hole Stories-25
Some Back Hole Mergers From LIGO-Virgo-KAGRA Observing Run O3

by Ajit Kembhavi

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In this story we will consider some interesting binary mergers detected during the observing runs O3 of the LIGO-Virgo-KAGRA detectors. But before that, we will describe a few astrophysical concepts which are important in understanding some of the mergers detected in O3 and O4.

2.1 Black Hole Mass Gap:

We have seen in earlier stories that at the end of the evolution of star with mass about 25 Solar masses, the core of the fully evolved star collapses to a black hole, and the outer layers are ejected in a supernova explosion. The mass of the remnant black hole depends on the mass of the initial star; its metallicity, which is the abundance of elements heavier than helium; the extent of mass lost by the star due to stellar winds which can carry away a substantial amount of mass during the course of the evolution; and how much matter falls back onto the core during the supernova explosion.

It follows from the theory of stellar evolution that there should be gap in the mass of remnant black holes in the range about 60 – 130 Solar masses. Why is there such a gap? Stars begin their evolution by converting hydrogen to helium through nuclear fusion. In the process, a large helium core develops in the central region. Stars of mass greater than 100 Solar masses develop a helium core with mass greater than about 32 Solar masses. The temperature of such massive cores is so high, that photons of the radiation have sufficient energy to form electron positron pairs through a process known as *pair creation*. With energy lost to the pairs, the pressure due to the radiation reduces, and the pressure exerted by the pairs is not sufficient to compensate for the decrease. The core then collapses very rapidly, and for helium core mass in the range of about 64 – 135 Solar masses, the energy released in the collapse leads to complete disruption of the star in a supernova, with no remnant left behind. Such an explosion is known as a pair instability supernova (PISN). For stars which develop helium cores more massive than 135 Solar masses, the pair instability leads to a direct collapse to a black hole.

For stars whose helium cores are in the mass range of about 32 – 64 Solar masses, the pair creation leads to a series of oscillations of the star known as *pulsational pair instability*(PPI), during which material is ejected from the star, and it returns to a stable configuration. After that there is a supernova explosion, and a black hole is left behind, which has a mass less than it would have had, in the absence of a PPI. The net result of the above processes is an expected gap in the mass of remnant black holes in the range of about 60 – 130 Solar masses. As we will see later, this gap is being breached by black holes in merging binary systems found through gravitational wave detections.

Intermediate Mass Black Holes:

We have encountered two kinds of black holes in our earlier stories: (1) Stellar mass black holes which are the remnants formed in the evolution of massive stars, which can range in mass from a few Solar masses to about a hundred Solar masses or more, depending on the mass of the star from which they formed and the conditions. Such black holes have been observed, for example, in X-ray binary systems. The more massive black holes in this range can be formed through processes mentioned in the discussion above on the black hole mass gap. (2) Supermassive black holes with mass greater than about 10^5 Solar masses. A very compact object with mass of $4.3x10^6$ Solar masses, which is believed to be a supermassive black hole, has been detected in our Galaxy (see BHS-1). Black holes with a mass of a billion Solar masses or more are believed to be the central engines that power the highly luminous active galactic nuclei (AGN) and quasars which have been observed across the electromagnetic spectrum, from radio to optical, to X-ray and Gamma-ray wavelengths.

Black holes in the mass range of about 10^2 – 10^5 Solar masses are known as intermediate mass black holes. The evidence for the existence of black holes in this range is much weaker than for the other two types of black holes, and the mechanisms for their formation are not well established.

One possibility is that they formed in the early Universe, through the direct collapse of very massive stars known as Population III stars. These were the first generation of stars which formed from the matter created in the big bang and consisted of hydrogen and helium, with only trace amounts of heavier elements. It is the absence of the heavier elements, and the dust which is present in present day interstellar matter, which makes massive star formation possible. The IMBH could also form in the early Universe through the collapse of gas clouds which have low rotation, which form a quasi-star. Such an object has a black hole at the centre and energy is released by matter falling on it, rather than through the fusion of lighter elements to heavier elements, happens in a normal star. The process is expected to produce IMBH.

IMBH can form in massive clusters of star and globular clusters. The latter have about 10^5 stars, with a high density of stars in their central region. The stars in these clusters are in incessant motion, and can randomly encounter other stars and merge with them, in a runaway process so that a very massive star is built up. An IMBH can form from the evolution of such massive stars. In the dense environment of a cluster centre, it is also possible for there to be encounters between black holes formed through stellar evolution. In a close encounter two black holes can form a binary system which can eventually merge together to form a larger black hole. IMBH are also associated with ultraluminous X-ray sources and with dwarf galaxies, where they become low luminosity active galactic nuclei. In spite of all these possibilities, as of early 2026 there has not been an unambiguous detection of an IMBH. We will see below examples such processes which have been spotted by gravitational wave detectors. In fact, some examples of binary mergers detected through their gravitational waves could be the first reliable gravitational wave detections.

