ISSN: 2634 - 8845

Journal of Earth and Environmental Science Research

Research Article | Open Access

Fullerene Formation in the Planetary Nebula Tc1: Constraints from JWST Mid-Infrared Imaging

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ABSTRACT

We analyse mid-infrared imaging observations of the planetary nebula Tc 1 obtained with the Mid-Infrared Instrument (MIRI) aboard the James Webb Space Telescope, with the aim of constraining the spatial distribution and formation conditions of fullerene molecules (C60). The data reveal a non-spherical nebular morphology characterized by concentric shells, filamentary structures, and a pronounced asymmetric feature. The emission attributed to C60 is not uniformly distributed, but is instead confined to localized regions within the nebula. Using the wavelength dependence of the observed emission, we estimate that the fullerene-rich regions correspond to intermediate dust temperatures in the range T ~ 200–350 K. This suggests that fullerene for-mation requires a restricted thermal environment, with sufficient energy to restructure carbonaceous material while avoiding destruction of the closed cage structure.

The spatial confinement of the emission further indicates that local physical conditions, including radiation field intensity and shock-driven processing, play a dominant role. We interpret these results within a curvature-driven framework in which fullerenes form through the transformation of quasi-planar carbon networks.

The introduction of pentagonal defects into a hexagonal lattice induces positive curvature, leading to the formation of stable closed cages. The JWST observations of Tc 1 are consistent with this mechanism, linking the molecular structure of C60 to the dynamical and thermal properties of the nebula. These findings provide observational con-straints on fullerene formation in evolved stellar environments and highlight the role of localized processes in governing complex carbon chemistry.

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Received: August 21, 2026; **Accepted:** August 25, 2026; **Published:** August 31, 2026

Keywords: planetary nebulae, individual, Tc1, ISM, molecules, infrared, ISM, astrochemistry, fullerenes

Introduction

Carbon-rich molecules play a fundamental role in the chemical evolution of the interstellar medium (ISM) and in the late stages of stellar evolution. Among these, fullerenes—closed-cage carbon structures exemplified by C60 and C70—have attracted significant attention due to their remarkable stability and potential as tracers of physical conditions in circumstellar environments. The first unambiguous detection of C60 in an astrophysical setting was reported in the planetary nebula Tc 1 by, establishing that complex carbon molecules can form in the circumstellar environments of evolved stars [1].

Planetary nebulae represent a brief but chemically rich phase in stellar evolution, during which low- to intermediate-mass stars ex-pel their outer envelopes, enriching the ISM with gas and dust [2]. The physical conditions in these environments characterized by strong ul-Tra violet radiation fields, shocks driven by stellar winds, and evolving dust populations are conducive to complex chemical processing.

However, the formation pathways of fullerenes in such environments remain debated. Pro-posed mechanisms broadly fall into two categories: (i) top-down" processes, in which larger carbonaceous grains or polycyclic aromatic hydrocarbons (PAHs) are photochemically processed into smaller, stable cages, and (ii) bottom-up" formation, involving the assembly of carbon clusters in dense, shielded regions [3,4].

Discriminating between these scenarios requires spatially resolved observations capable of linking molecular emission to local physical conditions.

The planetary nebula Tc 1 is a particularly compelling laboratory for such studies. Located at a distance of approximately 10 kpc, Tc 1 exhibits strong infrared emission features attributed to C60 and C70, while showing relatively weak signatures of PAHs, suggesting an environment favorable for fullerene production [5].

Previous observations with the Spitzer Space Telescope provided the first spectroscopic evidence for fullerenes in Tc 1, but lacked the spatial resolution required to map their distribution within the nebula [6].

The advent of the James Webb Space Telescope has transformed our ability to probe the infrared universe.

In particular, the Mid-Infrared Instrument (MIRI) provides imaging and spectroscopy over the wavelength range ∼5–28 µm with unprecedented sensitivity and angular resolution [7].

These capabilities enable, for the first time, detailed spatial mappin of fullerene emission and its relationship to nebular morphology, temperature structure, and radiation field variations.

