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Circadian Rhythm Adaptation Mechanisms in Extreme Environments

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Abstract:
Circadian rhythms coordinate physiology and behavior across species, yet on extreme photoperiodic cycles, in polar regions, in spaceflight, and deep sea, and in thermally extreme habitats, photic entrainment is disturbed. This review attempts to draw together evidence for clocks functioning well when light cues are unreliable; in doing this, it emphasizes non-photic Zeitgebers and molecular plasticity. The studies cite temperature cycles, altered gravity, feeding and social schedules, and magnetic inputs in terms of their abilities to entrain central and peripheral oscillators. We highlight at the molecular level epigenetic remodeling (DNA methylation, histone marks, and chromatin accessibility), non-coding RNAs, and post-translational modifications as the key mechanisms that under stress retune the CLOCK: BMAL1–PER/CRY feedback loops in metabolism and immunity. A comparative appraisal includes polar vertebrates maintaining rhythms in continuous light/darkness via thermal and seasonal signals; astronauts and model organisms adapting in microgravity with desynchronized tissue clocks and altered neurocardiac dynamics; and desert, polar marine, and deep-sea species responding to temperature, tidal, and lunar cycles. Overall, these findings reveal the flexible multi-cue architecture for temporal organization that directly pertains to human health and performance concerns in polar operations and long-duration spaceflight, as well as ecological resilience in rapid environmental change. The journey into how clocks reweight non-photic inputs and engage epigenetic flexibility underpins countermeasures (light, temperature, feeding schedules), which could lead to conservation methods aimed at reestablishing rhythmicity during conditions when photic cues become dysfunctional.

Keywords: Circadian Clock; Extreme Environments; Temperature.

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1. Introduction

Circadian rhythms are endogenous, near-24-hour cycles that regulate physiological and behavioral processes in alignment with the external day-night cycle [1]. In vertebrates, the core timekeeping network includes a master clock in the brain (the suprachiasmatic nucleus, SCN) and a constellation of peripheral clocks across tissues, all driven by transcription-translation feedback loops of clock genes and synchronized by Zeitgebers, most notably light detected by retinal photoreceptors [2].

In addition to light cues, circadian clock phase and amplitude can be modulated by non-photic factors such as temperature, metabolic signals, feeding schedules, mass gravitational force, or orientation. This suggests that when photic cues are unreliable or absent, non-photic cues become more prominent even in extreme environments, which are discussed later in the context of disturbances in the environment affecting rhythms and clock gene regulation [3].

Long-term continuous exposure to light or darkness can affect the regular photic zeitgebers factors in polar regions. Therefore, the entrainment pathways must be flexible and possess reliable non-phototransduction mechanisms to construct the temporal structure [2]. Polar vertebrates exhibit various rhythmic changes, ranging from the maintenance of daily rhythms during the polar day to the emergence of arrhythmic or free-running patterns under long-term light or darkness conditions, which demonstrates the diversity of the adaptation of the clock system and pathways of entrainment [4]. Artificial light-dark cycles and microgravity environments can separate the central clock from the peripheral clocks, thereby exerting downstream effects on metabolism, immunity, sleep and cognitive performance, highlighting the significance of clock adaptability in biomedical aspects under different gravity and light conditions [1]. The deep sea or thermally extreme conditions lead to specific temperature conditions, compounded by insufficient light, which poses additional challenges to the clock entrainment; this further indicates the molecular-level interaction between temperature cycles and photic cues [3].

It is indisputable that in extreme environments, the circadian rhythm holds significant ecological and biomedical significance. Just as the clock can optimize activity patterns, foraging behaviors, predator avoidance strategies, reproductive behaviors, and seasonal time arrangements, it can also optimize ecological effects [2]. Its biomedical effects include the connection between circadian disruption and dysregulated metabolism, immune perturbations, sleep disorders, and decreased performance capabilities, which are particularly important for astronauts, divers, and wild animals facing rapid changes in photoperiods and environments (e.g., continuous daylight, continuous darkness, or microgravity) [5].