The Third Observing Run O3

The observing run O3 began on April 1, 2019 and ended on March 27, 2020, when it was cut short due the Covid-19 pandemic. It had a break of a month in October 2019 for commissioning instruments, which divided O3 into O3a and O3b. During O3a a total of 44 binary merger events were detected and, during O3b another 35 detections were made. That took the total number of merging events detected by the end of the O3 to 90, including three events detected in O1 and eight in O2. Most of the O3 binaries have black holes as the two components (BH-BH). There are three detections with a black hole as one component, with the other component very likely to be a neutron star (BH-NS), and one detection with two neutron stars (NS-NS). The BH-NS and NS-NS mergers were not detected at any electromagnetic wavelength unlike the neutron star binary GW170817 from O2, which was widely observed over the electromagnetic spectrum. We will now describe some of the interesting sources from O2.

GW190412: This merger was detected on April 12, 2019, during the second week of the observing run O3a, by the two Advanced LIGO detectors and the

Advanced Virgo detector. It is estimated that the chance that such a source would appear to be detected due to a fluctuation in the noise ranges from < 1 per 10^5 years to < 1 per 10^3 years, depending on the method of analysis, so the event is statistically highly significant.

The primary component of the binary was of 30.1 Solar masses, while the less massive secondary component m^2 was of 8.3 Solar masses. These masses are within the range of component masses inferred from observing runs O1 and O2, but the ratio of the masses $\frac{m^2}{m_1}$ = 0.28 is much smaller than the ratios close to one found for the binaries detected in the two runs. The small mass ratio has implications for the possible formation mechanisms for the binary. The final mass of the remnant black hole after the merger after the merger is 37.3 Solar masses and the dimensionless spin parameter of the black hole remnant is 0.67 (the spin parameter for a rotating black hole is $a^* = cJ/GM^2$, where J is the spin angular momentum of the black hole, M its mass and G the constant of gravitation. The maximum permitted value of $a^* = 1$, see (BHS 9). The more massive black hole had dimensionless spin parameter 0.44. The distance to the merger is 740 Megaparsec. The values of the parameters depend somewhat on the exact method of analysis used.

The small mass ratio of the binary has an interesting implication. To understand that, let us first consider the electromagnetic radiation emitted by a change in circular motion in a magnetic field. The radiation emitted by such a charge can be considered to be made up of components known as multipoles. The lowest order of multipole present is known as dipole radiation. This is the dominant component when the charge moves non- relativistically, i.e. with speed much lesser than the speed of light. The frequency of the dipole radiation is equal to the frequency of rotation of the charge in its circular motion. As the speed of the charge increases, other multipole components known as quadrupole, octupole and so on make increasing contributions. The frequency of the radiation emitted in these components are higher harmonics of the frequency of the dipole component, i.e. integral multiples of the dipole frequency. The frequency of the dipole component is known as the first harmonic. There is no monopole electromagnetic radiation because of the conservation of electric charge.

Gravitational radiation also can be considered to made up of multipoles. In this case there is no monopole radiation, and also no dipole radiation, due to the conservation of momentum. The lowest order gravitational radiation is quadrupolar in nature. For a binary with equal mass components in circular motion the quadrupolar radiation is by far the dominant one. The dominant frequency of the radiation is twice the orbital frequency with which the two component black holes go round each other. However, when the mass ratio becomes significantly less than one, as in the case of GW190412, the higher multipoles become increasingly important. The multipole content also depends on the inclination of the orbital plane and the line of sight from the observer to the binary system. The higher multipoles have to be taken into account in the analysis leading to various parameters of the binary. It is found that the multipoles make a discernible difference to the values of the parameters determined from the data.

GW190425: This event was detected on April 25, 2019 by just the LIGO detector at Livingston, Louisiana, since the other LIGO detector at Hanford, Washington State was temporarily offline. The Virgo detector did not contribute to the detection itself, since the source was too weak to be observed by it, but the data gathered could be used in the subsequent analysis.

The mass of the more massive primary component was found to be in the range of 1.61-2.52 Solar masses with 90 percent confidence, while the mass of the less massive secondary was in the range 1.12-1.68 Solar masses. The total mass was independently determined to be in the range 3.3-3.7 Solar masses. The distance to the source is 159 Megaparsec.