In this work, we present an analysis of new MIRI observations of Tc 1, focusing on the spatial distribution and morphological context of fullerene emission.

The data reveal a complex nebular structure, including filamentary shells and pronounced asymmetries, with fullerene emission concentrated in localized regions rather than being uniformly distributed.

These findings provide new constraints on the physical conditions required for fullerene for-mation and survival.

We aim to address the following key questions:
(i) how is fullerene emission spatially correlated with nebular structure and infrared continuum emission, (ii) what do these correlations imply about the dominant formation pathways of fullerenes, and (iii) how do dynamical processes such as shocks and stellar wind interactions influence carbon chemistry in evolved stellar environments.

By combining high-resolution imaging with a physically motivated interpretation, this study seeks to advance our understanding of com-plex molecule formation in planetary nebulae and their contribution to the chemical enrichment of the ISM.
Fullerenes as Topological Derivatives of Graphene.

The structure of C60 is illustrated in Fig:1 Immediately after the dis-covery of fullerenes in astrophysical environments, the discovery has renewed interest in their structural origin and formation pathways.

From a condensed matter perspective, fullerenes can be understood as topological derivatives of graphene, the fundamental two-dimensional honeycomb lattice of carbon.

As discussed in, graphene constitutes the basic structural build-Ing block of graphitic materials of all dimensionalities and may be regarded as the material prima for a wide class of carbon allotropes [8].

Within this framework, the transformation of a planar graphene sheet into closed or curved carbon structures can be achieved through the introduction of topological defects. In particular, the incorporation of pentagonal rings into the otherwise hexagonal lattice induces positive Gaussian curvature, enabling the formation of closed spherical structures such as fullere.

Fullerenes, also known as buckyballs, are closed cage carbon.

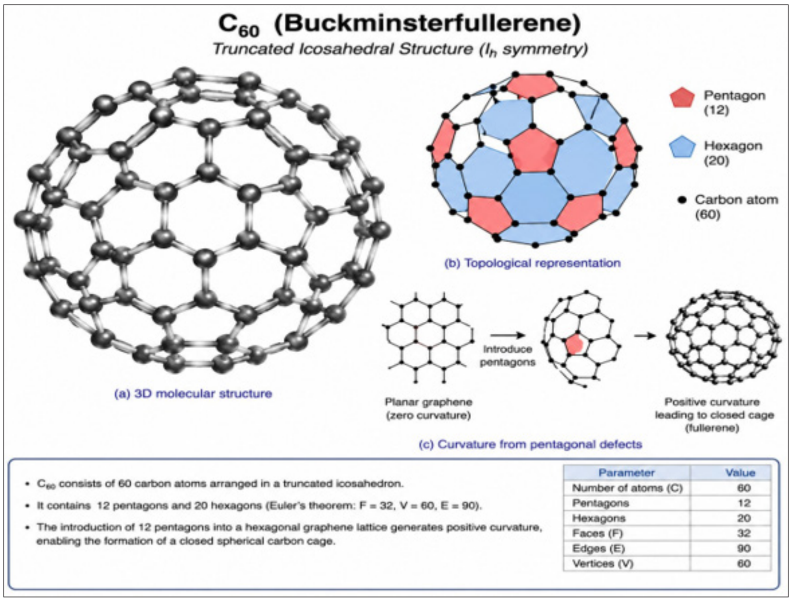

Figure 1: Molecular Structure of C60 (BUCKMINSTERFULLERENE), Consisting of 60 Carbon Atoms Arranged in a Truncated Icosahedral Geometry with 12 Pentagons and 20 Hexagons.

The Introduction of Pentagonal Rings into a Hexagonal Graphene Lattice Induces Positive Cur-Vature, Enabling the Transformation of a Planar Carbon Network into a Closed Spherical Cage [Credit: Author] Molecules Composed Entirely of sp2-Bonded Carbon Atoms Arranged in Pentagonal and Hexagonal Rings. The prototypical fullerene, C60, consists of 60 carbon atoms arranged in a truncated icosahedral geometry, comprising 12 pentagonal and 20 hexagonal plaquettes.

