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South Atlantic Magnetic Anomaly, Space Weather, UV Radiation, and Skin Cancer: A Regional Perspective

Introduction

The South Atlantic Magnetic Anomaly (SAA) is a unique region where Earth's magnetic field is unusually weak, centered over South America. In this area, the planet's protective magnetic shield is diminished, allowing more charged particles from space (cosmic rays and solar particles) to penetrate deeper into the atmosphere [1]. This review examines how the SAA's geomagnetic weakening may influence atmospheric chemistry and ground-level ultraviolet (UV) radiation in Paraguay and neighboring areas, and how these changes could affect human health – particularly the risk of skin cancer. We focus on the physical and chemical mechanisms linking space weather phenomena (solar activity, particle precipitation) to ozone layer dynamics and surface UV levels under the SAA, supported by recent studies and regional data.

The South Atlantic Magnetic Anomaly Over South America

Magnetic field intensity at Earth's surface in 2014 (top) versus 2025 (bottom), from ESA's SWARM measurements. The dark low-intensity patch over South America is the SAA, which has grown in extent and further weakened between 2014 and 2025 [2].

The SAA is defined as the region where Earth's inner Van Allen radiation belt comes closest to the surface (dipping down to ~200 km altitude), resulting in a locally increased flux of energetic charged particles [1]. Geographically, the SAA currently spans a large part of South America, including Paraguay, Brazil, Argentina, and Uruguay [3]. In this zone the magnetic field intensity is lowest – on the order of 22,000–28,000 nT, compared to >30,000 nT elsewhere – meaning the geomagnetic shielding against cosmic radiation is significantly weaker [4] [5]. Notably, the SAA has been expanding and drifting westward over time [5], exposing new areas to its influence. This weak-field anomaly effectively creates a "hole" in our magnetic defense, making the upper atmosphere above these regions a natural target for space weather effects that are usually confined to higher latitudes or altitudes.

Under normal conditions, Earth's magnetosphere deflects or traps many incoming charged particles, and most solar energetic particles primarily impact the polar atmospheres. However, in the SAA, the depressed field allows portions of the inner radiation belt and solar wind particles to penetrate unusually low in altitude at mid-latitudes [6] [7]. Satellites and the International Space Station crossing the SAA report intensified radiation exposure and upsets to electronics [1]. The SAA is therefore closely monitored by agencies like NASA as it evolves [8] [5]. This regional magnetic weakening provides a natural laboratory for studying how increased space radiation can affect the atmosphere and surface environment in populated areas.

Space Weather and Particle Precipitation in the SAA Region

Solar Activity and Energetic Particles: During episodes of intense solar activity – such as solar flares and coronal mass ejections – bursts of high-energy protons and electrons (solar energetic particles, or SEPs) can stream toward Earth. Normally, Earth's magnetic field funnels many of these particles toward the poles. But the weak field over the SAA means that some energetic particles from the Sun or trapped in the Van Allen belts can precipitate over low-latitude South America [9] [10]. Researchers have observed that major geomagnetic storms can trigger *aurora-like* effects in the SAA region's atmosphere, despite its low latitude [11] [12]. For instance, the extreme geomagnetic storm of May 10–11, 2024 caused enhanced particle precipitation into the SAA, with satellites detecting injections of energetic protons into the inner radiation belt over South America [13]. This resulted in a surge of ionization in the upper atmosphere above the SAA during the storm's peak [14].

Increased Ionization and Atmospheric Chemistry: When these energetic particles penetrate the atmosphere, they ionize atmospheric molecules and dissociate chemical bonds. In the SAA region, enhanced fluxes of electrons and protons have been shown to significantly raise ionization rates in the mesosphere and stratosphere [14]. Crucially, this particle precipitation initiates the formation of **odd nitrogen (NO_x) and odd hydrogen (HO_x) species** through reactions triggered in the upper and middle atmosphere [15]. NO_x and HO_x are well-known catalytic agents for ozone destruction. Studies comparing conditions inside and outside the SAA during geomagnetic disturbances found clear evidence of elevated electron densities and extra ionization over the SAA, consistent with an influx of charged particles [14] [12]. These effects resemble those typically seen in the polar auroral zones during solar storms, now observed at an unusual latitude (around 20–30°S) because of the SAA's weak magnetic shielding [16] [17].