The known masses of neutron stars in observed X-ray binary and binary neutron star systems are in the range 1.2 – 2.5 Solar masses. The lower estimated mass for the primary and secondary of GW190425 are consistent with this range, while the upper end of the primary mass could be somewhat greater than the maximum neutron star mass observed so far. But the theoretical maximum for a neutron star mass is about three Solar masses and it is therefore reasonable to assume that both components are neutron stars. The total mass of GW170817 before the merger was in the range of 3.3-3.7 Solar masses. As of early 2026, there are 17 known neutron star binary systems discovered through electromagnetic observations. The maximum total mass of these systems is 2.89 Solar masses. So if GW190425 is indeed a binary neutron star, then its total mass is in excess of the total neutron star binary mass observed so far, and some novel mechanism may be needed for its formation.

GW190425 is the second neutron star binary merger observed. But unlike in the case of the first binary neutron star merger GW170817, which we described in detail in BHS-23, no electromagnetic emission has been observed to be associated with GW190425. There are two reasons why the electromagnetic emission may have been missed: GW190425 is at the larger distance of 159 Megaparsec compared to the distance of 40 Megaparsec of GW170817. Moreover, since GW190425 was observed by a single detector, it could be localised only within the much large area of 8284 square degrees of the sky, compared to the 28 square degree localisation of GW170817. That makes it very difficult to try to find an electromagnetic counterpart of the merger.

If the two components are neutron stars, the tidal effect of each component on the other would distort its shape. Since black holes are point particles, they are not subject to such distortions. In the case of the neutron star binary merger GW170817, tidal distortions have been detected from the change that they make to the gravitational wave signal. Tidal distortions have not been confirmed in GW190425, so either one or both components could be black holes. But that leads to another interesting situation. The most massive neutron star known has a mass of about 2.5 Solar masses, while the least massive black hole known has a mass of about 5 Solar masses. So there is a mass gap in the 2.5 - 5 Solar mass range. It is not known whether this gap is real and if it is, what would be the astrophysical reason for the gap. If GW190425 is a black hole binary, then the black holes would significantly below the currently known minimum black hole mass. If the primary is a neutron star, it could be in the mass gap region. So we see that GW190425 will require new astrophysical ideas, regardless of the nature of the components.

GW190521: This detection was made on May 21, 2019 by the two LIGO detectors and the Virgo detector. The gravitational wave signal lasted for a short duration of about 0.1 s. The false alarm rate, which is the rate at which such a signal would arise because of a fluctuation in background is less than 1 in 4990 yr. The source is of special interest because of the high masses of the components: the primary was of 85 Solar masses and the secondary 66 Solar masses. The total of 150 Solar masses was the largest mass detected until then. It will be noticed here that the total mass as quoted is different from the sum of the primary and secondary masses. The reason is that the quoted values for each of the three masses, primary, secondary and total, are median values for the statistical distribution of each of the masses obtained from detailed analysis of the gravitational wave data. Therefore the total mass does not turn out to be simply be the addition of the other two masses. Similar considerations apply to all the masses quoted for this source, as well as for the other gravitational wave sources described here.

The mass of the remnant black hole from the merger was found to be 142 Solar masses, and 7.6 Solar masses were lost from the system to gravitational radiation generated during the merger. The high value of the lost mass makes this source the most energetic merger detected until early 2026. The gravitational radiation is mainly emitted over a short period of time of about 0.1 second, and the peak luminosity, which is the maximum rate of energy emission, was $3.7x10^{56}$ erg/s. This luminosity is much large than the luminosity of a supernova at its peak, which is about 10^{44} erg/s, and the luminosity of the brightest known quasar which is about 10^{48} erg/s, and the highest observed luminosity of a Gamma-ray burst of about 10^{54} erg/s. While the peak luminosity of the merger is far higher than that of the other highly luminous source, the burst emission is of gravitational radiation, which can only be detected by gravitational wave detectors, unlike the other sources which emit at electromagnetic wavelengths. The distance to the merger is 5.3 Gigaparsec. The remnant black hole has a dimensionless spin parameter of 0.72.

The mass of the primary is in the mass gap region of 65 – 135 Solar masses, which exists due to the pair instability process which occurs during the course of evolution of a massive star, which we discussed above. The mass of the remnant puts it in the range 100 – 10^5 Solar masses of intermediate mass black holes, also discussed above, which makes it the first black hole with such a measured mass. But the short duration of this event, and the small number of cycles which have been observed, lead to the possibility that this was not a merger of a black hole binary in a nearly circular orbit, as has been assumed. We will discuss such a possibility further when we come to the source GW231123 from the observing run O4.

