HEALTH · RESEARCH REVIEW

Space Weather's Human Health

A graded review of clinical cosmobiology — the association of geomagnetic storms with cardiovascular events and the weaker evidence for other endpoints. Research awareness only, not medical advice.

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Scope & evidence classes. This report grades each claim it surveys: ESTABLISHED — replicated, broad peer-reviewed consensus · CONTESTED — real evidence, but disputed or mixed · HYPOTHESIS — a proposed mechanism with limited or no confirmation. The signal is strongest for the association of geomagnetic storms with cardiovascular events; most mechanisms and secondary endpoints are weaker, and are graded accordingly. Synthesized from the local research corpus and peer-reviewed sources.

This is research and educational awareness only. It is not medical advice, diagnosis, treatment, prevention, or individual risk prediction. Do not change medication, monitoring, activity, sleep, travel, or treatment plans based on this material. For personal health questions, consult a qualified healthcare professional. For emergency symptoms, use emergency services.

1. Introduction: Clinical Cosmobiology in 2026

The discipline of heliobiology — increasingly formalized as *clinical cosmobiology* — examines whether and how variations in solar and geomagnetic activity influence human physiology. After roughly a century of work since the foundational writings of Tchizhevsky (1924), the most recent peer-reviewed systematic review of the field is (10.1007/s00484-026-03220-6), which catalogued 99 papers indexed in Web of Science and used a hallucination-anchored ChatGPT extraction protocol to characterize what has actually been studied.

Two complementary recent reviews frame the current state: (10.1007/s00484-026-03134-3) — a short mechanism-focused review — and (10.3390/atmos12030346) — a systematic review across physiological systems.

The empirical signal is uneven. are the most studied (~68 of 99 papers in Arnaut 2026 incorporate at least one cardiovascular parameter) and the most consistently positive in

associations with geomagnetic activity. are *under-studied* (only ~13 of 99 papers, 13.1%) and the evidence base is correspondingly thinner. Cosmic-ray and solar-flare effects on health are than geomagnetic storms despite plausible mechanistic relevance. Schumann-resonance effects on health were at all, so the literature behind that section here is curated independently and graded conservatively.

This synthesis presents what is supported, with explicit evidence grades per section, and is honest about what is currently mechanism-only or single-study.

1.1 The Physical Parameters of Space Weather

Heliobiological research uses a small set of standard physical parameters as exposure proxies. Different studies emphasise different ones; Arnaut 2026 found that sunspot number (47 instances), Ap index (41), generic geomagnetic-storm activity (25), Kp index (24), and Dst index (21) dominate, while cosmic rays (15), solar flares (12), and solar-wind velocity (12) are comparatively under-utilised.

— quantified by *Kp* (quasi-logarithmic, 0–9), *Ap* (linear equivalent), and *Dst* (ring-current intensity). Both the amplitude *and* the rate of change (`dB/dt`) of the field are reported as biologically relevant (Maghrabi & Maghrabi 2026).

— modulated inversely by solar activity. Sudden depressions during geomagnetic storms are termed . Singh, Siingh & Singh (2011) (10.1016/j.atmosenv.2011.04.027) review the atmospheric and biological pathways.

— sporadic high-energy proton fluxes from major flares, capable of polar-cap absorption events; correlated with acute neurological and immunological responses in some studies.

— quasi-standing electromagnetic waves in the Earth-ionosphere cavity, fundamental ≈ 7.83 Hz with harmonics ≈ 14, 20, 26, 33 Hz. Solar activity modulates their amplitude and Q-factor.

— direction matters: a southward-pointing *Bz* component allows magnetic reconnection and seeds severe storms; this vector component is often the strongest acute predictor.

A central caveat highlighted by that this report adopts: most of the corpus uses *daily-aggregated* exposure (54 of 99 papers); hourly resolution is rare (8 of 99). Most studies are *single-city* (53 of 99), heavily concentrated in Europe (50) and Asia (15), with only 2 from South America, 3 from Australia, and . Sex stratification is absent from 60.6% of the corpus. Solar parameters are typically applied as across the population, which may produce ecological fallacies. Where this synthesis cites a single study, treat the magnitude as suggestive rather than population-generalisable. Finally, some plausibly-relevant endpoints have only the thinnest literature: respiratory disease (asthma, COPD) has no dedicated space-weather cohort study — only a single children's-asthma conference abstract — so its near-absence is a coverage gap, not a tested negative.

2. Biophysical Mechanisms of Transduction: Beyond the "Thermal Noise" Objection

CONTESTED overall — three candidate mechanisms have real laboratory support that addresses the classical thermal-noise objection, but direct in-vivo human evidence that any one of them is the *operative* pathway during a real storm remains absent. Per sub-mechanism: CONTESTED for biogenic magnetite (§2.1); HYPOTHESIS for the cryptochrome radical-pair mechanism in humans (§2.2); CONTESTED for voltage-gated calcium channels / oxidative stress in cell culture (§2.3).

