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Exomoons and Exorings: Detection, Formation and Habitability under the Influence of Gamma-Ray Bursts

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

The study of exomoons and exorings represents a growing frontier in exoplanetary science, illuminating planetary formation, system evolution, and the search for habitable environments beyond Earth. Although no confirmed exomoons have yet been identified, advances in transit timing and duration variations, direct imaging, astrometry, radial velocity, and microlensing have improved detection sensitivity. This review consolidates advances in detection strategies, moon and ring formation theory, and astrophysical habitability contexts, emphasising the vulnerability and resilience of exomoons and exorings to GRB exposure. By linking detection feasibility to GRB-

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conditioned habitability priors, it presents a unified framework bridging planetary science, astrophysics, and astrobiology. Theoretical models predict diverse and stable moon systems with typical satellite-to-planet mass ratios of ∼ 10−4, many capable of sustaining habitable conditions through tidal heating, magnetic shielding, and subsurface oceans. Exorings, inferred from asymmetric transit light curves and forward-scattering signals, offer diagnostic insight into circumplanetary disk evolution and angular momentum processes. Their survivability, however, remains uncertain under the influence of stellar radiation, collisions, and magnetic drag. Gamma-ray bursts (GRBs), delivering fluences of ∼ 10–100 kJm^{-2}, can erode atmospheres, deplete ozone layers, and perturb climates, imposing episodic but severe constraints on long-term habitability.

Keywords: Moon systems; exomoons; exorings; gamma-ray bursts; formation.

1. INTRODUCTION

Over the past two decades, the catalogue of known exoplanets has expanded dramatically, providing unprecedented insights into the formation and evolution of planetary systems. This rapid growth in exoplanetary discoveries has revealed remarkable diversity in planetary architectures, atmospheric compositions, and dynamical interactions. Within this broader context, the study of circumplanetary environments—particularly exomoons and exorings—has emerged as a frontier in planetary science. Understanding how giant and terrestrial planets form and evolve, what their internal structure is and that of their atmosphere, represents one of the major challenges of modern astronomy, which is directly connected to the ultimate search for life at the horizon 2030–2050 (Chauvin, 2023). Despite the absence of confirmed exomoon detections, candidate systems and novel observational methods have stimulated increasing scientific interest (Agnor & Hamilton, 2006, Ayliffe & Bate, 2009). These efforts parallel our long-standing fascination with the rich diversity of moons and ring systems within our Solar System, which serve as critical benchmarks for understanding habitability beyond Earth.

A key dimension that has only recently begun to receive attention is the influence of high-energy astrophysical phenomena on the evolution and habitability of circumplanetary systems (Horvath et al., 2024). Among these, gamma-ray bursts (GRBs) represent one of the most energetic and destructive processes in the universe (Bansal & Mishra, 2025, Bansal et al., 2025). GRBs, originating from catastrophic stellar events such as core-collapse supernovae or compact-object mergers, emit intense bursts of high-energy photons capable of profoundly altering planetary and exomoon environments even at considerable distances (Barr, 2016, Berger, 2014). Two different sub-classes of GRBs have been clearly identified: those related to the merger of a binary system of two neutrons stars or a neutron star and a black hole (producing GRBs with prompt emission duration shorter than ∼2 s) and those triggered by the core collapse of a massive star (in this case, the prompt emission lasts typically more than 2 s) (Nava, 2021). Their transient but extreme radiation can strip away atmospheres, disrupt chemical equilibria, and affect surface and subsurface habitability.

For exomoons, which may orbit within the habitable zones of their host stars, GRBs pose both direct and indirect challenges to sustaining life. The direct effects include atmospheric erosion, radiolysis, and the suppression of potential biosignatures (Borucki et al., 2010). Indirectly, GRBs may alter the stellar or circumstellar environment, influencing the thermal and magnetic conditions required for long-term stability of circumplanetary systems. The extent of such effects depends critically on factors such as the moon's atmospheric composition, magnetic shielding (either intrinsic or induced by the host planet), and its geological capacity to support subsurface refugia (Bowler, 2016, Callingham et al., 2024).

This review aims to synthesise the existing literature at the intersection of exo-moon research and high-energy astrophysics, with particular emphasis on GRBs as a constraint on circumplanetary habitability. While the broader exoplanetary community has made substantial progress in developing and refining detection methodologies—including astrometry, radial velocity, direct imaging, transit timing variations, and gravitational microlensing—the implications of extreme astrophysical radiation environments for exomoons remain underexplored. By consolidating current knowledge, we seek to highlight the dual challenge of detecting exomoons and evaluating their vulnerability to catastrophic astrophysical events.