The gravitational wave research group from the Indian Institute of Technology was involved in a study to assess the detection significance of GW190521 along with the colleagues of LIGO-Virgo scientists. In addition, the group contributed to assessing the distance reach of various searches in the intermediate mass black hole parameter space. The research group at the Indian Institute of Technology, Gandhinagar was involved in developing the filter bank used for the detection of the black holes in the third observing run, along with other LIGO-Virgo scientists.

GW190814: This merger was first detected on August 14, 2019 by LIGO detector in Livingston, and by the Virgo detector. The later analysis also used data from the LIGO detector at Hanford. The data covered 300 cycles of the binary rotation above a gravitational wave frequency of 20 Hz, so it is possible to tightly constrain the source properties. The mass of the primary component of the binary was 23.3 Solar masses, while the secondary component was of 2.59 Solar masses, and the final mass of the black hole after the merger is 25.6 Solar masses. The. The component masses in this case are even more unequal than in the case of GW190425 with the component mass ratio $\frac{m^2}{m_1}$ = 0.11. As mentioned in that case, the small mass ratio means that the higher order multipoles of the gravitational wave emission should be present in the data. There is strong evidence that such is the case with GW190814 data, which leads to more precise measurements of the system parameters.

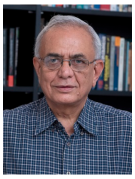
We mentioned in the description of GW190425 that there is a gap in the region 2.5 – 5.0 Solar masses in the known mass of neutron stars and black holes, with neutron stars being below the gap and black holes above it. In of GW190814, the mass of the secondary is in the gap region, so it could be either a unusually massive neutron star or a black hole with unusually low mass. So while the massive primary can be identified as a black hole, the nature of the secondary remains in doubt. There has been no identified electromagnetic counterpart of the merger, and other signs like a tidal deformation of the secondary, which should be present if it were a neutron star, have not been. It is also possible that the secondary mass exceeds the maximum mass permitted for a neutron star. So it seems likely that the observed merger was of two black holes, rather than a black hole and a neutron star. In that case, the low mass ratio of the two black holes poses challenges to black hole binary formation mechanisms.

textbfGW200105 and GW200115: These two sources of gravitational waves are BH-NS binaries and are similar in nature, so we describe them together. GW200105 was observed by LIGO Livingston and Virgo on January 5, 2001. It has components with mass 8.9 and 1.9 Solar masses respectively and the mass ratio $\frac{m^2}{m_1}$ = 0.22. The distance to the source is 280 Megaparsec. From the data, and various astrophysical assumptions, it can be estimated that the probability for the secondary mass to be below the maximum mass of a neutron star is in the range 89% - 96%. It is therefore likely that GW200105 is a BH-NS binary merger.

textbfGW20015 was observed by both LIGO detectors and the Virgo detector on January 15, 2021. The component masses in this case are 5.7 and 1.5 Solar masses respectively, with mass ratio $\frac{m^2}{m_1}$ = 0.26. The distance to the source is 300 Megaparsec. The probability that the secondary mass is below the maximum neutron star limit is in the range 87% - 98% , so this source too is likely to be a BH-NS binary merger.

In the next story we will consider a few novel black hole binaries detected in observing run O4, which will provide us with further insight into the physics of black holes and black hole binaries.

About the Author



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X-ray Astronomy: Theory

by Aromal P

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3.1 Introduction

In the previous article, we discussed X-ray emission from accretion disks in X-ray binaries and compared its efficiency to that of nuclear fusion. We concluded by asking whether the accretion disk is the only source of X-ray emission in X-ray binaries. In today's article, we will focus on a specific type of X-ray emission found in Neutron Star Low-Mass X-ray Binaries: the thermonuclear X-ray burst. As a personal note, my research centers on the observational studies related to this phenomenon.

3.2 Thermonuclear X-ray burst

We have already discussed how accretion disks form in X-ray binaries. In neutron star X-ray binaries, if the neutron star is relatively old and has a weaker magnetic field, the accreted material will eventually be deposited onto its surface. If this accumulated matter undergoes an unstable nuclear reaction, it can burn instantaneously due to nuclear processes, leading to a thermal runaway.

This thermal runaway happens because the accreted hydrogen and helium fuel experiences intense hydrostatic compression as it continues to pile onto the surface of the neutron star. Within hours or days, the accumulating material reaches extreme ignition temperatures and densities. The core physical mechanism driving this violent eruption is known as the thin-shell instability.