For decades, the standard objection to heliobiology was the *thermal-noise problem*: the energy delivered by geomagnetic micro-Tesla fluctuations is orders of magnitude below random thermal motion, so cells cannot in principle detect the signal. Three candidate mechanisms address this objection by providing amplification or coupling that bypasses thermal averaging.

2.1 Biogenic Magnetite: Ferromagnetic Transduction

Magnetite (Fe_3O_4) crystals have been identified throughout human brain tissue (, 10.1073/pnas.1605941113). Unlike the diamagnetic and paramagnetic constituents of most tissue, ferromagnetic magnetite has a magnetic moment many orders of magnitude larger and interacts strongly with external fields. When organised in chains and coupled to cytoskeletal elements, magnetite crystals can transduce field changes into mechanical torque on
(Maghrabi & Maghrabi 2026).

The strongest direct human evidence is from a magnetically shielded Faraday-cage study (, 10.1523/eneuro.0483-18.2019) showing reproducible alpha-band (8–13 Hz) EEG desynchronisation under controlled rotations of an Earth-strength field — *polarity-dependent*, ruling out induction (which is polarity-symmetric) and the radical pair mechanism (which is polarity-insensitive). Theoretical sensitivity for chain-organised receptors is on the order of a few nT, consistent with the magnitude of geomagnetic micropulsations (Pc1–Pc5).

2.2 The Radical Pair Mechanism (RPM)

Cryptochromes (CRY) are flavoproteins resident in the retina and circadian pacemakers. Following blue-light absorption they form a spatially separated *radical pair* whose singlet/triplet ratio depends on the angle and intensity of the ambient magnetic field. (10.4081/dr.2012.e4) propose that geomagnetic-storm stress responses may be mediated through the cryptochrome compass system.

Human cryptochrome (hCRY2) restores magnetic-field sensitivity in transgenic *Drosophila*, demonstrating that the molecular hardware is preserved in humans, but
. Treat this as a plausible mechanism, not a demonstrated one. Because cryptochromes are integral to the BMAL1 / PER2 / CRY1 circadian feedback

loop, RPM-mediated disturbance is the leading mechanistic candidate for the observed circadian effects (§5.1).

Two recent reviews bracket the current consensus. Zadeh-Haghighi & Simon (2022) (10.1098/rsif.2022.0325) survey the breadth of magnetic-field effects across biology that are consistent with a radical-pair origin and argue the mechanism is broadly plausible. Against this, Zhang & Malkemper (2023) (10.3389/fphys.2023.1250798) caution that *mammalian* cryptochromes are most likely light-independent — estimating that less than 7% of human CRY2 and 16% of CRY1 carry the FAD cofactor required for photo-induced radical-pair chemistry — so a bird-style light-driven magnetosensor is and may, in their framing, be "a possibility or misconception." The honest position for humans remains: hardware plausibly present, in-vivo operation unproven.

2.3 Voltage-Gated Calcium Channels (VGCC) and the Oxidative-Stress Cascade

Weak magnetic fields can perturb the flow of Ca^{2+} across cell membranes via L-type VGCCs. The detailed physics is debated (ion-cyclotron resonance, Larmor precession on the hydration shell), but the *outcome* is robustly observed in cell culture: an increase in intracellular Ca^{2+} (1.5×–3.5× baseline in skeletal muscle and mesenchymal stem cells exposed to fields slightly stronger than ambient geomagnetic levels). Ca^{2+} is a universal second messenger; sustained elevation activates nitric-oxide synthase, raising NO, which combines with superoxide to form peroxynitrite — i.e., . This connects field exposure to inflammation, vascular dysfunction, and altered metabolism in a model that does not require specialised receptors — though whether it operates at true geomagnetic field strengths in vivo remains HYPOTHESIS.

3. The Cardiovascular System: The Best-Evidenced Target

ESTABLISHED for the population-level association of geomagnetic storms with myocardial infarction (MI), acute coronary syndrome (ACS), and stroke (Gaisenok et al. 2025 meta-analysis; Zilli Vieira et al. 2019, 2022 multi-city studies). CONTESTED for heart-rate-variability reduction. HYPOTHESIS for the "blood sludge" hemorheological narrative.

The cardiovascular system is the most consistently affected target across the heliobiological corpus, which is plausibly mediated through autonomic regulation (the autonomic nervous system being the body's primary environmental-adaptation interface).