This geometric requirement arises from Euler's theorem for polyhedral networks and is essential for achieving a stable, closed-shell configuration. The same topological framework also explains the formation of one-dimensional carbon nanotubes (CNTs) through the rolling of graphene sheets, as well as the stacking of layers to form three-dimensional graphite.

Thus, graphene provides a unifying structural paradigm linking carbon allotropes across dimensionalities (0D, 1D, and 3D).
In an astrophysical context, this perspective suggests that fullerene formation in environments such as planetary nebulae may proceed via the restructuring of pre-existing carbonaceous materials, including graphene-like sheets or large polycyclic aromatic

hydrocarbons, under the influence of radiation fields, shocks, and thermal processing.
This topological viewpoint offers a physically motivated framework for in-terpreting the presence of fullerenes in the planetary nebula Tc 1, where the observed C60 emission may trace regions in which planar carbon networks un-dergo curvature-driven reconfiguration into energetically stable closed cages. Incorporating such condensed matter insights into astrophysical models may help bridge the gap between molecular-scale processes and large-scale nebular dynamics.

Observations and Data
The observational data analysed in this study were obtained using the Mid-Infrared Instrument (MIRI) aboard the James Webb Space Telescope [9].

MIRI provides imaging and spectroscopic capabilities over the wavelength range ∼5–28 μm, enabling high-sensitivity observations of dust and molecular emission in planetary nebulae (Rieke et al., 2015).

The target of this study, the planetary nebula Tc 1, is located at a distance of approximately 10 kpc and is known for its prominent fullerene emission features (Cami et al., 2010).

The dataset consists of multi-band mid-infrared imaging obtained using a combination of filters spanning wavelengths from5.6 to 25.5 μm. These bands are particularly well suited for tracing thermal dust emission as well as characteristic vibrational modes of fullerene molecules such as C60. The MIRI images were processed using standard JWST calibration pipelines, including detector-level corrections, background subtraction, and flux calibration (Rieke et al., 2015).

The final science-ready images were further refined using established image processing techniques to enhance structural detail and contrast across the nebula.

The resulting composite image reveals a complex morphology characterized by concentric shells, filamentary structures, and pronounced asymmetries in the spatial distribution of infrared emission.

In the processed images, shorter-wavelength channels (5.6–10 μm) predominantly trace hotter gas and dust components, while longer wavelengths (15–25.5 μm) are sensitive to cooler material.

This wavelength-dependent mapping enables a qualitative assessment of temperature gradients across the nebula.

Notably, the fullerene emission features, particularly those associated with C_{60}, fall within this spectral range and can therefore be spatially correlated with the observed infrared structures.

The spatial resolution of JWST/MIRI represents a significant improvement over previous infrared observatories, allowing for the first time a detailed examination of the distribution of fullerene-rich regions within Tc 1. These observations provide the foundation for the analysis presented in the subsequent sections.

Results
Global Morphology
The mid-infrared imaging of Tc 1 reveals a complex and highly structured nebular morphology. The emission is distributed in a series of concentric shells surrounding the central star, with significant deviations from spherical symmetry. The outer regions exhibit diffuse emission, while the inner regions display enhanced brightness and structural complexity. A prominent asymmetric feature, resembling an inverted question-mark morphology, is observed extending from the central region into the surrounding nebula. As shown in Fig:2 the nebula exhibits a complex morphology with significant asymmetry. The morphology shows clear wavelength dependence. Emission at shorter wavelengths (5.6–10 μm) is more centrally concentrated and traces relatively hotter components, whereas longer wavelengths (15–25.5 μm) high-light cooler, more extended structures. This spatial segregation indicates the presence of temperature gradients across the nebula.