Since the burning layer is exceptionally thin, only a few meters deep compared to the neutron star's typical radius of around 10 kilometers, the initial nuclear heating causes the shell to expand, but this is insufficient to reduce the local pressure and cool the region. Additionally, in this dense environment, the electrons are mildly degenerate, meaning their pressure does not significantly depend on temperature. This further prevents the expanding gas from effectively dissipating the heat generated. As a result, the temperature spikes dramatically, accelerating nuclear reaction rates and triggering a localized thermonuclear runaway.

The specific dynamics of this thermonuclear runaway depend heavily on the mass accretion rate and the chemical composition of the infalling material. At relatively low accretion rates, hydrogen burns unstably via the Carbon-Nitrogen-Oxygen (CNO) cycle, which can subsequently trigger helium ignition. At intermediate mass accretion rates, hydrogen burns continuously and stably via the hot CNO cycle, completely exhausting itself and gradually building up a dense, pure helium layer beneath it. Once critical conditions are met, this pure helium layer violently detonates via the triple-alpha process, producing a short, intense X-ray burst that typically lasts around ten seconds. At even higher accretion rates, the conditions for helium ignition are met much faster, before the hydrogen has fully burned, resulting in a mixed hydrogen and helium flash. The initial helium ignition generates extreme temperatures that trigger breakout reactions, bypassing the standard CNO cycle and initiating the rapid-proton (rp) process. During the rp-process, a rapid succession of proton captures and slower beta decays synthesizes heavier elements, significantly extending the energy release and creating

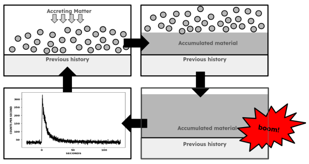

Figure 1: Graphical representation of occurrence of thermonuclear X-ray Burst

a burst tail that lasts for tens to hundreds of seconds.

The ignition itself is highly complex; rather than erupting uniformly across the entire sphere, the runaway typically sparks at a localized point, often near the equator, where the effective surface gravity is slightly reduced by the star's rapid rotation. From this ignition point, a thermonuclear flame front propagates laterally across the neutron star, engulfing the entire surface in approximately one second. In the most powerful of these events, the extreme local luminosity can temporarily exceed the Eddington limit, causing the outward radiation pressure to overcome the immense inward gravitational pull. When this threshold is breached, the outermost layers of the neutron star's photosphere are physically lifted off the surface and driven outward, creating a Photospheric Radius Expansion (PRE) burst. As the thermonuclear fuel is exhausted, the lifted photosphere eventually contracts and settles back onto the stellar surface before an extended cooling phase takes over. Ultimately, while continuous accretion generates a steady baseline X-ray luminosity, the sudden, localized burning of stored fuel temporarily outshines this persistent emission by a factor of ten or more, producing thermonuclear X-ray bursts

Thermonuclear X-ray emission is predominantly thermal and is well-described by a blackbody spectrum with peak temperatures reaching 2–3 keV. Consequently, bursts are most prominent in the soft X-ray energy band (typically below 10 keV), where they temporarily outshine the persistent X-ray emission from accretion by an order of magnitude or more

The intense photons from a thermonuclear X-ray burst drastically alter the surrounding accretion environment, primarily affecting the corona, the accretion disk, and the companion star. When the burst injects a massive influx of soft X-ray photons into the hot electron corona, it triggers inverse Compton scattering that rapidly cools the coronal plasma. This cooling manifests observationally as a sharp deficit in hard X-ray emission during the burst peak. In extreme cases, the burst's immense radiation pressure may completely blow the corona away, which could temporarily shut off the collimated radio jets that are linked to coronal magnetic fields. The burst also strongly impacts the physical structure of the accretion disk. Irradiation can heat the disk, causing it to puff up and increase its scale height, while the intense photon flux can induce Poynting-Robertson radiation drag, forcing the inner disk material to drain onto the neutron star. Furthermore, burst photons scattering off the inner accretion disk generate observable reflection features, such as fluorescent iron emission lines and absorption edges. Finally, photons that reach the cooler outer accretion disk and the donor star are reprocessed, producing transient optical and ultraviolet flashes.

Studying thermonuclear X-ray bursts provides a unique astrophysical laboratory to probe matter and physical processes under extreme conditions that cannot be replicated on Earth. One of the primary motivations for studying these powerful explosions is to constrain the Equation of State (EoS) of the supranuclear dense matter inside neutron star cores. By using methods like Photospheric Radius Expansion (PRE) bursts and continuum spectrum modeling, researchers can accurately measure a neutron star's mass and radius, thereby ruling out specific theoretical models of exotic matter. Thermonuclear Burst allows astronomers to dynamically probe the accretion process by observing how burst photons interact with the accretion disk and the hot electron corona. Finally, they provide a testing ground for complex nuclear physics, such as the rapid-proton (rp) process, and multidimensional hydrodynamics like flame spreading.