In response to extremely harsh environmental conditions, new methods have been developed to identify powerful self-regulation strategies, which will help enhance the adaptability of biological rhythms and provide guidance for future research in polar chronobiology and space physiology. The current comprehensive research results are of great significance for establishing health management systems for astronauts and other individuals in extreme environments, and this synthesis aims to advance in this field.

2. Mechanisms of Circadian Rhythm Regulation in Extreme Environments

2.1 Temperature, Gravity, and Non-Photic Cues

In environments where photic information is unreliable, temperature changes can play an essential role in regulating the biological clock, influencing both the central and peripheral biological clocks. The temperature variation patterns in the environment will act on the phase and amplitude of the biological clock gene network, thereby effectively controlling the timing of physiological processes in situations where light signals are scarce or irregular (Fig. 1) [3]. The interface between the temperature sensing component and the core clock ensures that re-entrainment or phase adjustment can be achieved without the need for light, thereby ensuring the stability of the rhythm even in low-light conditions [5]. Among polar vertebrates, temperature cues are particularly important. They can make up for the lack of light input and enable the metabolic cycle to match the resource supply situation and seasonal demands. These findings highlight the circadian system's flexibility in utilizing alternative environmental cues for temporal regulation, which can utilize thermal signals to ensure precise timing even under extreme environmental conditions [4].