A 2025 scoping review (Belenko, Cancel & Mayrovitz, 10.7759/cureus.99851) frames the field state honestly: of 36 cardiovascular studies included from 1,718 screened (1964–2023), with geomagnetic or space-weather activity and — a predominantly, but not unanimously, positive literature, much of it ecological in design. That split (roughly 3.5:1 positive) is the fair summary of where cardiovascular heliobiology stands.

3.1 Heart Rate Variability (HRV) as a Prognostic Biomarker

CONTESTED — multiple cohorts show HRV reductions on geomagnetically active days, but the smaller studies weaken once serial autocorrelation is controlled. HRV — the variation in time intervals between consecutive heartbeats — is a widely accepted measure of autonomic balance. High HRV indicates a flexible, vagally-toned system; low HRV is associated with rigidity, sympathetic dominance, and excess mortality.

(Boston, n = 809 elderly men, 16-year follow-up) — Zilli Vieira et al. (2019) (10.1186/s12940-019-0516-0) and the 2022 update (10.1016/j.scitotenv.2022.157286) — show statistically significant reductions in SDNN and HF-power HRV indices on days with elevated Kp. HF power tracks parasympathetic (vagal) tone; its withdrawal during storms is consistent with the autonomic-stress framing.

(10.1007/s00421-020-04369-7) — n = 19, 30-day daily-monitored design — corroborates HRV reductions on geomagnetically active days at smaller scale, but the authors also caution that several associations weaken once serial autocorrelation is accounted for — a reminder that much of this literature lacks rigorous multiple-comparison control.

(10.1038/s41598-018-20932-x) — long-term HRV monitoring across the solar cycle — finds HRV responses tracking solar / geomagnetic environment, supporting the chronicity claim rather than a strictly acute response.

: effects are typically observed within 24 h of the geomagnetic disturbance, with persistent reduction across multi-day storm periods.

3.2 Myocardial Infarction, Acute Coronary Syndrome, and Stroke

ESTABLISHED — this is the field's strongest claim, surviving systematic review and meta-analysis. The 2025 systematic review and meta-analysis of in *Journal of Medical Physics* (10.4103/jmp.jmp_122_24; also at PMC12005662) is the current canonical quantitative summary:

: mean Relative Risk (30–50% increase) on geomagnetic storm days versus quiet baseline.

: mean Relative Risk .

Meta-analysis was over 6 included studies after PubMed screening (March 2023, 644 articles initially). The authors note small-study heterogeneity as the principal limitation.

The earlier multi-country population study by (10.1161/STROKEAHA.113.004577) covered Australia, France, Sweden, and the UK (n = 11,453). Severe storms (Ap ≥ 60) were associated with a 19% increased stroke risk overall, with the (>50% increase). This counter-intuitive age skew is hypothesised to reflect higher autonomic reactivity in younger subjects.

Sex-stratified data are beginning to qualify the population-level figures. (10.1038/s43856-025-00887-7), analysing 1,340 myocardial-infarction admissions in São José dos Campos, Brazil (1998–2005), report that the male-to-female admission ratio fell from 1.98× on geomagnetically quiet days to 1.22× on disturbed days, with the MI occurrence rate among women roughly *doubling* under disturbed conditions in both the 31–60 (11.2% vs 7.1%) and over-60 (13.5% vs 9%) age bands. These are *descriptive relative frequencies, not modelled risk ratios* — the authors deliberately avoid a significance-tested model and caution that a single mid-size city is not conclusive — but the direction suggests women may carry a larger share of the storm-associated MI excess than the sex-undifferentiated meta-analytic figures imply.

Population-level mortality evidence comes from , which found enhanced total and cardiovascular mortality across during geomagnetically disturbed periods. (10.1007/s11356-016-7056-8) reports analogous heart-disease morbidity and mortality associations with helio-geophysical factors.

(10.33069/cim.2024.0001) explicitly examines the *combined* influence of local atmospheric conditions and space weather on chrono-periodic systems in cardiovascular pathology — relevant because pure geomagnetic-only models can be confounded by air-pollution and pressure covariates that fluctuate in parallel.

(Indian Pacing Electrophysiol J PMC1501097) reviews specifically cardiac arrhythmia and geomagnetic activity — sudden cardiac death and life-threatening arrhythmias are over-represented on geomagnetically active days in multiple cohorts.

3.3 Blood Pressure and Microcirculation

CONTESTED — review-level and cohort evidence supports systolic/diastolic elevations during geomagnetic disturbance, but the hemorheological "sludging" narrative is HYPOTHESIS.

in *Cureus* (10.7759/cureus.45637) reviews the blood-pressure literature and concludes there is moderate, mechanism-supported evidence for systolic and diastolic elevations during geomagnetic disturbance, mediated by sympathetic activation, endothelial dysfunction, and changes in baroreflex sensitivity.