We will discuss more methods of producing X-rays in the upcoming articles.

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About the Author

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Part III

Biosciences

The Genetic Whisper: Unlocking Biodiversity with eDNA

by Geetha Paul

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Figure 1: An illustration of the core elements of a Biodiversity research: the endemic Odonata of the Western Ghats (specifically Vestalis apicalis) flying near a water surface, integrated with a glowing DNA double helix structure that transitions from blue to green. The image is set against a lush, biodiverse wetland, symbolising the intersection of traditional zoology and modern eDNA technology.

1.1 Introduction

Environmental DNA (eDNA) is a powerful biomonitoring method that allows scientists to detect the presence of organisms, from bacteria to blue whales, by analysing the genetic material they leave behind in their environment.

For centuries, the study of biodiversity required the physical presence of the observer and the observed. To confirm a species lived in a habitat, a scientist had to see it, catch it, or find its remains. In the dense, monsoon-swept wetlands or the intricate canal networks of the Western Ghats, this traditional approach often hits a wall. Many species are elusive, nocturnal, or exist only as microscopic larvae/nymph hidden in the silt. Enter Environmental DNA (eDNA), a revolutionary molecular tool that has turned the natural world into a giant, living library of genetic information.

eDNA refers to the genetic material shed by organisms into their surrounding environment, water, soil, or even air, via skin cells, faeces, mucus, or decaying tissue. This genetic soup allows researchers to detect entire communities without ever seeing a single animal. It is the forensic science of ecology, where a single litre of river water can reveal the presence of everything from endangered dragonflies to migratory fish. For a professional scientist, eDNA represents a shift from searching for life to filtering for it. It bypasses the limitations of human observation, providing a high-resolution map of life that is non-invasive and incredibly sensitive. As we face a global biodiversity crisis, eDNA has emerged as the early warning system of the 21st century, offering a way to monitor ecosystem health in real-time and at a scale previously thought impossible. It is the bridge between traditional zoology and high-throughput genomic science, ensuring that even the most cryptic inhabitants of our planet are no longer invisible to conservation efforts.

1.2 What is eDNA?

At its core, eDNA is extra-organismal DNA. Unlike traditional sampling, which requires a tissue biopsy from a captured specimen, eDNA is collected from the medium in which the organism lives. In freshwater systems, this DNA remains suspended in the water column for roughly 7 to 21 days before degrading. By targeting specific barcode genes, most commonly the Cytochrome c oxidase I (COI) gene, scientists can identify a species' genetic fingerprint from a simple water sample.

1.3 The Role of eDNA in the Modern World

In an era defined by rapid climate change and habitat loss, eDNA enables biosecurity and industrial-scale monitoring. Its primary roles include,

Detecting Invasive Species: Identifying harmful pests (like the Apple Snail) before they become established and cause economic damage. Invasive species typically follow an invasion curve. Traditional monitoring (visual sightings) usually only detects a species once it has already reached the **Exponential Growth** phase, at which point eradication is nearly impossible. eDNA, however, can detect the Genetic Whisper of a single organism during the **Lag Phase** allowing for immediate, low-cost intervention.

Tracking Rare Species: Confirming the survival of Lazarus species or endemics in remote, inaccessible areas of the Western Ghats. The ability to detect Lazarus species, those thought to be extinct but rediscovered and rare endemics, is perhaps the most magical application of eDNA. In the rugged, high-altitude streams of the Western Ghats, traditional sampling is often dangerous or physically impossible. eDNA allows us to survey a mountain peak by simply sampling the stream at its base.

Ecosystem Health Assessment: Providing a Biotic Index that reflects the total health of a watershed based on the presence of sensitive indicator species like Odonates. By utilising Odonates as biological sensors, the e-Biotic Index transforms molecular data into a high-resolution map of watershed health. This framework assigns sensitivity scores to Odonata families detected via eDNA; for instance, the presence of intolerant families, such as Gomphidae or Chlorocyphidae, indicates a pristine, oxygen-rich environment, while a dominance of tolerant species, such as Brachythemis contaminata, signals a degraded or polluted ecosystem. By calculating a **Multi-Metric Index (MMI)** from these genetic reads, researchers can objectively categorise water bodies into conservation or restoration zones, identifying early-stage ecological shifts long before physical changes become visible to the naked eye.