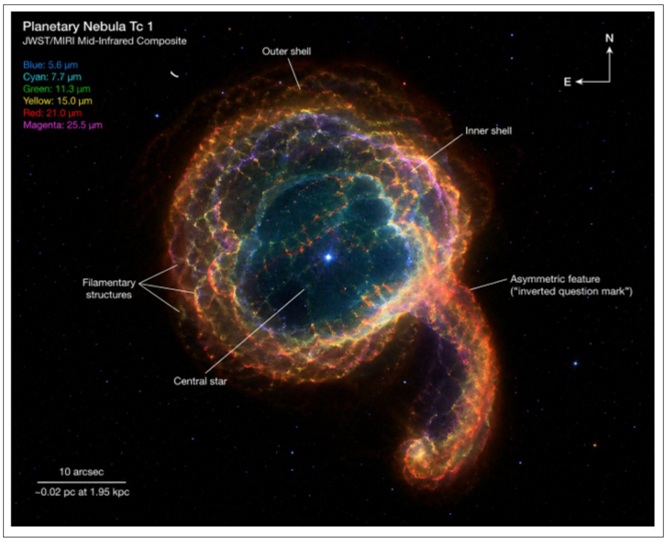

Figure 2: Mid-Infrared Composite Image of Tc 1 Obtained with the James Webb Space Telescope/MIRI. The Image Combines Multiple Wave Length Bands Spanning 5.6–25.5 μm and Reveals a Complex Nebular Morphology Characterized by Concentric Shells, Filamentary Structures, and a Pronounced a Symmetric Feature Resembling an Inverted Question Mark. Shorter Wavelengths Trace Hotter Components, While Longer Wave Lengths Highlight Cooler Material [Credit: NASA/ESA/CSA/J. Cami et al.]

Spatial Distribution of Fullerene Emission
The emission features attributed to C60 are detected within the MIRI wavelength range and exhibit a non-uniform spatial distribution across Tc 1. Rather than being evenly distributed throughout the nebula, the fullerene emission is concentrated in localized regions that coincide with zones of enhanced midinfrared brightness. These regions are predominantly associated with the inner shell structures and along the asymmetric feature identified in the morphology. The spatial confinement of fullerene emission suggests that the physical conditions required for the formation or survival of these molecules are restricted to specific environments within the nebula.

Temperature Structure and Infrared Colour Gradients
The multi-band imaging enables a qualitative assessment of the temperature structure of Tc 1. Regions emitting strongly at shorter wavelengths correspond to relatively higher temperatures, while those dominating at longer wavelengths indicate cooler material. The transition between these regimes is gradual, reflecting a continuous variation in thermal conditions rather than discrete zones. The fullerene-rich regions appear to be preferentially located in intermediate zones, where neither the hottest nor the

coolest components dominate. This spatial correlation suggests that fullerene emission is associated with a specific range of physical conditions within the nebula.

Structural Asymmetry and Filamentary Features

In addition to the global shell structure, the nebula exhibits filamentary features and localized enhancements in emission. The inverted question-mark structure is particularly notable, displaying a coherent morphology that extends across multiple wavelength bands. This feature appears to connect inner and outer regions of the nebula, potentially indicating a dynamical origin. Smaller-scale filaments and clumps are also evident, contributing to the overall inhomogeneity of the emission. These structures are more pronounced at longer wavelengths, suggesting an association with cooler dust components.

Summary of Observational Findings

The JWST/MIRI observations of Tc 1 reveal: (i) a non-spherical, multi-shell morphology with significant asymmetry, (ii) a non-uniform spatial distribution of fullerene emission concentrated in localized regions, (iii) a clear temperature gradient traced by wavelength-dependent emission, and (iv) the presence of filamentary and asymmetric structures, including a prominent inverted question-mark feature. These observational characteristics provide the basis for the physical interpretation discussed in the subsequent section.

Quantitative Constraints on Fullerene Formation

The spatial confinement of C60 emission to intermediate regions of the nebula (Section 3.2) suggests that fullerene formation occurs within a restricted thermal window. A simple estimate can be obtained by associating the MIRI bands with characteristic dust temperatures.

Assuming optically thin emission, the dust temperature **T** can be approximated from Wien's law, $\lambda_{peak}\,\mathbf{T} \simeq 2898\ \mu m\ K$. (1) Emission dominating the 5.6–10 **μ**m bands corresponds to **T** ~ 300–500 K, while emission in the 15–25.5 μm range traces cooler material with **T** ~ 120–200 K. The regions where fullerene emission is most prominent lie between these limits, suggesting a characteristic temperature range **T** ~ 200–350 K.