In doing so, this work emphasises the importance of integrating planetary science, astrophysics, and astrobiology in addressing the question of habitability beyond our Solar System. Future research will require not only improved observational capabilities but also robust modelling of high-energy processes and their long-term biological consequences. Such integrative approaches will be essential in assessing whether exo-moons can serve as stable and life-supporting environments despite their exposure to one of the universe's most extreme hazards—gamma-ray bursts.

2. DETECTION METHODS

This section explores the primary methods used in exoplanet detection, highlighting their strengths and limitations in the context of discovering exomoons and exorings. While most techniques were originally developed to detect exoplanets, many have been adapted to search for circumplanetary structures such as moons and rings (Canup & Ward, 2002, Ayliffe & Bate, 2009).

2.1 Astrometry

Astrometry is one of the foundational techniques in exoplanet detection. It measures the tiny positional shifts in stars caused by the gravitational influence of orbiting planets. By carefully monitoring a star's motion over time, scientists can infer the presence of an exoplanet and calculate its orbital parameters, including mass, period, and orbital geometry (Canup & Ward, 2006).

Astrometric techniques are particularly effective in detecting massive planets, as their gravitational tug induces more noticeable shifts in the host star's position. Advances in space-based astrometric missions, such as ESA's *Gaia*, have significantly improved the precision of these measurements, enabling the detection of smaller planets with greater accuracy (Chauvin, 2023).

Table 1 summarises key parameters relevant to astrometry-based exoplanet detection.

2.2 Radial Velocity (Doppler Method)

The radial velocity, or Doppler method, detects exoplanets by observing periodic shifts in the spectral lines of stars. As a planet orbits, it causes its star to move toward or away from Earth, resulting in alternating redshifts and blueshifts in the starlight. By analysing these shifts, the planet's minimum mass and orbital parameters can be determined (Chauvin et al., 2004).

Table 1. Astrometric detection parameters

Parameter	Description
Stellar Parallax	Shift in position due to Earth's orbit
Proper Motion	Star's actual movement through space
Gravitational Wobble	Oscillations due to planetary mass
Precision Requirements	Microarcsecond precision
Mission Example	Gaia

This technique is highly sensitive to massive planets in close orbits but is limited by intrinsic stellar activity, which can mimic the signal of smaller planets (Crida & Charnoz, 2012).

2.3 Direct Imaging

Direct imaging is the most visually intuitive method of exoplanet detection, as it involves capturing actual images of planets around distant stars. This technique typically uses coronagraphs or starshades to block out the bright light from the host star, allowing the faint reflected or emitted light from the planet to be seen (Domingos et al., 2006, Dumusque et al., 2012).

The main challenge with direct imaging lies in the stark brightness contrast between the planet and the star, as well as their small angular separation. Direct imaging is most successful with young, massive planets located far from their stars, where the brightness contrast is more favourable (France et al., 2021).

2.4 Transit Methodology

The transit method relies on detecting periodic dips in the brightness of a star as a planet passes in front of it, briefly blocking some of the starlight. This method can reveal the planet's size, orbital period, and even atmospheric composition (through transit spectroscopy) (Gardner et al., 2006, Gargaud et al., 2015).

Though highly effective, transit detections require a fortuitous alignment between the observer and the planetary system. The probability of detecting a transit decreases with increasing orbital distance. For exomoons, transit timing variations (TTVs) and transit duration variations (TDVs) have been proposed as promising detection techniques (Canup & Ward, 2002).

Table 2 lists factors influencing the detection of transiting exoplanets.

Table 2. Factors affecting transit detection

Factor	Effect
Orbital Inclination	Determines the likelihood of alignment
Planetary Radius	Larger planets cause deeper transits
Stellar Brightness	Brighter stars allow higher detection accuracy
Orbital Period	Shorter periods yield more frequent transits

2.5 Gravitational Microlensing

Gravitational microlensing occurs when a massive object, such as a star, passes in front of a distant light source, temporarily magnifying the background light. If a planet orbits the intervening star, it creates an additional perturbation in the light curve, revealing its presence (Gaudi, 2012, Giovannelli, 2025).

This method is unique in its ability to detect planets at great distances, including those in wide orbits or free-floating planets (Heller, 2013). However, microlensing events are rare and cannot be observed repeatedly, limiting their use for follow-up studies.

3. FORMATION PATHWAYS

3.1 Moons

Understanding the formation pathways of exomoons is crucial for deciphering the diversity observed in distant planetary systems. Existing literature suggests three primary pathways: capture scenarios, co-formation with the planet, and giant impact hypotheses (Heller & Barnes, 2014, Heller et al., 2014). However, the boundaries between these pathways may not be rigid, as some scenarios could be considered extreme examples of others.