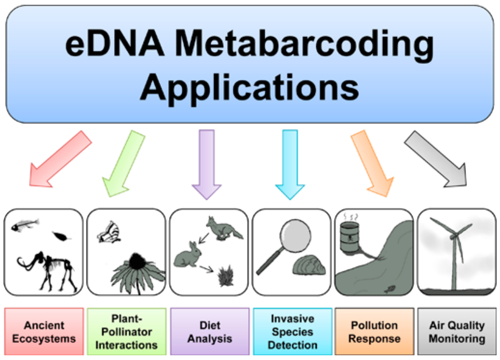


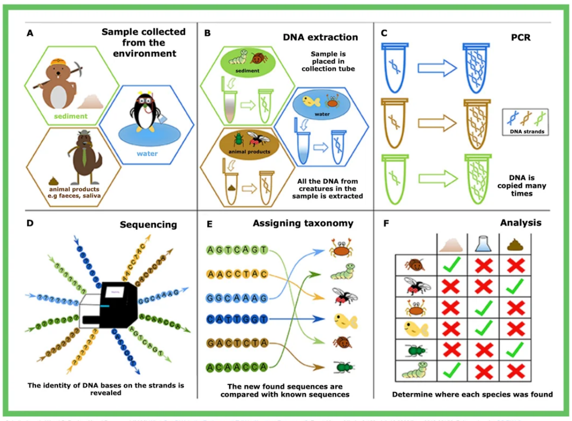
Figure 2: This infographic illustrates the Genetic Soup concept of environmental DNA (eDNA) within an aquatic ecosystem. It serves as a visual model of how biological information moves from an organism into the surrounding medium, a foundational principle for modern molecular monitoring.

Image courtesy: https://c02.purpledshub.com/uploads/sites/62/2023/02/what-is-eDNA-0f1b49d.png?w=1200&webp=1

1.4 Applications in New Era Science

1.5 The eDNA Metabarcoding Model

Modern science is moving toward Metabarcoding, the ability to simultaneously sequence thousands of species from a single sample. Metabarcoding is a high-throughput molecular technique that enables the identification of entire biological communities from a single environmental sample. While traditional DNA barcoding focuses on a single individual at a time, metabarcoding uses Next-Generation Sequencing (NGS) to read thousands of distinct DNA tags simultaneously. Advances in technology have made this process potentially faster, less expensive and more thorough than traditional identification methods. The workflow follows a rigorous pipeline that moves from the riverbank to the bioinformatic cloud:



Schallenberg L, Wood S, Pochon X and Pearman J (2020) What Can DNA in the Environment Tell Us About an Ecosystem?. Front. Young Minds. 8:150. doi: 10.3389/frym.2019.00150. Released under CC BY4.0

Figure 3: This diagram shows the steps in the eDNA process, including sample collection from the environment, DNA extraction, PCR amplification, Sequencing, Sequence comparison with known sequences, and species assignment.

Image courtesy: https://www.integratesustainability.com.au/wp-content/uploads/2019/11/Ruppert-eDNA-Metabarcoding.png

1.5.1 Field Collection & Filtration:

Water is collected and passed through fine filters (typically 0.45µm or 0.22µm) to trap cellular debris, scales, and metabolic waste.

1.5.2 DNA Extraction:

In the lab, the trapped cells are lysed (broken open), and total genomic DNA is purified. This sample is a genetic soup containing DNA from fish, insects, bacteria, and even humans.

1.5.3 Library Preparation (Universal PCR):

Unlike your previous work with species-specific primers, metabarcoding uses Universal Primers. These target a highly conserved region (e.g., a specific segment of the COI or 12S rRNA gene) that is present in all target organisms but contains sufficient internal variation to distinguish species.

1.5.4 Multiplexing & Sequencing:

Unique molecular indices (barcodes for the barcodes) are added to each sample so multiple sites can be sequenced in one run on platforms like **Illumina MiSeq** or **NextSeq**.

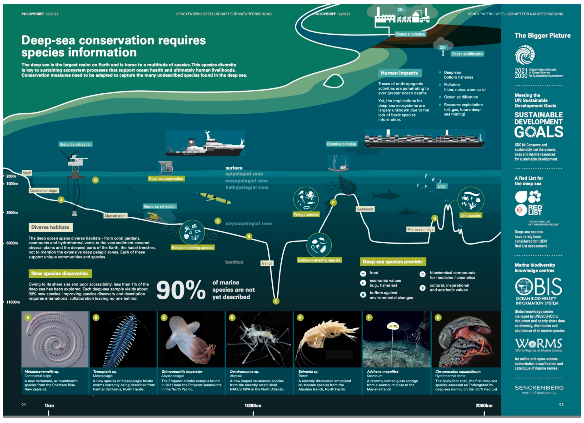


Figure 4: Without knowledge of deep-sea species, effective conservation is impossible, leading international marine scientists warn in a new policy brief presented at the UN Biodiversity Conference (COP15) in Montreal.