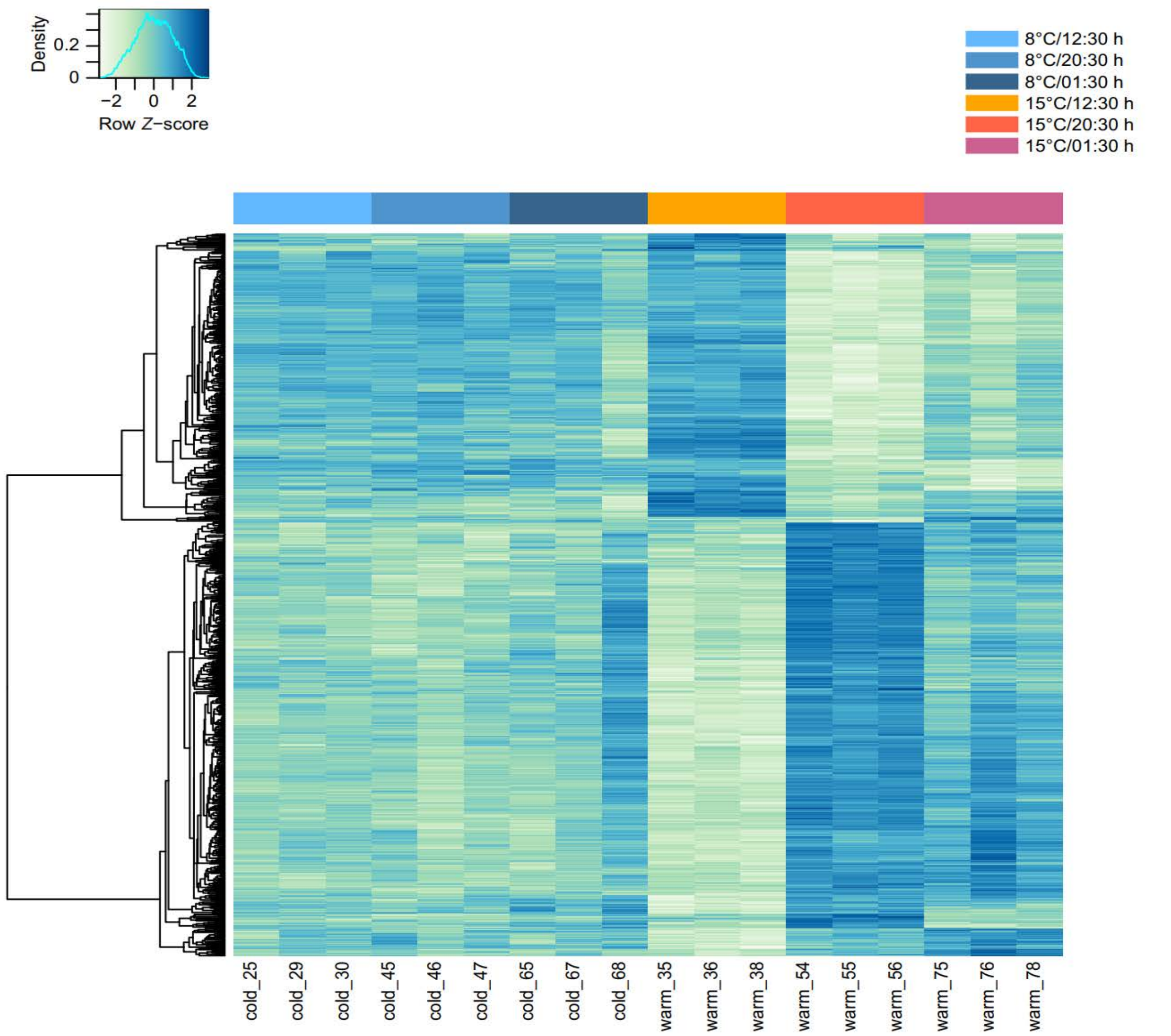

Fig. 2. Heatmap showing standardized mRNA levels of genes with significant temporal variation (false discovery rate, FDR <0.01) between three time points in the liver of the Arctic char *Salvelinus alpinus* acclimated at 15°C for 1 month, measured using RNA sequencing. At 15°C, 747 rows (genes) showed temporal variation. In contrast, in fish held at 8°C for a month, no genes were differentially expressed between time-points at this FDR. Data are from Prokkola et al. (2018).

Fig. 1 Hierarchical Clustering Heatmap of Gene Expression Profiles under Different Temperature and Time Treatments [3]

In addition to the direct temperature effect, microgravity and the altered gravity also have different impacts on the clock machinery and signal networks. In space or other low-gravity environments, the usual biological clock information transmission pathway from the brain to the surrounding tissues may be disrupted, resulting in changes in phase relationships and partial desynchronization between tissues [6]. Usually, the neural circuits and hormonal axes that convey time information may be disrupted, thereby altering how clocks are entrained. Therefore, hormonal mediators such as melatonin and cortisol can be re-adjusted to change the timing and robustness of entrainment, leading to frequent disruptions in the sleep-wake patterns that occur during space flights [5, 6]. In fact, some measures that incorporate scheduled zeitgebers (such as carefully scheduled light exposure times and meal times) will be adopted, along with strategies to stabilize hormone signal transduction, in order to maintain the synchronization of the biological clock in a microgravity environment. This indicates that non-photic cues can be utilized to alleviate the biological clock disorders caused by gravity [7].

Apart from non-photonic factors such as temperature and gravity, other factors such as meal times, activity patterns, magnetic fields, and social cues also play an essential role in the formation of the rhythm when photic information is unreliable. A regular meal schedule enables adjustments to metabolic and hormonal pathways, which in turn feed back into the expression of circadian genes,

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helping to maintain the rhythmicity in the absence of reliable light signals [6]. Similarly, scheduled activities and social interactions can reset or strengthen the circadian phase, enabling peripheral clocks to align with energy consumption and the readiness of the immune system (Fig. 2) [5]. Although the mechanistic details are still not fully understood, it is believed that magnetic cues and social environments can modulate the timing signals and promote ensemble entrainment, especially in social or communal species that live in extreme light conditions [3]. The space-context studies on polar and space environments under non-photic conditions further indicate that in situations where light conditions are limited, multiple factors work together to maintain the biological rhythm. This demonstrates the powerful and multi-signaling architecture for circadian regulation [2].

From the perspective of ecological physiology, the alignment of non-photic cues with metabolic requirements and immune preparation status can have significant consequences. When feeding, activity, and environmental cues align with the biological clock phases, organisms can optimize the intake and expenditure, which is a crucial advantage under fluctuating resource availability [5]. The regulatory mechanism of circadian rhythms also affects the readiness state of the immune system; the non-photic entrainment can affect the inflammatory response and the ability to defend against pathogens, and in extreme environments, the stress and isolation conditions will further intensify the impact of this factor [6].