Giant impacts represent one significant formation mechanism, as highlighted by Nesvorný et al., (2007) and Canup and Asphaug (Horvath et al., 2024). This pathway is evident in the creation of Earth's Moon and Pluto's large moon Charon, along with its smaller satellites (Hussmann et al., 2006, Kipping, 2009). The Galilean moons of Jupiter, residing in an elegant Laplace resonance, are believed to have formed within a circumplanetary disk, accreting material from the protoplanetary disk (Kipping, 2009a, Kipping, 2009b, Kipping et al., 2014, Kopparapu et al., 2013).

On the other hand, Neptune's largest moon, Triton, with its retrograde orbit, is cited as a prime example of gravitational capture. Irregular moons, characterised by eccentric, inclined, or retrograde orbits, constitute the majority of known moons around major planets, and their existence is generally attributed to capture mechanisms.

The expectation that processes at work in our Solar System apply universally raises intriguing questions about the prevalence and diversity of exomoons. Nesvorný et al., (2007) point out that if moons form in our Solar System through various pathways, it is plausible to expect a similar abundance of moons in other planetary systems. However, the uniqueness of our Solar System, as revealed by recent discoveries of compact super-Earth systems and Hot Jupiters, prompts contemplation about the commonality of systems like ours in the Milky Way.

Thus, open questions remain about the distribution, size, potential habitability, and Earth-like characteristics of exomoons. The following sections delve into observational and theoretical advances to shed light on the intricacies of exomoon formation and implications for habitability.

3.2 Moon System Architectures

The moons we consider here must exhibit long-term stability to be detectable after the circumplanetary disk (CPD) stage. Since we typically observe planetary systems during their prolonged middle age, a detectable moon must form, survive a tumultuous infancy, and maintain a stable orbit for billions of years.

Fundamentally, a moon must orbit its planet between the Roche limit—inside of which tidal forces would disrupt it—and the Hill radius (R_{Hill}), beyond which the planet's gravity cannot retain it. However, these constraints are broad. Liebig & Wambsganss, (2010) found that prograde moons are generally stable only up to 0.4895 R_{Hill}, while retrograde moons may be stable up to 0.9309

R_{Hill}. More recent findings by Limbach et al., (2024) suggest a prograde stability limit of 0.4061 R_{Hill}, with stability up to 0.4895 R_{Hill} only in some cases. Stability also depends on inclination, planetary eccentricity, tidal quality factor, and planetary oblateness.

The formation pathway of a satellite system strongly influences its architecture. For example, the Galilean moons exhibit different mass ratios and resonant configurations compared to Earth's Moon or Pluto's moons, which in turn differ from those of Mars or Neptune. Exomoon architectures could therefore provide critical insights into the histories of their host planets.

Simulations of CPDs offer insights into satellite system outcomes. Key factors include the inflow rate from the protoplanetary disk (Lingam & Loeb, 2019), gas dissipation timescales (Lovis et al., 2006), dust-to-gas ratio (Kopparapu et al., 2013, Lunine & Stevenson, 1982), accretion disk geometry (Macintosh et al., 2015), resonances (Kipping, 2009b), and CPD temperature profiles (Mao & Paczyński, 1991, Marois et al., 2008).

For moons formed in CPDs, the total satellite mass rarely exceeds a mass ratio of 10^{-4} relative to the planet (Mayor & Queloz, 1995), consistent with Solar System observations. However, impact-generated moons represent another pathway. Melott et al., (2004) suggest that forming detectable exomoons through a single impact event is difficult, while Mészáros, (2006) predict planets below 6 $M_{\oplus}$ may more easily form moons via collisions, since larger planets' gas envelopes suppress satellite survival. Thus, smaller terrestrial planets may be prime targets for detectable moons due to stronger transit and timing signals.

Captured exomoons remain another possibility. Candidate detections (Moraes, 2025, Mori et al., 2025) suggest some exomoons could be far larger than those in our Solar System. Theoretically plausible pathways for such massive captures have been proposed (Heller & Barnes, 2014), though their frequency remains uncertain. Close encounters, as frequent as planetary collisions, may facilitate capture, but direct observational evidence is still lacking.

In summary, moon system architectures are shaped by formation pathways, orbital dynamics, and planetary characteristics. Each system provides a unique window into the evolutionary history of its host planet and broader planetary system.

4. SIGNATURES OF OBSERVATION

4.1 Observational Signatures of Exo-moons

Moons are illuminated by their host star in much the same way as planets. However, the reflected light from exomoons will generally be too faint to observe directly with current facilities, similar to most exoplanets. Infrared observations offer an alternative: young giant planets and their environments can be self-luminous at thermal wavelengths, enabling direct detections at wide separations (several AU) primarily due to their youth and ongoing cooling (Domingos et al., 2006, Mosqueira & Estrada, 2003).