Credit: Senckenberg Research Institute and Natural History Museum. https://www.infohackit.com/wp-content/uploads/2023/02/Senckenberg-Infographic.png

1.5.5 Bioinformatics Pipeline:

The raw sequence data (millions of reads) is filtered, denoised, and compared against global databases like **BOLD** or **GenBank**. The output is a comprehensive **Taxon List** of every species present in that litre of water.

1.6 Deep-Sea Exploration:

Mapping life in the midnight zone where submersibles cannot easily reach. In the midnight zone or bathypelagic layer (1,000 to 4,000 meters deep), the immense pressure and absolute darkness make traditional visual surveys with Remotely Operated Vehicles (ROVs) incredibly expensive and technically limited. eDNA serves as a genetic telescope in these depths, allowing scientists to identify giant squid, rare bioluminescent fish, and entire microbial communities by simply sampling the surrounding seawater. Since DNA can persist in the cold, high-pressure environment of the deep sea, a single water sample can provide a snapshot of the hidden biodiversity that submersibles often miss because their lights and noise scare away sensitive deep-sea creatures.

Figure 5: Illustration of Environmental DNA collected from open environments to identify terrestrial vertebrates, as this genetic material remains detectable in the air several hundred meters from its biological source.

Image courtesy: https://tse2.mm.bing.net/th/id/OIP.8lrNxI4M_5EmgcDYG_NlFQHaEK?rs=1&pid=ImgDetMain&o=7&rm=3

1.7 Airborne eDNA:

Sucking air through filters to detect birds and mammals in tropical rainforest canopies. Airborne eDNA (airDNA) represents the latest frontier in terrestrial biomonitoring, particularly in dense, multi-layered environments like the tropical rainforests of the Western Ghats. In these habitats, traditional visual surveys are often obstructed by thick canopy cover, and many mammals and birds are highly elusive or canopy-dwelling. By using high-volume air samplers or specialised vacuum filters, researchers can capture microscopic fragments of DNA, carried in skin cells, fur, feathers, or dried saliva, that have become aerosolised. This technique effectively turns the air into a biological record, allowing for the simultaneous detection of entire terrestrial communities from a single stationary point.

1.8 Ancient DNA:

Extracting eDNA from permafrost or cave sediments to reconstruct ecosystems from thousands of years ago. Extracting ancient environmental DNA **aDNA** from permafrost or cave sediments allows scientists to perform biological time travel. Unlike modern eDNA, which reflects current populations, ancient eDNA is preserved for millennia by the cold, stable conditions of ice or deep soil. By sequencing these microscopic fragments, researchers can reconstruct entire extinct ecosystems, identifying the plants, megafauna (like mammoths), and even the microbial communities that existed long before human records. This sedimentary ancient DNA **sedaDNA** provides a high-resolution chronicle of how life on Earth responded to past climate shifts, offering vital clues for predicting how current biodiversity might survive modern global warming.

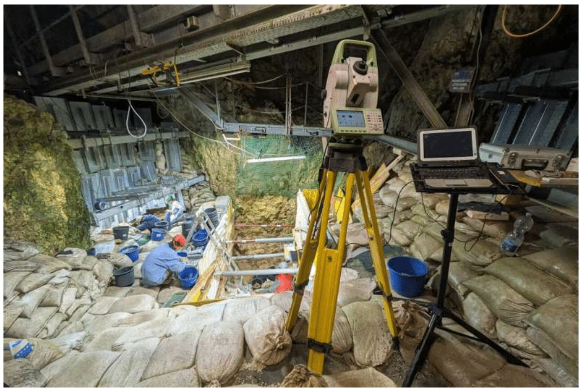


Figure 6: A recent breakthrough, highlighted bythe Conversation, reveals how analysing DNA from cave sediments could unveil long-hidden secrets about life during the Ice Age. This exciting research may reshape our understanding of the ecosystems that existed thousands of years ago and provide insight into the species, including humans, who once inhabited these regions.

Image courtesy: https://indiandefencereview.com/wp-content/uploads/2025/12/image-15.png

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About the Author

Geetha Paul is one of the directors of airis4D. She leads the Biosciences Division. Her research interests extends from Cell & Molecular Biology to Environmental Sciences, Odonatology, and Aquatic Biology.

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.