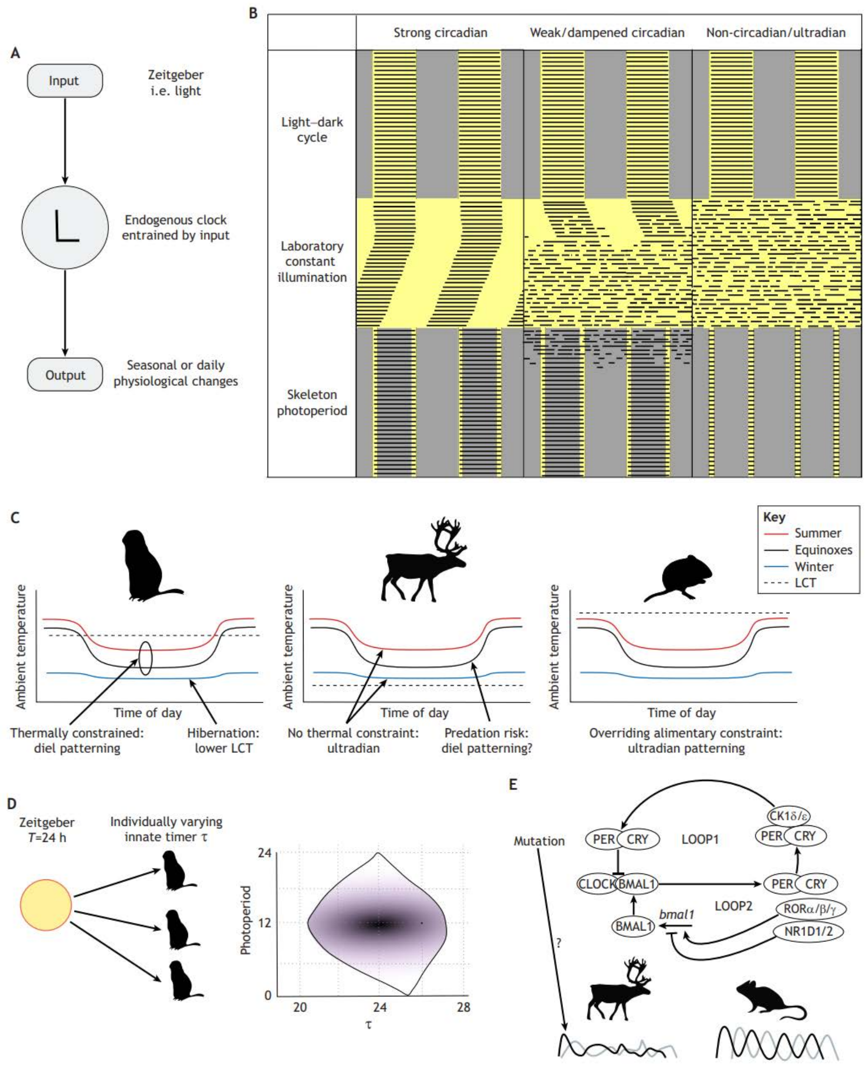

Fig. 2 Multilevel Regulation of Circadian Rhythms: External Zeitgebers, Behavioral Adaptations, and Molecular Mechanisms [5]

2.2 Molecular and Epigenetic Regulation

As 2.1 shows, in extreme environments, non-photic cues such as temperature fluctuations, changes in gravity, feeding schedules, and social signals enable the circadian system to adapt and regulate its functions. These cues affect the timing and stability of the circadian rhythm, and the ultimate flexibility of the circadian clock is achieved through epigenetic reprogramming at the molecular level, chromatin remodeling, non-coding RNA, and post-translational modifications. Now, in Section 2.2, we will explore how core circadian clock genes and regulatory circuits respond to environmental stress through these epigenetic and post-translational processes, and illustrate the mechanisms for re-adjusting the dynamics of CLOCK-BMAL1 and the control output of the circadian clock in terms of energy metabolism and immunity by referring to the three provided articles.