Angular resolution is a central challenge for imaging exomoons. Typical planet– moon separations at the distances of nearby stars correspond to sub-diffraction scales for most instruments. With sufficiently large apertures and high-contrast imaging, exomoons might be observable in reflected or emitted light. If unresolved, a planet–moon pair could still betray a companion via wavelength-dependent photocenter (flux-centroid) shifts when the moon outshines the planet at some wavelengths but not others, owing to different albedos and thermal spectra.

4.1.1 Tidal heating

Tidally heated exomoons may be identifiable even when the planet and moon are not individually resolved, by modelling the *combined* spectral energy distribution (SED) (Nava, 2021). Orbital flexing converts orbital energy into heat through internal friction, increasing the moon's effective temperature and boosting its infrared output. In an unresolved system, this manifests as:

- **Temperature signature:** elevated brightness temperatures relative to expectations for the planet alone;
- **Infrared excess:** an SED excess at mid/far-IR wavelengths beyond a planet-only model;

- **Spectral departures:** deviations from a single blackbody (or atmosphere model) fit consistent with an additional, warmer component.

Detectability depends on the moon's size, tidal forcing (eccentricity, resonance), interior dissipation, and observing bandpass and sensitivity (Nava, 2021).

4.1.1.1 Spectral energy distribution (SED)

The SED encodes temperature and composition. For unresolved planet–moon systems, multi-band photometry or low-resolution spectroscopy can be fit with two-component models (planet+moon) to test for a tidally heated companion and to bound its temperature and radius.

4.1.2 Magnetospheric interactions

Planet–moon electrodynamic coupling (e.g., Io–Jupiter analogues) can drive auroral currents and radio emission modulated at the moon's orbital period. In a magnetized giant-planet system, induction in a conductive moon and plasma interaction within the planetary magnetosphere can yield periodic radio bursts and narrowband features (Nesvorný et al., 2007, Pe'er & Zhang, 2024). In principle, periodic radio modulations reveal the moon's orbital period and constrain its orbital radius and sense (prograde/retrograde), while long-term stability of the signal constrains system architecture.

4.1.3 Moon transits across planets

A moon transiting *its host planet* (from the observer's vantage) causes a small, time-correlated dimming of the planet's flux. For planet-only self-luminous systems, this would appear as shallow dips in the planet's light curve; for star-illuminated reflected-light systems, it modulates the phase curve. Duration, depth, and shape diagnose the moon's size, orbital distance, and period.

Even around isolated or free-floating planetary-mass objects, a bound moon can transit its primary, producing detectable photometric dips with sufficiently precise monitoring. Space telescopes with high-precision photometry and time coverage are critical. Future wide-field IR surveys (e.g., the *Nancy Grace Roman Space Telescope* microlensing program) will expand discovery space for bound and unbound systems and provide exquisite time series for transient and exoplanet science (Peale et al., 1979).

Direct imaging combined with integral-field spectroscopy may also sense planet reflex motion induced by a massive moon via astrometric or spectro-astrometric shifts across spectral channels, offering a path to measuring planet–moon mass ratios in favourable systems [e.g. (Penny et al., 2019, Perryman et al., 2014).

Microlensing can, in principle, detect moons through short-lived anomalies superposed on a planetary lensing event, constraining mass ratios and projected separations; degeneracies remain a challenge, but feasibility studies show a non-negligible fraction of events would be informative (Peters & Turner, 2013, Giovannelli, 2025).

4.1.3.1 Pulsars and pulsar timing

Reflex motion from planets around pulsars imprints microsecond-level variations in pulse times of arrival. An additional moon perturbs the planet's motion about the planet–moon barycenter, introducing characteristic, coherent timing residuals whose amplitudes and phases encode the moon's mass and orbital radius (Piersanti et al., 2023). With modern timing precision, such perturbations are, in principle, detectable for massive moons in compact systems.

4.1.3.2 Time between planet and moon transits

Transit Timing Variations (TTVs) arise because the transiting planet orbits the planet–moon barycenter rather than the star directly, advancing or delaying transit mid-times. Transit Duration Variations (TDVs) arise from changes in the planet's projected velocity (TDV-V) and impact parameter (TDV-TIP) as it orbits the barycenter. A diagnostic hallmark of a single moon is that TTVs and TDVs appear in quadrature (out of phase by $\pi/2$) (Piran, 2004, Rauer et al., 2014). Joint fits to TTV+TDV constrain the moon-to-planet mass ratio and the moon's orbital semimajor axis.