A direct cohort signal beyond the review level comes from (10.1161/jaha.120.021006) in the *Journal of the American Heart Association*: across 675 elderly men of the Normative Aging Study (1,949 blood-pressure measurements, Boston, 2000–2017), higher solar and geomagnetic activity was associated with elevated systolic and diastolic blood pressure. As with the HRV (§3.1), endothelial (§3.4), and cognition (§4.5) findings, this is the same NAS cohort — corroborating, not an independent replication.

Older hemorheological reports describe rouleaux formation (red-cell stacking), increased viscosity, and capillary "sludging" during storms, particularly in patients with ischemic heart disease. Modern replications are sparse; treat the hemorheology framing as HYPOTHESIS until updated data is available.

3.4 Endothelial Activation and Inflammatory Markers

CONTESTED — a human in-vivo molecular bridge between geomagnetic exposure and the cardiovascular endpoints above comes from (10.1371/journal.pone.0268700), working in the VA Normative Aging Study cohort (742 older men, 2,273 visits, 2000–2017). Using 28-day moving-average exposures, a one-IQR increase in interplanetary-magnetic-field strength was associated with a and a — endothelial adhesion molecules that mark vascular activation — while sunspot number tracked smaller C-reactive-protein increases. C-reactive protein was *not* significantly associated with Kp or IMF and one fibrinogen–Kp coefficient ran weakly negative, so the picture is endothelial activation more than a uniform inflammatory surge. Because this is the same cohort and overlapping authorship as the HRV (§3.1) and cognition (§4.5) findings, it is corroborating mechanism rather than an independent replication.

3.5 Diabetes and Metabolic Effect-Modification

HYPOTHESIS — single-city, single-solar-maximum evidence. Pre-existing metabolic disease appears to amplify space-weather cardiovascular risk. (10.1007/s00484-016-1200-5), studying 1,548 acute-coronary-syndrome patients in Kaunas, Lithuania (2000–2003), found that on high-speed-solar-wind days the ACS risk in patients with diabetes rose roughly two-fold (OR 1.95, 95% CI 1.36–2.79) versus quiet days, with further elevation when storms coincided with high-speed streams (OR 2.31, 1.28–4.17) or solar proton events (OR 2.72, 1.09–6.83); metabolic syndrome showed a parallel, smaller effect. The authors title it a "*possible* association," and it rests on one cohort — but it is consistent with the recurring theme that destabilised physiology (here glucose dysregulation and its vascular sequelae) is the susceptible substrate.

4. The Nervous System and Psychopathology

CONTESTED for population correlations between Kp and suicide, and for psychiatric admissions (with caveats). HYPOTHESIS for Schumann–EEG / HRV synchronisation (limited cohort sizes), cognitive-performance effects in routine populations, and the human geomagnetic–seizure link. Arnaut 2026 explicitly identifies psychological-state research as — only ~13% of the corpus.

4.1 Suicide and Psychiatric Endpoints

CONTESTED — population correlations exist across several countries with sex-specific patterns, but designs are largely ecological.

(10.1002/bem.20190) — the most-cited paper on geomagnetic-suicide associations — reports a positive correlation between storm activity and suicide rates in Australian data, with sex-specific patterns.

(10.3390/ijerph17061998) — Taiwan suicide attempts 1997–2013, cross-sectional design — finds male suicide-attempt rates correlated with Kp, cosmic-ray flux, and temperature,

while female rates also correlate with the F10.7 solar-flux index.

The proposed mechanism is melatonin-serotonin axis disruption (§5.1), with the storm acting as a *threshold* trigger in already-vulnerable individuals rather than as a primary cause.

Evidence on ordinary depression hospital admissions is mixed; (10.1016/j.mehy.2009.01.047) reports an association with dream bizarreness, illustrating the broader subclinical signal that may underlie the threshold-trigger model.

A distinct — and comparatively strong — mood signal comes from solar *insolation* rather than geomagnetic storms. The Bauer / ChronoRecord consortium reports, across 4,037 bipolar-I patients at 36 sites in 23 countries (, 10.1016/j.jad.2014.05.032), that greater springtime solar insolation predicts an *earlier* age of onset, and in a larger 7,488-patient successor at 75 sites in 42 countries (, 10.1016/j.jpsychores.2022.110982) that a larger annual *swing* in insolation predicts a depressive rather than manic first episode (β = −1.109, Exp(β) = 0.330, P < 0.001). These are the same consortium lineage (not independent cohorts) and concern the slow solar/seasonal light environment rather than acute storms — but they are among the largest multi-national datasets in the entire field.