This estimate is consistent with laboratory and theoretical studies indicating that fullerene stability requires moderate temperatures: sufficiently high to enable restructuring of carbonaceous material, but not so high as to destroy the closed cage structure. The JWST data therefore support a scenario in which fullerene formation is favoured in intermediate-temperature zones within the nebula.

Discussion

Formation Pathways of Fullerenes in Tc 1

The non-uniform spatial distribution of C_{60} emission in Tc 1 indicates that fullerene formation is controlled by local physical conditions rather than by a uniform nebular process. The concentration of fullerene emission in selected regions suggests that radiation field intensity, dust processing, and gas density all play important roles in determining where stable carbon cages can form and survive. Two broad formation pathways may be considered. In the top-down scenario, large carbonaceous grains, graphene-like fragments, or polycyclic aromatic hydrocarbons are progressively processed by ultraviolet radiation and shocks, leading to the formation of closed carbon cages. In the bottom-up scenario, smaller carbon clusters assemble into stable fullerene structures in dense and partially shielded regions. The morphology revealed by JWST/MIRI appears more consistent with a localized top-down processing mechanism, although a contribution from bottom-up chemistry cannot be excluded. This interpretation is testable: spatially resolved spectroscopy targeting the 17.4 and 18.9 μm bands of C_{60} should show enhanced emission confined to the intermediate-temperature regions identified here.

Graphene Topology and Curvature-Driven Cage Formation

The curvature-driven transformation of graphene into fullerene structures is illustrated schematically in Fig:3 The structural connection between graphene and fullerenes provides a useful framework for interpreting fullerene formation in planetary nebulae. Graphene represents a two-dimensional honeycomb carbon lattice, while C_{60} can be formed by introducing twelve pentagonal defects into an otherwise hexagonal network. These pentagonal defects generate positive curvature, allowing the planar carbon sheet to close into a spherical cage. In this con-text, fullerene formation in Tc 1 may be interpreted as a curvature-driven reconfiguration of planar or quasi-planar carbonaceous material. Radiation and shock processing may fragment or restructure larger carbon networks, while topological defects promote closure into stable cage-like molecules. This interpretation naturally connects the molecular structure of C_{60} with the astrophysical environment in which it is observed.

Implications of the Asymmetric Morphology

The inverted question-mark structure observed in Tc 1 suggests that the nebula has experienced non-spherical mass loss or asymmetric dynamical shaping. Such structures may arise from anisotropic stellar winds, density inhomogeneities, magnetic fields, or interaction with previously ejected material. The association of fullerene-rich regions with asymmetric and filamentary structures suggests that molecule formation may be enhanced in zones where shocks and radiation-driven processing are strongest. This morphology therefore provides an important clue to the physical conditions under which complex carbon molecules form. Rather than being distributed uniformly throughout the nebula, fullerenes appear to trace specific dynamical and chemical environments.