4.1.4 Detecting volcanic or cryo-volcanic activity

Energetic outgassing from tidal or radiogenic heating can produce plume clouds and extended exospheres. During stellar transits of the *planet*, wavelength-dependent absorption by species such as SO_2 (volcanism) or H_2O (cryo-volcanism) can deepen the effective transit radius at specific bands, yielding multiwavelength transit-depth anomalies. Time variability across epochs offers an additional discriminant from static planetary atmospheres.

5. MOON HABITABILITY

The habitability of exomoons—moons orbiting exoplanets—presents a compelling frontier in astrobiology. Recent theoretical work suggests that small to Mars-sized icy exomoons may harbour subsurface environments conducive to life, extending the search for habitable real estate beyond the classical circumstellar habitable zone (CHZ) defined for planets (Ronnet & Johansen, 2020, Bowler, 2016). This section synthesises key conditions for exomoon habitability with emphasis on subsurface environments, tidal heating, and magnetic protection, and outlines observational implications.

5.1 Exomoon Characteristics and Habitability

Moons with masses comparable to or exceeding that of Mars can sustain significant internal heating and, under suitable conditions, maintain long-lived subsurface oceans beneath icy shells, akin to Europa and Enceladus in the Solar System (Rosario-Franco et al., 2020). Tidal forces arising from gravitational interactions with their host planets play a central role in maintaining liquid water and potentially energy gradients relevant for metabolism (Ruderman, 1974, Bowler, 2016). When combined with radiogenic heat, tidal dissipation can stabilise ocean layers over geologic timescales, decoupling habitability from direct stellar insolation.

5.2 Subsurface Habitability

Two broad criteria guide subsurface habitability:

- **Thermal boundary conditions:** Surface temperatures typically below the sublimation point of water ice (∼150 K) allow a mechanically strong ice shell that protects and insulates the interior ocean from space weathering and volatile loss (Rosario-Franco et al., 2020).
- **Internal heating:** Sustained internal heating (tidal and/or radiogenic) must be sufficient to keep water liquid at depth. Modest orbital eccentricities, resonant forcing, and appropriate interior rheology can maintain the necessary dissipation (Sagynbayeva et al., 2025, Bowler, 2016).

Because tidal heating does not depend directly on stellar flux, habitable exomoons may exist well beyond the circumstellar snow line; in such cases, the habitable “edge” is set by the balance of tidal heating, heat transport, and ice-shell conductivity rather than by the stellar greenhouse budget (Bowler, 2016).

5.3 Tidal Heating and Key Influencing Factors

The strength and spatial distribution of tidal heating depend on:

- **Host-planet mass and moon semimajor axis:** Stronger tidal forcing occurs for massive hosts and close-in moons subject to Roche-limit constraints (Bowler, 2016).
- **Orbital eccentricity and resonances:** Nonzero eccentricity—often maintained by mean-motion resonances with sibling moons—sustains long-term dissipation (Bowler, 2016, Sagynbayeva et al., 2025).
- **Interior structure & rheology:** Ice/rock layering, ocean depth, and viscoelastic parameters govern how efficiently tidal work converts to heat (Rosario-Franco et al., 2020).
- **Thermal blanketing:** A porous, low-conductivity regolith and warm ice shell can reduce heat loss, easing the required tidal power for ocean maintenance (Rosario-Franco et al., 2020).

Models suggest that even mid-sized icy moons in the outer Solar System (e.g., Uranian satellites) could host internal oceans under plausible conditions, in some cases with limited reliance on present-day eccentricity forcing (Rosario-Franco et al., 2020).

5.4 Observational Implications

High-precision time-series photometry and spectroscopy enable indirect constraints on exomoon properties. Transit timing and duration variations (TTVs/TDVs) offer mass-ratio and orbital-radius constraints when modelled jointly, exploiting the $\pi/2$ phase offset that is diagnostic of a single satellite (Piran, 2004, Rauer et al., 2014). Past and current facilities (e.g., *Kepler*) and future missions (*JWST*, *PLATO 2.0*) provide improved photometric precision and cadence, expanding discovery space for exomoon signatures (Scharf, 2006, Seager & Deming, 2010, Gardner et al., 2006). Direct-imaging pathways may probe massive, young planet–moon systems via astrometry and integral-field spectroscopy, including spectro-astrometric shifts and multi-component SED fits sensitive to tidally heated moons (Nava, 2021). Candidate exomoon systems have been discussed in the literature (e.g., Kepler-1625b), though confirmation remains debated (Moraes, 2025).