4.2 Migraine and Headache

CONTESTED — the two best studies disagree in a reconcilable way. (10.1038/srep39769) examined ~63 million Twitter messages for migraine and headache mentions against solar-eruption timing and reported at the 24-hour resolution achievable from social-media data. Earlier, in-clinic studies (Kuritzky et al. 1987, 10.1111/j.1526-4610.1987.hed2702087.x) reported that *severity* (not *frequency*) of migraine attacks rose with geomagnetic activity. The two findings are reconcilable if storms shift the severity distribution of headaches that would have happened anyway.

For wellness-app advisory purposes the practical signal is: a Kp ≥ 5 sustained event is associated with a meaningful *severity* uplift in migraine-prone individuals, but not a population-wide rise in incidence.

4.3 Epilepsy and Seizure Thresholds

HYPOTHESIS — a strong laboratory effect in rats that does not translate cleanly to human epidemiology.

(10.1007/s00484-004-0234-2) — controlled-laboratory experiments on epileptic rats exposed to nocturnal magnetic-field changes shaped to mimic geomagnetic storms — show elevated seizure incidence and mortality in the exposure groups. Pro-convulsant effects of magnetic *variability* (not absolute level) are the consistent finding.

In humans, the evidence is more mixed: some clinical series report fewer seizures on bright sunny days (high steady solar irradiance — possibly via vitamin-D / melatonin), while others report increased seizures during disturbed magnetic conditions. The interpretation that *steady* high solar activity is protective and *unstable* magnetic disturbance is provocative is consistent across the available data but not yet definitive.

A 2023 prospective human study points the other way: (10.1016/j.eplepsyres.2023.107164) tracked 431 seizures in Zagreb over 2020–2021 and concluded that "local geomagnetic activity had no direct effect on the occurrence of epileptic seizures" (the K-index distribution during seizures tracked the quiet background at r = 0.998), though the site's geomagnetic range was limited (K < 4 some 93% of the time). The human geomagnetic–seizure signal, where present, is weak and not consistently reproduced; Persinger's strong *laboratory* effect in rats has not translated cleanly to human epidemiology.

4.4 Schumann Resonances and Brainwave/HRV Synchronisation

HYPOTHESIS — the strongest study is a 10-participant cohort; larger replication is absent. The Schumann fundamental ≈ 7.83 Hz overlaps with human alpha/theta EEG bands; the harmonics overlap with beta and gamma. The strongest published evidence for human-Schumann coupling is (10.3390/ijerph14070770) — *Synchronization of Human Autonomic Nervous System Rhythms with Geomagnetic Activity in Human Subjects* — which monitored 10 participants across 31 days in geographically separated locations and reported HRV-rhythm synchronisation with Schumann time-varying magnetic fields. Cohort size (n = 10) is a real limitation; the result is suggestive, not conclusive.

The earlier mechanism review (10.1023/A:1015637127504 — *Natural Hazards* 26:279–331) proposed that SR exposure modulates pineal melatonin secretion and that the SR signal serves as a biological reference frequency. This remains the most-cited mechanism-side paper but is not itself a clinical trial.

The cited a non-peer-reviewed commercial bioresonance vendor for Schumann-HRV claims; that citation has been removed. Treat Schumann effects on health as HYPOTHESIS until larger replicated cohorts are reported. Schumann is *not* in the search-term list of Arnaut 2026's systematic review, so its absence from that review's findings should not be mistaken for negative evidence.

4.5 Cognitive Performance

HYPOTHESIS — a single cohort with a mixed-direction signal. (10.1016/j.envint.2024.108666) add a cognition limb from the Normative Aging Study: a one-IQR increase in same-day sunspot number and Kp index was associated with , respectively, of a low Mini-Mental State Examination score, with a parallel decline in backward digit span (−0.08 SD). The effect was heterogeneous across tests — a global composite score even rose slightly with sunspot number — so this is a single-cohort, mixed-direction signal, sharing the NAS cohort (and overlapping authorship) with §3.1 and §3.4 rather than independently replicating them.

5. Endocrine and Molecular Responses

CONTESTED for melatonin suppression during geomagnetic storms (multiple cohorts, consistent direction). HYPOTHESIS for the broader "geomagnetic transcriptome" claim (mostly cell-culture or spaceflight-confounded by microgravity).

5.1 Melatonin and the ”False Light” Signal

CONTESTED — repeatedly observed across several cohorts, with a coherent mechanism, but in-vivo causation remains debated. The pineal gland's nocturnal melatonin secretion is repeatedly observed to be reduced or phase-shifted on geomagnetically disturbed days. The proposed pathway is that magnetic field fluctuations are perceived by the retina (cryptochrome RPM) or directly by the pineal as a quasi-light signal, inhibiting N-acetyltransferase (the rate-limiting enzyme for melatonin synthesis). Because melatonin is also a powerful antioxidant, oncostatic agent, immune regulator, and *cardioprotective* hormone, suppression during storms has knock-on effects across the systems described in §3 and §4.