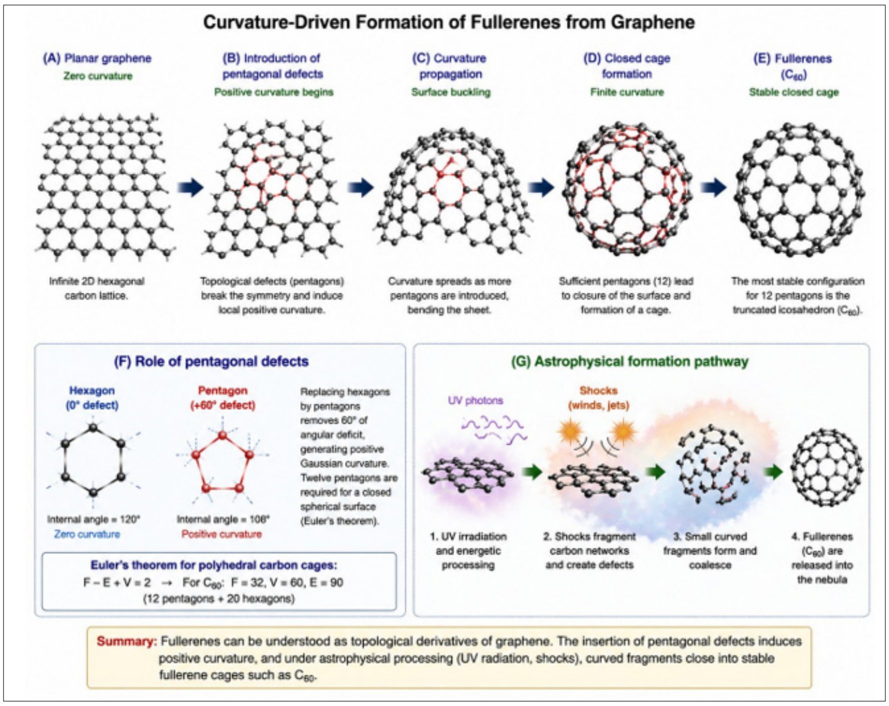

Figure 3: Schematic Illustration of Curvature-Driven Fullerene Formation from Graphene. Starting from a Planar Hexagonal Carbon Lattice, the Introduction of Pentagonal Defects Induces Positive Gaussian Curvature, Leading to Progressive Bending of the Sheet. The Accumulation of Curvature Ultimately Results in the Closure of the Structure into a Stable Fullerene Cage, Such as C60. In Astrophysical Environments, this Transformation May be Facilitated by Ultraviolet Irradiation and Shock-Driven Processing, Which Restructure Carbonaceous material and promote the formation of topological defects [Credit: Author]

Astrochemical Implications

The presence of C60 in Tc 1 demonstrates that planetary nebulae can con-tribute complex carbon molecules to the interstellar medium. Since fullerenes are chemically robust, they may survive beyond the planetary nebula phase and become incorporated into the diffuse ISM.

This has broader implications for the cosmic carbon cycle and for the inventory of stable carbonaceous molecules available in later phases of star and planet formation. The JWST/MIRI observations therefore provide a bridge between molecular-scale carbon chemistry and large-scale circumstellar evolution. Tc 1 serves as a laboratory in which the transformation of carbonaceous dust into stable molecular cages can be studied under astrophysical conditions.

Conclusions

We have presented a detailed analysis of mid-infrared observations of the planetary nebula Tc 1 obtained with the Mid-Infrared Instrument aboard the James Webb Space Telescope. These observations provide unprecedented spatial resolution of the distribution of fullerene emission within the nebula. The principal findings of this study may be summarized as follows. First, the nebula exhibits a complex, non-spherical morphology characterized by concentric shells, filamentary structures, and a pronounced asymmetric feature resembling an inverted question mark. Second, the emission attributed to C60 is not uniformly distributed, but is instead confined to localized regions that correlate with enhanced mid-infrared emission. Third, the multi-wavelength imaging reveals a clear temperature gradient across the nebula, with fullerene-rich regions preferentially associated with intermediate thermal conditions.

These results provide new constraints on the formation pathways of fullerenes in evolved stellar environments. The observed spatial confinement of fullerene emission supports a scenario in which their formation is governed by local physical processes, such as radiation-driven processing and shock inter actions, rather than by uniform nebular conditions. Within a structural frame-work, fullerene formation may be interpreted as a curvature-driven trans-formation of planar carbonaceous material into closed cage-like molecules, facilitated by the introduction of topological defects. The high-resolution capabilities of the James Webb Space Telescope open a new window for investigating complex carbon chemistry in planetary nebulae.

The case of Tc 1 demonstrates that fullerene formation is closely linked to nebular morphology and dynamical processes, providing important insights into the lifecycle of carbon in the interstellar medium.

Future work incorporating spatially resolved spectroscopy and detailed modelling will be essential to further constrain the physical conditions governing fullerene formation and to extend these results to a broader class of evolved stellar systems.