5.5 Magnetic Protection and Atmospheric Retention

Atmospheric retention against stellar wind and high-energy particle sputtering is enhanced by magnetic shielding. An exomoon's intrinsic dynamo or residence within a giant planet's magnetosphere can mitigate escape and surface radiation, thereby improving long-term habitability prospects (Bowler, 2016). Star–planet–moon magnetic coupling can also generate auroral power and observable radio modulations, offering indirect probes of system architectures while informing space weather exposure (Nesvorný et al., 2007).

5.6 Habitability Limits

Habitability is bounded by two energy-flux thresholds:

- **Runaway-greenhouse limit:** Excess net energy input (stellar illumination + planetary illumination + tidal dissipation) drives a runaway greenhouse instability, desiccating the moon and sterilising surface environments (Spinelli et al., 2023, Bowler, 2016).

- **Maximum greenhouse (outer) limit:** Insufficient net energy fails to sustain liquid water, even with maximal plausible greenhouse forcing; for exomoons beyond the stellar HZ, adequate tidal heat can partly compensate, but too little dissipation freezes the ocean (Spinelli et al., 2023, Bowler, 2016).

These combined limits delineate a circumplanetary "habitable edge" governed by the moon's orbit, mass, interior structure, and the radiative environment.

Exomoon habitability broadens the classical concept of habitable real estate. By integrating subsurface ocean physics, tidal heating, and magnetic protection with emerging observational strategies, we can identify high-priority targets for future facilities. Continued refinement of coupled thermal–orbital–magnetospheric models, together with precise time-domain surveys and direct-imaging spectroscopy, will be pivotal in assessing the prevalence of life-supporting moons beyond the Solar System.

6. GAMMA-RAY BURSTS AND PLANETARY HABITABILITY

Gamma-ray bursts (GRBs) are the most luminous transients in the Universe, briefly outshining their host galaxies and releasing up to $\sim 10^{53}$ erg of high-energy radiation in collimated jets. The combination of short duration, extreme photon energies, and strong beaming makes GRBs a salient external stressor for planetary atmospheres and surface biospheres. Their capacity to alter atmospheric chemistry, drive volatile loss, and impose acute biological stress suggests that GRBs are an important boundary condition for planetary and exomoon habitability on galactic scales (Bansal & Mishra, 2025, Bansal et al., 2025). The damage potential depends on the burst fluence at the planet, jet orientation, and spectral hardness, and the planet's atmospheric column, chemistry, and magnetic shielding (Berger, 2014, Barr, 2016).

6.1 Mechanisms of Atmospheric and Biological Impact

A GRB beaming toward an Earth-like atmosphere initiates a cascade of photochemical and particle-interaction processes. High-energy photons and their secondary particles dissociate N_2 and O_2, generating odd-nitrogen (NO_x) species that catalytically destroy ozone and elevate NO_2 opacity. Radiative-transfer models indicate that even modest changes to the ozone column can substantially increase biologically harmful solar UVB at the surface for years to decades, with additional shortwave dimming from NO_2 that perturbs the climate (Stern et al., 2006, Berger, 2014). Earlier work estimated that fluences of order 10–100 kJ m^{-2} could yield tens of per cent to $\gtrsim 60\%$ ozone depletion, with recovery on decadal timescales depending on background chemistry and in isolation (Stern et al., 2006, Strøm, 2024).

Beyond chemistry, enhanced ionisation can increase surface and near-surface radiation doses and, for thin or hydrogen-rich atmospheres, can amplify non-thermal escape, gradually eroding volatiles that are critical to long-term habitability (Sumi et al., 2011).

Recent observations anchor these models with geospace responses to real events. The exceptionally bright GRB 221009A (*the "BOAT"*) on 2022 October 9 produced measurable, global ionospheric disturbances detected via VLF/LF propagation changes and independent diagnostics, demonstrating that GRB photon showers can couple to the D- and E-regions of Earth's ionosphere on timescales of minutes to hours (Teachey, 2024, Teachey & Kipping, 2018, Thomas et al., 2005). Although Earth's stratospheric chemistry and deep atmospheric column buffered any catastrophic outcome from this particular event, the observed geophysical perturbations confirm the efficiency with which GRB radiation modifies upper-atmospheric electrodynamics and, by inference, supports the plausibility of stronger chemical impacts for closer, harder, or longer-lived bursts.

6.2 Astrobiological Consequences and the Role of Subsurface Habitats

The biological implications of post-GRB atmospheres are twofold. First, transient ozone depletion dramatically increases surface UVB, raising mutational loads and sterilisation risk for exposed ecosystems, particularly in shallow marine photic zones; second, climate and photoperiod changes associated with NO_2 opacity and altered shortwave flux can disrupt primary productivity and ecological networks (Stern et al., 2006). GRBs have therefore been advanced as plausible triggers of mass extinctions on Earth, including the Late Ordovician hypothesis in which sudden biodiversity collapse and geochemical indicators are consistent with severe UV stress (Berger, 2014, Yuan et al., 2016). While the strength of any single palaeobiological association remains debated, the mechanism is well posed and constrained by atmospheric photochemistry.