2.2.1 Core Clock Genes and Regulatory Loops Under Stress

The core oscillator in mammals relies on CLOCK and BMAL1 to drive the transcription process of PER and CRY. These transcriptional products, in turn, will inhibit the activity of CLOCK: BMAL1. Under stressful conditions (such as encountering situations in extreme environments), the expression dynamics and feedback intensity of these components can be re-adjusted through epigenetic modifications and changes in the accessibility of transcription factors. This re-adjustment can recalibrate the period, amplitude and phase of the clock, making it adapt to harsh environments or specific energy, or immune challenges encountered during space flights (Fig. 3) [8]. In the field of hematology, it has been confirmed that the epigenetic inactivation of BMAL1 is a mechanism that disrupts the normal biological clock function and can affect cell cycle and metabolic control. This indicates that the biological clock dysregulation at the epigenetic level can have an impact by triggering changes in cell behavior under stress conditions. This highlights a potential vulnerability and adaptive pathway of the biological clock in diseases or extreme circumstances [9]. Among all mammals, there is evidence suggesting that environmental stress factors (including metabolic stress and inflammatory signals) can alter the transcriptional program of clock genes through changes in chromatin status, thereby adjusting the downstream clocks in tissues related to high metabolism or immune function. This implies that the clock can re-adjust its regulatory output to meet the immediate physiological needs [10].

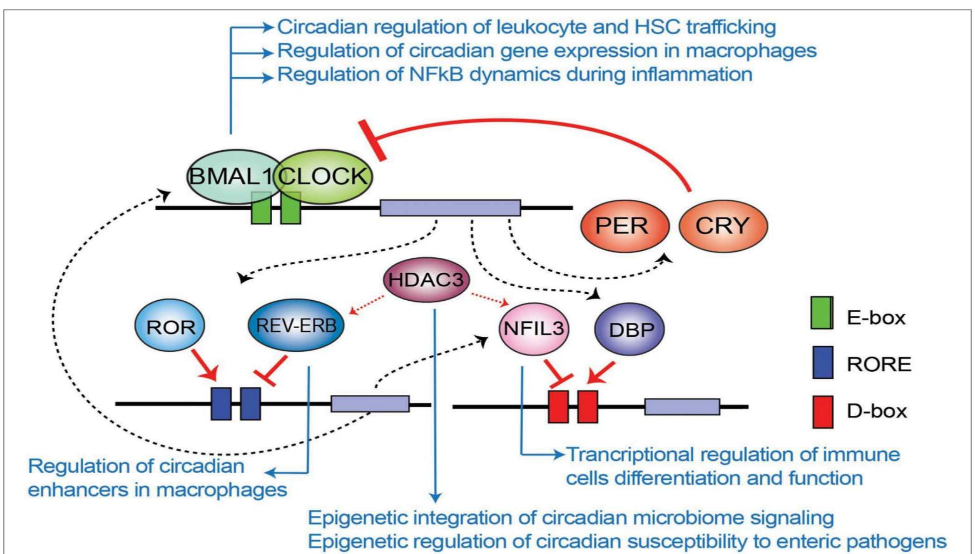

FIGURE 1 | Transcriptional-translational feedback loops control circadian gene expression. Rhythmic binding to e-boxes on chromatin of the clock components of the positive loop, CLOCK:BMAL1, induce the expression of clock-controlled genes and the clock negative regulators PER and CRY. Additionally, the nuclear receptor REV-ERBα and ROR impose transcriptional rhythms on genes via RORE cis regulatory elements, while the PAR-bZIP transcription factors DBP, and the repressor NFIL3 interplay to drive transcriptional rhythms in a set of genes through binding to D-boxes. Blue arrows relate molecular components of the clock TTFL involved in epigenetic regulation of the indicated mechanisms of immunity and infection, which are further discussed across the text.

Fig. 2 Figure from Ricardo Orozco-Solis [8]

2.2.2 Epigenetic Mechanisms Shaping Clock Regulation

The methylation status of the promoter or enhancer regions of the clock gene can either inhibit or promote the transcriptional response to stress. Environmental factors may trigger dynamic methylation changes, thereby altering the phase or amplitude of the clock output, especially in hematopoietic tissues and metabolic tissues [8].