The Burch, Reif & Yost (1999) (10.1016/S0304-3940(99)00308-0) study of electric-utility workers (peak 6-OHMS reductions on days when 36-hour Ak or aa exceeded 30 nT, with the strongest reductions when GMA was paired with elevated 60 Hz field exposure or low ambient light) is the operative mechanism citation; a follow-up by the same group (, 10.1016/j.neulet.2008.04.031) reports the same direction of effect on melatonin-metabolite excretion, corroborating the 1999 finding. Effect timing was 15–33 hours from exposure to peak suppression — this informs the lag structure on the app's sleep-disruption awareness notice.

5.2 Geomagnetic Transcriptome

HYPOTHESIS — Extremely Low Frequency (ELF) magnetic fields can entrain the expression of core circadian-clock genes (*BMAL1*, *PER2*, *CRY1*) in cell-culture and animal models, supporting the framing of magnetic exposure as a *Zeitgeber* that competes with the photic light/dark cycle. In spaceflight gene-expression studies, NF-κB and miR-21 changes indicate a generalised cellular stress response — but spaceflight is confounded by microgravity and altered radiation environment, and ground-based magnetic-only studies remain limited in cohort size. (10.1002/bem.22062) reviews the candidate biological mechanisms linking geomagnetic activity to physiology — circadian, developmental, and stress pathways among them — and underscores how few have been confirmed in controlled human studies.

5.3 Reproductive Outcomes

HYPOTHESIS — a real but minor single-centre signal. The reproductive literature is thin but not empty. (10.1515/jbcpp.2007.18.2.149), analysing 1,006 very-low-birth-weight infants over 96 months in Israel (1995–2002), found the monthly count of preterm births correlated *positively* with solar-activity indices ($r = 0.32$, $p = 0.0016$) and *inversely* with cosmic-ray activity ($r = -0.3$, $p = 0.008$);

the association held for singleton but not multiple pregnancies, and geomagnetic indices were largely non-significant. With effect sizes around $|r| \approx 0.3$ from a single centre, this is mechanistically tentative — plausibly mediated by the melatonin disruption of §5.1 — but a real, if minor, signal worth recording rather than omitting.

6. Critical Variables and Modifiers

CONTESTED — effects are *not* uniform across sex, latitude, and pre-existing disease status; the direction of bias depends on the system and is not fully consistent across studies. A useful framing here is the : the relationship between geomagnetic activity and physiological strain is not simply monotonic. Reviews of the broader solar/geomagnetic-health literature (, 10.1007/s10712-006-9010-7) have argued for a response in which *extremely quiet* geomagnetic conditions can also be adverse, not only storms, and estimate that on the order of 10–15% of the population is physiologically predisposed to react at all — the rest being largely insensitive. This shape is the rationale for treating both the disturbed and the very-quiet ends of the geomagnetic range as worth flagging for susceptible individuals.

6.1 Sex Dimorphism

Sex stratification is missing from 60.6% of Arnaut 2026's reviewed corpus, so claims here are based on the minority of papers that *do* stratify.

: women appear more sensitive to geomagnetic effects in several cohorts; sex-specific Kp + F10.7 correlation in Tsai 2020.

: men, particularly over 40, often show stronger associations with circulatory mortality in specific storm types; post-menopausal women also show significant correlations during severe events.

: estrogen-modulated autonomic and neuroprotective tone interacting with the melatonin/serotonin disruption; vulnerability windows differ between sexes.

6.2 Latitude

High-latitude regions (Scandinavia, Canada, Russia) experience the largest storm-day geomagnetic excursions due to the auroral oval. Studies based in those regions report stronger correlations than equatorial-latitude studies. Local crustal magnetic anomalies may also modulate response but are less well-studied.

6.3 Age and Pre-existing Health Status

The dominant pattern is that *unstable organisms* are the primary target. Healthy individuals with high HRV typically adapt to a storm without symptomatology. Patients with ischemic heart disease, hypertension, depression, epilepsy, or migraine — those operating near a physiological boundary — are

pushed across it. The Normative Aging Study cohort was selected for elderly men precisely because of reduced homeostatic reserve.

The Vencloviene/Feigin et al. (2014) finding of *stronger* effects in subjects under 65 is the principal exception and suggests that autonomic *reactivity* may sometimes outweigh homeostatic *reserve* as the dominant susceptibility factor for stroke.

7. Cosmic Rays, Radiation Exposure, and Methodological Considerations

HYPOTHESIS for direct cosmic-ray/Forbush effects on cardiovascular endpoints — mechanism plausible (Singh, Siingh & Singh 2011) but population-level epidemiology is sparse compared to geomagnetic-storm studies.