For exoplanets and exomoons, the same physics implies that lethal-window GRBs act as an external filter on surface habitability. Worlds with thick atmospheres, robust ozone production, or magnetospheric shielding may experience reduced surface doses. Crucially, bodies with subsurface oceans—including tidally heated exomoons— are naturally buffered: ice shells and overlying water columns attenuate UV and ionising radiation by orders of magnitude, preserving niches where life could persist through recurrent astrophysical catastrophes. In this sense, GRBs sharpen the contrast between surface and subsurface habitability, without precluding long-term biosignature potential for ocean worlds.

6.3 Rates, Environments, and the Galactic Context

Assessing long-term habitability requires integrating GRB demographics with galactic structure. Long-duration GRBs (collapsars) preferentially occur in low-metallicity, intensely star-forming environments, whereas short-duration GRBs (compact-object mergers) are more broadly distributed across galaxy types. Modelling the Milky Way with realistic metallicity and star-formation gradients suggests that the inner disk and bar regions incur higher probabilities of lethal fluence over Gyr timescales, while the Solar neighbourhood remains comparatively benign but not immune (Strøm, 2024, Vidmachenko & Mozghovyi, n.d.). Updated habitability assessments argue that, within the Milky Way, there is a non-negligible probability that at least one GRB with fluence sufficient to impose severe ozone depletion has intersected Earth over the past 10^9 yr, with median expectations of order one event within ~0.5 Gyr depending on beaming and luminosity-function assumptions (Zarka, 2007, Strøm, 2024). Extragalactic and cosmological extensions further imply that low- low-metallicity dwarf irregulars and high-redshift disks are, on average, harsher locales for persistent surface biospheres (Wang et al., 2018).

Despite progress, key uncertainties remain. The fluence thresholds for severe ozone depletion depend on spectral hardness and atmospheric state, including background halogen chemistry and stellar UV environments; robust predictions therefore require coupled photochemical–climate models spanning broader parameter space than Earth's present atmosphere. The frequency of very bright, nearby long GRBs in metal-rich spirals remains a leading-order uncertainty for local galactic habitability. Observationally, the

2022 GRB 221009A has catalysed a new era of space-weather style diagnostics for GRBs, motivating coordinated ionospheric, atmospheric, and radiative monitoring to calibrate models across fluence and zenith-angle regimes (Teachey, 2024, Teachey & Kipping, 2018 Thomas et al., 2005). For exoplanets and exomoons, the interplay of atmospheric mass, composition, magnetospheric topology, and subsurface refugia demands end-to-end modelling to translate GRB statistics into biosignature priors. Future time-domain facilities and high-energy missions, combined with climate–chemistry simulations tailored to diverse atmospheres, will be decisive in quantifying how GRBs sculpt circumstellar and circumplanetary habitable real estate across the Galaxy.

Table 3 summarizes the principal pathways by which GRBs influence atmospheres and biospheres, together with representative habitability consequences discussed.

Recent work at the interface of biology, chemistry, and astrophysics highlights parallel strategies by which complex systems maintain function under stress. For example, Bansal et al. (2025) revisit theories of ageing and emphasize the role of systemic maintenance, repair, and negligible senescence in delaying functional decline, whereas (Bansal and Mishra, 2025) demonstrate that reactive carbocations can be stabilized in aqueous microdroplets that provide confined, nonequilibrium environments. Together, these studies suggest that compartmentalization, continuous turnover, and protective buffering can enhance resilience in both biological organisms and reactive chemical systems. In an Astro biological context, micro structured phases such as icy brines, hydrothermal plumes, or atmospheric aerosols on planets and exomoons may similarly stabilize reactive intermediates and sustain far-from-equilibrium chemistry, particularly when combined with shielding by ice shells, oceans, or dense atmospheres. This analogy can be framed as a heuristic of “resilient complexity,” in which systems that couple sustained reactivity or metabolism to effective repair or shielding are more likely to persist under stochastic perturbations, including high-energy events such as gamma-ray bursts. While speculative, such cross-disciplinary perspectives may help connect droplet-scale chemistry and longevity biology to planetary-scale assessments of habitability and the long-term persistence of biosignatures.