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Changes like acetylation (H3K27ac) and methylation (H3K4me3) in the regulatory region of clock genes affect chromatin accessibility as well as the transcription rhythm. It is well known that environmental signals such as stress (whether from inflammation or energy deficiency) can modify these marks for the regulation of CLOCK/BMAL1 activity and the inhibitory cycle of PER/CRY. This adds another level of environmental control on the core oscillator [10].

The ATP-dependent remodeling factors and higher-level chromatin structures can reconfigure the clock gene loci under extreme conditions, thereby providing or restricting the access of the transcription machinery and accessory factors to the entry channels. These remodeling processes can synchronize the peripheral clock with the cellular energy state and immune signals [8].

MicroRNAs and other non-coding RNAs regulate the components of the biological clock during the post-transcriptional stage, responding to stress by adjusting the levels of BMAL1, CLOCK, PER, and CRY. For instance, microRNAs that respond to inflammatory or metabolic signals can either inhibit or enhance the transcription of biological clock genes, thereby altering the oscillation pattern to adapt to the physiological priorities in extreme exposure situations [8].

The phosphorylation, acetylation and ubiquitination of clock proteins can affect their stability, nuclear localization and feedback intensity. Stress signals often modify these modifications, thereby adjusting the feedback loop of the clock and its ability to synchronize metabolism and immune functions [10].

3. Species-Specific Adaptions

3.1 Polar Animals

Intense illumination is imposed in summer continuous daylight and in winter prolonged darkness during polar and near-polar environments. Such high variability in photoperiod among polar vertebrates' manifests in entrainment and functioning of the biological clock. This can indicate both robustness and plasticity of circadian systems and its tremendously important impacts on health and ecological fitness.

The polar and near-polar environments have such extremely severe photoperiods. One summer has continuous sunlight for the length of winter; the other has long, dark days with poor light fell on occurrences. In polar vertebrates, the regulation and performance of the biological clock under such conditions indicate the strength and plasticity of the circadian rhythm system, which has a great influence on health and ecological adaptability.

3.1.1 Entrained Features in Extreme Photoperiods

Mammals from the Arctic and the sub-Arctic are conditioned, by ambient cues other than light, into central and peripheral clocks when photic signals are deficient or absent. Studies of Arctic and polar mammals show that non-photic cues (for example, ambient temperature cycles) serve as Zeitgebers of locomotor activity and core clock outputs, shaping the daily rhythms under unconventional photoperiods: for example, continuous daylight or darkness [11]. For instance, Arctic ground squirrels, polar mammals, and other high-latitude species, where the circadian system can maintain strong rhythmicity even in long days or nights, are possible under these conditions. These results emphasize that timing signals and clock outputs, such as melatonin rhythms, body temperature, etc., can be entrained or reoriented by atypical cues when light becomes non-informative [2].

3.1.2 Adaptations

Changes in activity patterns: Polar animals often shift activity to follow the most favorable resource windows and thermal conditions, thus modifying their behaviour to long photoperiods. In an Arctic or polar setting, animals may blunt or restructure activity timing in order to optimize energy expenditures in any given condition of either prolonged daylight or continuous darkness [12].

Adaptations to metabolic rate: The energy balance under extreme photoperiods is the primary selective agent that metabolic rhythms of the clock have evolved to adapt to long summer days and long winter nights and conserve energy; clock outputs then continue to coordinate feeding, thermoregulation, and reproduction where possible [4].

Melatonin signaling and circadian clock-gene expression: Melatonin profiles and expression of clock genes are modulated by seasons and photoperiod to temporally align peripheral clocks with the environment. In polar vertebrates, melatonin rhythm and clock gene dynamics show patterns of seasonal adjustment to assist in maintaining temporal organization across extreme photoperiods [4]. Peripheral clocks: Seasonal re-entrainment and synchronization of clock genes in peripheral tissues allow for tissue-specific adaptation to photoperiod extremes and resulting physiological consequences and fitness costs.