7.1 Cosmic Rays and Forbush Decreases

HYPOTHESIS — Galactic cosmic rays (GCR) reach Earth modulated by solar activity; the heliosphere expands during high solar activity and shields Earth more effectively, depressing GCR flux.
are sudden ~24–48-hour drops in cosmic-ray flux during the passage of a coronal mass ejection. Some authors have proposed that Forbush events may have cardiovascular effects independent of (or stronger than) the parallel geomagnetic storm.
(10.1016/j.atmosenv.2011.04.027) review the proposed atmospheric-ionisation and biophysical pathways.

The strongest population evidence for cosmic-ray correlations is currently in
rather than incidence — Zilli Vieira et al. (2019) include neutron-monitor data as a covariate alongside geomagnetic indices. A direct physiological study exists at smaller scale:
(10.3390/atmos15020158), using Athens neutron-monitor data across solar cycle 24, report measurable heart-rate responses to combined geomagnetic and cosmic-ray activity. But a cohort-level meta-analysis of Forbush-decrease cardiovascular triggering specifically is
; it remains a research priority for clinical cosmobiology going forward.

7.2 Occupational and Spaceflight Radiation: Aircrew and Astronauts

HYPOTHESIS — and, on current evidence, leaning toward a null. Beyond storm-day effects on the ground, the occupational space-radiation literature carries a genuine, unresolved controversy worth presenting honestly. (10.1038/srep29901) reported that proportional cardiovascular-disease mortality among the seven deceased Apollo lunar astronauts (43%) was four-to-five times that of non-flight (9%) and low-Earth-orbit (11%) astronauts, proposing deep-space-radiation damage to the vascular endothelium. The finding .
(10.3357/amhp.4757.2017), applying age- and follow-up-adjusted cohort / standardised-mortality methods to the same astronauts, found no significant lunar-versus-non-lunar CVD difference (SMR 117, 95% CI 24–343) and attributed Delp's signal to age-structure and competing-risks confounding;
(10.1038/s41598-018-25467-9), analysing radiation dose directly in 73 early astronauts,

likewise found no significant dose–CVD association (all dose trends negative) — while themselves cautioning that statistical power was below 6%. The honest reading: Apollo-era cohorts are too small to settle whether deep-space radiation harms the cardiovascular system, and the widely-quoted 4–5× figure should never be cited without its non-replication. For aircrew, the large cosmic-radiation cancer-cohort literature is predominantly *null* at occupational dose levels — relevant context for the app's ground-level-event awareness notice, which flags the rare events most relevant to flight crews and astronauts.

7.3 Hypomagnetic-Field Biology

HYPOTHESIS — strong animal evidence, scarce human data, relevant to deep-space flight rather than terrestrial space weather. A distinct frontier concerns the *absence* of a magnetic field rather than its disturbance — the hypomagnetic environment of deep space beyond Earth's magnetosphere. In male mice, (10.1038/s41467-021-21468-x) showed that prolonged hypomagnetic exposure (~190× below geomagnetic strength) impaired adult hippocampal neurogenesis and learning, with the deficit driven by a *reduction* in endogenous reactive oxygen species — reversible either by restoring ROS pharmacologically or by returning the animals to a normal field. A 2024 *National Science Review* perspective (, 10.1093/nsr/nwae395) argues that hypomagnetic exposure (< 5 μT) is a significant but routinely under-estimated deep-space health risk, citing the animal neurogenesis findings and one human study in which 45 minutes of exposure raised average task-completion time by ~1.5%. Direct human data remain scarce — but the frontier completes the picture of the geomagnetic field as a biologically relevant variable across its full range: disturbance at one end, absence at the other.

7.4 Causality, Dosimetry, and the "Daily Aggregates" Limitation

Most human studies are *epidemiological and correlational*. Convergence with cell-culture and animal-model mechanism work strengthens the causal argument, and the absence of meaningful nocebo effects in unconscious-subject studies (sleeping subjects, animals, cells) further supports a real physical interaction.

A major methodological limitation, raised explicitly by Arnaut 2026: most studies use exposure (Kp daily mean, daily mortality counts) and apply solar parameters as exposure proxies across the population. This approach is vulnerable to:

— population-level associations need not hold at the individual level.

— a sub-daily storm impulse may not register in a daily mean.

— daily-aggregated atmospheric/pollution covariates fluctuate on similar time scales (Hayrapetyan et al. 2024 explicitly addresses this).

The corpus is also uneven by *endpoint*, not just by method: cardiovascular outcomes dominate (~68 of 99 papers in Arnaut 2026), psychological endpoints are thin (~13%), and some plausibly-relevant

systems — respiratory disease above all — have essentially no dedicated study. Those silences are coverage gaps, not tested negatives.