Acknowledgments

This research is financed by Kesariya Food Court, Kalam Bagh Chawk, Muzaffarpur, Bihar, India. This research is financed by Prashant Memorial Charitable Hospital, Muzaffarpur 842001, Bihar, India. This research is sponsored by the University Grants Commission (UGC), India, under the Emeritus Fellow Scheme (Grant No. EMERITUS/2012-13-GEN-855). Lastly, but not least, the author acknowledges the computing facilities availed from the computer system installed at Radha Krishna Monastery, Village Mahanth Maniari, 842119, District Muzaffarpur, Bihar, in preparing this paper.

Funding
This research is financed by Kesariya Food Court, Kalam Bagh Chawk, Muzaffarpur, Bihar, India. The research paper Article Processing Charges have been financed by Prashant Memorial Charitable Hospital, Muzaffarpur,842001, Bihar, India This research is sponsored by the University Grants Commission (UGC), India, under the Emeritus Fellow Scheme. Recipient: Dr. Bijay Kumar Sharma. Grant ID: EMERITUS/2012-13-GEN-855.

Declaration of Interests
The author declares no competing financial or non-financial interests.

Declaration of Generative AI and AI-Assisted Technologies
During the preparation of this work, the author used generative AI tools, including ChatGPT, DeepSeek, and Perplexity, for reasoning and drafting support. After using these services, the author reviewed, edited, and verified all content as needed and takes full responsibility for the accuracy and integrity of the publication

Ethics, Consent to Participate and Consent to Publish
Not applicable.

Author Contributions
The author collected data regarding the Length of Day (LOD) from popular science literature by Isaac Asimov, George Gamow, and Carl Sagan. Following the NASA press release on the Silver Jubilee Anniversary of the Moon landing (20 July 1994), reporting that the Moon has receded by approximately 1~m in the preceding 25 years, the author reanalyzed the Earth–Moon system and presented the results at the 82nd Session of the Indian Science Congress (Jadavpur University, Kolkata, 1995).

Subsequently, the author presented the Kinematic Model of the Earth–Moon system at the World Science Congress (Houston, 2002). In 2004, at the 35th Scientific Assembly of COSPAR, the author presented a new perspective on the birth and evolution of the Solar System and exoplanetary systems. In 2012, at the 39th Scientific Assembly (Mysore, India), the paper "Iapetus sub-satellite revisited and it reveals the celestial body formation in the Primary-Centric Framework" (B03-0011-12) was presented. In 2017, at CELMEC VII (Rome), the advanced Kinematic Model of the Earth–Moon system was presented and subsequently published in the Journal of Geography and Natural Disasters, demonstrating a close match between observed and theoretical LOD curves. Further related studies on the Earth–Moon system and its habitability were published in JMTCM.

Subsequent work extended the Primary-Centric Framework to stellar and exoplanetary systems, including stars near Sagittarius A*, the 51 Pegasi system, the WASP-12 system, and several other exoplanetary systems, which are currently under peer review. Another paper continues this research pro-gram by applying the framework to early stellar evolution and chemically primitive stellar systems. Another work studies a scenario where a multiplanetary system is just being born and is in infancy. A work deals with a long duration Gamma Ray Burst. This is under peer review. The next work un-der peer review deals with Saturn mass exo-planet orbiting a binary M-Dwarf System. Another work deals with super puffed exoplanets. Another work deals with a quadruplet star system. Another work provides key insights into non-standard planetary formation pathways. The present work looks at the environment in which exoplanets have buckey balls.

Data Availability
The data underlying this article are available within the article and in its online supplementary material. All figures in this paper were generated by the author using published observational data and empirical relations.

Clinical Trial Registration
Not applicable.

Declaration of Interests
The author declares no competing financial or non-financial interests.

Declaration of AI-Assisted Tools
During the preparation of this work, the author used OpenAI ChatGPT and DALL·E for conceptual visualization and figure generation. All scientific interpretation, analysis, and conclusions are solely those of the author.

Code Availability
The analysis code used in the study is available from the author on rea-sonable request.

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