3.1.3 Implications for Health and Ecological Fitness

Well-being: In polar species, a reliable circadian organization allows for metabolic homeostasis, immune function, and hormonal control to be maintained across seasonal cycles. Such interruptions to signaling from the circadian clock would create energy imbalance and improperly adjust reproductive timing and stress-resilient mechanisms, especially during rapid changes of environment [4]. Ecological fitness: In circadian system under polar conditions, seasonal resources coordinate foraging, predator avoidance, and social interaction. Entrainment to a variety of environmental cues (not just light) could improve fitness through flexible adjustment of the timing of activity and physiological processes to cope with unpredictable photoperiods [12].

3.2 Astronauts and Model Organisms in Space (astronauts and model organisms in space)

Microgravity, radiation, and the irregular light-dark schedule that spaceflight would present unique sets of challenges to circadian biology. In most of the humans and model organisms, they exhibit resilience and vulnerability of circadian systems, which has consequences concerning health, performance, and long-duration missions to space.

3.2.1 Spaceflight Conditions and Clock-system Responses

Long-duration space missions have revealed perturbation in cardiovascular regulation and autonomic control in microgravity plus radiation environments. The heart rate's circadian rhythms showed partial resilience in that some intrinsic regulation (β, a fractal-like slope of HRV) might prove unsuitable for entire adaption to microgravity. Complex, multi-frequency adaptations manifest in such time scales as circadian and ultradian dynamics [13]. Disrupted light-dark cycles, along with other sources of circadian misalignment, have caused spaceflight misalignment, resulting in sleep disorders, changes of cognitive performance, and human physiology. Astronauts' adaptations in HRV indices and brain network dynamics vary depending on circadian stage, implying that the responses are modulated by the circadian clock in adapting to microgravity [13].

3.2.2 Clock-system Responses: Molecular and Epigenetic Regulators

HRV and brain networks: The default mode network (DMN) undergoes distinct reorganizations when exposed to microgravity, with some astronauts showing a propensity to an alerting default mode alongside circadian timing. Resting-state networks and HRV bands (e.g., HRV-SFO and HRV-VSFO) are proxy measures for prompting adaptation of brain networks to space, representing a type of circadian-brain integration in the adaptation to altered gravity and environmental cues [13]. Epigenetics and molecular regulation: Spaceflight studies highlight the existence of clock gene networks in diverse tissues, and disruption of these clock genes leads to broad physiological dysregulation. "Although direct epigenetic measurements in space remain limited in the datasets offered, the literature on circadian disruption consistently documents perturbations in gene networks in response to microgravity and radiation exposure, with downstream metabolic and neural effects" [13].

3.2.3 Model Organisms

Drosophila and mice: Model organisms are used to parse the mechanisms of space-induced circadian disruption. In spaceflight contexts, Drosophila and rodent models help delineate the consequences of gravity and radiation changes on clock gene circuits, neural circuits, and behavior. The camel/polar literature provides broader context about non-photic entrainment and environmental cue processing to compare against canonical photic entrainment in lab models [13]. For instance, in vitro systems or cell-based models serve as platforms for investigating the molecular regulators and the epigenetic modifications that occur under the space condition, thereby complementing whole-animal data.

3.2.4 Implications for Human Space Exploration and Countermeasures

Lighting design and task timing: Countermeasures employing adapted lighting schedules, timed tasks, and circadian-friendly routines are essential to counter circadian disruption and promote alertness, sleep, and performance during protracted missions. Pharmacological modulation: Knowledge of HRV bands and brain network engagement suggests possible pharmacological or chronobiological interventions that might stabilize circadian function or facilitate adaptation to microgravity in particular situations when environmental cues are inconsistent with internal clocks.

3.3 Extreme Terrestrial and Aquatic Species

Extreme temperatures on land and water—from deserts to polar seas, even to deep-sea trenches—foster adaptations to clocks that optimize energy use, predator–prey dynamics, and timing of ecological interactions. The circadian system exhibits both clock plasticity and resilience within these ecological contexts, reflecting the tidal, lunar, and seasonal cycles.

Extreme environments-such as in terrestrial to aquatic ranging from deserts to polar seas to deep-sea trenches-evoke clock adaptations that optimize energy use, predator-prey dynamics, and timing of ecological interactions. The circadian system also shows clock plasticity and resilience in these cases, mirroring high-low cycles of ecologically relevant events such as tides, lunar phases, and seasons.