Table 3. Principal GRB effects on atmospheres and biospheres, with indicative consequences for habitability

Process	Physical/Chemical Pathway	Habitability Consequences
Ozone depletion and NO_2 opacity	High-energy photon/secondary-particle dissoci-ation of N_2 and O_2; catalytic NO_x cycles; altered radiative transfer (Stern et al., 2006, Berger, 2014)	Enhanced surface UVB for years–decades; possible climate dimming; ecosystem stress and potential mass extinctions
Surface/near-surface irradiation	Prompt γ-ray and secondary-particle ionisation cascades; depends on column mass and composition (Bansal & Mishra, 2025)	Elevated mutation and mortality rates in exposed biomes; stronger impact on thin/erosive atmospheres
Atmospheric escape pathways	Ionisation and heating drive non-thermal and thermal escape, especially for light species (Sumi et al., 2011)	Long-term volatile depletion (e.g., H_2O), reducing surface habitability resilience
Ionospheric and space-weather coupling	D/E-region electron-density perturbations and global VLF/LF anomalies observed for GRB 221009A (Teachey, 2024, Teachey & Kipping, 2018)	Validates rapid upper-atmosphere response; provides empirical benchmarks for model calibration
Environmental shielding and refugia	Thick atmospheres, magnetospheres, oceans, and ice shells attenuate radiation	Subsurface habitability persists on ocean worlds and tidally heated exo-moons despite surface sterilisation episodes

7. DISCUSSION

The exploration of exomoons and exorings sits at the crossroads of observational astronomy, planetary science, and astrobiology. Each detection methodology—whether astrometry, radial velocity, transit timing variations, direct imaging, or microlensing—offers unique opportunities and challenges. While transit methods remain the most sensitive for exomoon detection, particularly through timing and duration variations, the complementary roles of other techniques are indispensable for cross-validation. However, observational limitations, such as signal-to-noise constraints and degeneracies in planetary system architectures, continue to slow progress in the confirmation of exomoon candidates.

Theoretical investigations into formation pathways underscore the diversity expected in exomoon populations. Capture events, co-formation in circumplanetary disks, and giant impacts are all plausible origins, each predicting distinct system architectures and evolutionary trajectories. Numerical simulations suggest that orbital stability, constrained by Hill spheres and resonant interactions, is a central determinant of long-term survivability. The diversity of moon systems in our Solar System—ranging from the Galilean satellites to Triton—illustrates that multiple formation mechanisms likely operate in tandem, with implications for both detectability and habitability.

Habitability introduces further layers of complexity. While tidal heating, magnetic protection, and subsurface oceans may extend habitable potential far beyond classical circumstellar habitable zones, these same processes impose energetic and geophysical limits. Exomoons may host stable surface or subsurface environments, but their vulnerability to stellar activity and astrophysical transients remains a critical uncertainty. In this context, gamma-ray bursts (GRBs) are of particular significance. Their capacity to induce atmospheric erosion, ozone depletion, and photochemical changes suggests that even moons in otherwise benign stellar environments may experience episodic sterilisation events. Yet, geological refuges such as subsurface oceans provide a plausible mechanism for biological persistence, mitigating the existential risks imposed by high-energy astrophysics.

Taken together, the study of exomoons reveals both promise and vulnerability. Detection challenges are gradually being overcome by increasingly sophisticated instruments and data analysis strategies, yet the broader question of long-term habitability demands interdisciplinary approaches that unite planetary dynamics, radiation astrophysics, and biological resilience.

8. CONCLUSION

Exomoons and exorings represent the next frontier in exoplanetary science. Although no confirmed detections have yet been made, the convergence of improved detection methodologies, refined theoretical models, and enhanced computational resources is steadily advancing the field. These efforts highlight that circumplanetary systems are not mere extensions of planetary architectures but are themselves diverse and dynamic environments with profound astrobiological implications.

This review emphasises that the habitability of exomoons cannot be considered in isolation from the astrophysical context in which they exist. Gamma-ray bursts, as among the most energetic events in the cosmos, illustrate the fragility of exomoon habitability on astronomical timescales. While these bursts may impose episodic con-constraints on surface life, the resilience of subsurface habitats and the potential for recovery underscore the importance of nuanced, probabilistic models of habitability rather than binary assessments of survival or extinction.

Future progress will hinge on the synergy of observational advances and theoretical integration. Next-generation observatories, such as the James Webb Space Telescope, PLATO, and ground-based extremely large telescopes, will enhance sensitivity to circumplanetary signatures. Concurrently, improved models of high-energy astrophysical environments will refine our estimates of habitability under transient catastrophic conditions. Ultimately, the study of exomoons and their exposure to extreme astrophysical phenomena will enrich our understanding of life's resilience, guiding the search for habitable worlds in the universe.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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