7.5 Research Implications and Awareness Boundaries

The practical translation goal is analogous to heatwave advisories. This synthesis underwrites the wellness-awareness taxonomy in the Carrington app: Kp-thresholded awareness notices for cardiovascular vulnerability, cognition and mood, sleep (with the 15–33-hour melatonin lag), balance, migraine severity, a stroke sub-tier on top of the cardiovascular notices, and a developing cosmic-ray / Forbush-decrease cardiovascular awareness notice in the particle-flux processor. The evidence added in this revision further supports a (§3.5) and an on ground-level events (§7.2) — both framed as awareness for the affected groups, not medical direction.

People living with implantable cardioverter-defibrillators, prior MI/ACS, severe migraine, severe depression, epilepsy, or poorly-controlled diabetes may find it useful to maintain their existing clinician-directed routine and to avoid unusual physical or emotional stress on storm days — the same general advice that applies to any stressor. Aircrew and astronauts experience unfiltered space weather and are an occupational priority. ; they are health-context awareness, and any change to medication, monitoring, or activity belongs with a qualified clinician.

8. Conclusion

Heliogeophysical influence on human physiology is a peer-reviewed scientific topic, not a fringe speculation, and the best-evidenced effects — geomagnetic storm associations with myocardial infarction, acute coronary syndrome, and stroke (Gaisenok et al. 2025 meta-analysis, RR ≈ 1.3–1.6) — survive systematic review and are graded ESTABLISHED here. Mechanism candidates (biogenic magnetite ferromagnetic transduction, cryptochrome radical-pair quantum biology, voltage-gated calcium channels with downstream oxidative stress) have converged enough to refute the historical thermal-noise objection, though their in-vivo operation during real storms remains CONTESTED.

What is *not* strongly supported, and is presented honestly here as HYPOTHESIS, includes: direct human in-vivo evidence of cryptochrome-mediated magnetic transduction (and, per Zhang & Malkemper 2023, the very premise of a light-driven mammalian magnetosensor); large-cohort confirmation of Schumann–EEG/HRV synchronisation; cohort-level Forbush-decrease cardiovascular epidemiology; cohort-confirmed deep-space-radiation cardiovascular harm (the Apollo 4–5× figure does not survive re-analysis); replicated hemorheology effects; a reproducible human geomagnetic–seizure link (Sulentic 2023 is null); and most psychological-state findings (the under-studied minority of the corpus per Arnaut 2026).

The Carrington wellness awareness notices and the *Wellness Current Conditions* page derive from this evidence base, and each notice links back to the peer-reviewed sources that justify it. The conservative reading is the appropriate one: space weather is *one* environmental stressor among many

that interacts with individual physiology in ways that matter most for already-vulnerable people. Healthy people will rarely notice. Vulnerable people may benefit from the awareness.

Limitations & Open Questions

This synthesis is a graded review of an uneven literature. Its main limitations, and the questions that would most move the claims, are:

Most studies use daily-mean exposure applied uniformly across a population (§7.4), so associations are vulnerable to ecological fallacy and exposure misclassification. Sub-daily resolution and individual-level continuous physiological monitoring would most strengthen causal inference.

Several endpoints surfaced or strengthened in recent revisions — diabetic effect-modification (§3.5), reproductive outcomes (§5.3), hypomagnetic-field biology (§7.3), and the cognitive-performance signal (§4.5) — rest on single cohorts and are graded HYPOTHESIS until independently reproduced.

Air pollution, barometric pressure, and temperature fluctuate on the same daily time scales as geomagnetic indices; only a minority of studies (e.g. Hayrapetyan et al. 2024) explicitly control for them.

The corpus is concentrated in Europe and Asia, with no African cohort, and 60.6% of studies do not stratify by sex — so sex- and latitude-dependent claims (§6) rest on a minority of the literature.

Covered but not alert-ready

Several systems are covered in this synthesis but are deliberately turned into wellness awareness notices, because the evidence is mechanism-only, single-study, or human-null. They are documented here so the conservative non-alerting stance is explicit rather than implicit:

— no dedicated space-weather cohort; only a single children's-asthma conference abstract.

— mechanistic plausibility via melatonin immune modulation (§5.1), no human cohort.

(§5.3) — one single-centre signal at $|r| \approx 0.3$.

(§7.3) — animal evidence relevant to deep-space flight, not terrestrial space weather.

(§4.4) — the human coupling evidence is a single 10-participant cohort.

If strong new evidence appears for any of these, the rule (this report first, then any notice) applies: the synthesis is updated with the evidence grade before any awareness notice is added.

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