3.3.1 Environments and clock features

A hot desert is a fitting name for a trained desert mam-

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mal. In desert environments, extreme heat and water parameters impose strong constraints. Desert mammals entrain their locomotor activities by daily ambient cues (Ta cycles) and LD cycles for their energy balance and water economy. Deserts also provide a clear example of the interplay between photoperiodic cues and temperature cycles in determining the timing of daily activity: the Ta cycle acts as a powerful zeitgeber-a central clock input-modulating important outputs like Tb, Mel, and locomotor activity. Such Ta-driven entrainment in the camel, even in the absence of light cues, highlights the clock's plasticity under extreme heat stress and begs the question regarding the role of water conservation strategies [11]. Deep-sea trenches, salt flats, polar seas: In extreme aquatic and high-latitude systems, timing of ecological processes (feeding, predation, reproduction) can be synchronized with tides, lunar cycles, and seasonal resources. Polar marine and aquatic species possess mechanisms to adjust circadian and circannual rhythms to ecological cycles, with peripheral clocks being seasonally regulated to optimize energy utilization and ecological fitness [14].

3.3.2 Features and Adaptations

Modifications in Clock for Energy Use and Predator-prey Interaction: Species are known to tune their clock outputs to energy budgets and the timing of predator-prey encounters. For example, temporal niche switching from diurnal to crepuscular/nocturnal activity in desert ungulates and desert mammals reduces their heat load and water loss while synchronizing activity peaks with resource availability and risk from predators. Ta cycles entrain the central clocks in desert-adapted species, with the modulation of its outputs, such as Tb, Mel, and locomotor activity, optimizing the energy balance [11] Ecological cycles and clock plasticity: The circadian timing system is subject to tidal, lunar, and seasonal cycles in shaping activity and physiology in aquatic or polar species. Flexible responses to the variability of environment, therefore, support the resilience of the extreme habitat through that plasticity of circadian timing [14].

3.3.3 Implications for Clock Plasticity and Resilience

Clock plasticity: Such extreme environment species demonstrate the fact that the circadian system provides several other models besides photoperiodism. Temperature cycles and tides can, along with ecological rhythms, induce control of central and peripheral clocks with downstream effects on metabolism, behavior, and reproduction.
Resilience: The ability to alter clock timing under different environmental cues confers resilience against changing or variable conditions so that an organism can maintain its homeostasis and ecological fitness in the face of harsh or shifting environments.

4. Conclusion

System circadian differentially flexible mechanisms such as reweighting nonphotonic elements or reallocating molecular flexibility into compensating temporal order that would have otherwise been disordered by such extreme conditions. In this light, when light is unreliable, temperature cycles, feeding and activity schedules, social signals, magnetic inputs and altered gravity will intervene. The mechanistic core of this is epigenetic reprogramming, chromatin remodeling, non-coding RNAs and post-translational modifications that reconfigure CLOCK: BMAL1-PER/CRY dynamics. Cross-species comparisons-from Arctic mammals and polar marine fauna to desert ungulates and space flown humans and model organisms-underline both resilience and limits: peripheral clocks can decouple from central pacemakers; cardiac and neural networks can undergo reorganization; and performance and sleep may break down without properly structured Zeitgeber regimens.
And all these practical and ecological dimensions remain significant with respect to human activity in space and at high latitudes. This structured schedule should include spectrum-tailored-light, temperature, feeding schedule, timed activity combined with hormone support to minimize desynchrony. Among various cycles, such as thermal, tidal, and lunar cycles acknowledged by wildlife, the impact of these cycles on entrainment can be considered in conserving wildlife under warming environments and changing photoperiods. Future research should (1) causally map the epigenetic mechanisms of clock adaptation in vivo across tissues; (2) develop and test nonphotic countermeasures and multi-cue entrainment protocols for long-duration missions; (3) longitudinal, multi-omic studies linking circadian health to metabolic and immune outcomes in extreme environments; and (4) simulate how climate-mediated modifications in thermal and seasonal cues will redefine chronobiology and fitness at the population level.

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