It is important to note that under quiet solar conditions, the SAA's impact on radiation levels in the lower atmosphere is relatively minor. Comprehensive measurements at commercial flight altitudes (~13 km) during solar minimum found **no significant increase in cosmic radiation dose** when flying through the SAA, compared to equivalent flights elsewhere [18]. In other words, the "background" galactic cosmic ray exposure at aircraft and ground level is governed more by atmospheric depth and latitude than by the SAA. The major effects of the SAA emerge during *space weather events* – when magnetospheric disturbances dump particles into the atmosphere. During such events, the SAA acts as a conduit for extra radiation at altitudes that matter for chemistry, as described next.

Ozone Depletion Mechanisms Under the SAA

One of the most critical implications of increased particle precipitation is its impact on the ozone layer. The stratospheric ozone layer (roughly 15–35 km altitude) is Earth's natural UV shield, absorbing most incoming UV-B and all UV-C from sunlight. However, ozone is vulnerable to chemical destruction by certain reactive species. Enhanced ionization from energetic particles leads to the production of NO_x (primarily nitric oxide, NO, and nitrogen dioxide, NO₂) and HO_x (hydroxyl radical OH and related species) in the upper atmosphere [15] [19]. These molecules can catalytically destroy ozone (O₃) through well-known reactions: for example, NO can react with O₃ to form NO₂ and O₂, and OH can react with O₃ to form water and O₂. A single NO or OH radical can destroy many ozone molecules in a chain reaction before being sequestered, thus even a modest increase in NO_x/HO_x can deplete ozone locally.

Over the SAA, recent observations have confirmed that geomagnetic storms can induce measurable ozone losses. **During the May 2024 extreme storm, satellites observed an abrupt ozone depletion**

in the mesosphere above the SAA region, coincident with spikes in precipitating electron fluxes in the inner belt [14] [17]. Model analyses indicate that ozone in both the mesosphere and upper stratosphere was reduced over South America as a result of the energetic particle precipitation (EPP) during the storm's main phase [14]. This mirrors phenomena previously documented in polar regions, where solar proton events and auroral electrons have caused short-term ozone thinning in the middle atmosphere. The key difference in the SAA is that such effects occur at **much lower latitudes** – directly over populated areas – rather than being confined near the poles.

The efficiency of translating upper-atmospheric ionization into stratospheric ozone loss can depend on atmospheric dynamics. In the polar regions, NO_x produced in the mesosphere during winter can be transported down into the stratosphere by the polar night jet, causing ozone depletion that persists into spring. In the SAA region (low latitudes), vertical transport is less efficient; consequently, a portion of the NO_x/HO_x may not reach the lower stratosphere before being destroyed [20]. Nonetheless, studies have noted that even **minor stratospheric ozone decreases** were detected over SAA longitudes after major solar proton events [21]. These findings align with a broader hypothesis that mesospheric ozone depletion events may cluster over the SAA due to its geomagnetic vulnerability [10]. In essence, the SAA allows what is normally a high-latitude space weather effect to imprint itself on the ozone layer in the subtropical Southern Hemisphere.

Beyond episodic events, the gradual weakening of Earth's magnetic field (about 5% per century globally, and faster in the SAA) could have a cumulative influence. If the geomagnetic field continues to weaken, more cosmic and solar particles will penetrate the atmosphere at all latitudes [22]. An extreme scenario is a geomagnetic reversal or excursion (when the field is very weak or multipolar): *model simulations indicate that under such weak-field conditions, a large solar particle storm could deplete the ozone layer globally and dramatically increase surface UV radiation* [22] [23]. While such extreme cases are rare (millennia apart), the SAA can be viewed as a localized preview – a place where even under today's field strength, we see amplified impacts of space weather on ozone. Some researchers have suggested that the ongoing expansion of the SAA might already be contributing to climate and atmospheric changes, by triggering ozone disruptions and stratospheric temperature anomalies that could affect circulation [9] [10]. These ideas remain active areas of investigation, but the fundamental link between geomagnetic weakening, particle precipitation, and ozone chemistry is grounded in the observations above.

UV Radiation at the Surface in Paraguay and the SAA Region

If the ozone layer thins, more ultraviolet radiation – especially UV-B (280–315 nm wavelength) – will reach the surface. UV-B is the portion of sunlight most responsible for sunburn and DNA damage in living tissues, and it is normally filtered by ozone. In Paraguay and surrounding countries under the SAA, ground-level UV has long been high even under normal conditions due to the tropical latitude and seasonally clear skies. In fact, many locations in South America routinely experience **extreme** UV Index values (>11) for much of the year [24] [25]. For example, measurements in Asunción (Paraguay, ~25°S) and São Paulo (Brazil, ~23.5°S) often record midday UVI in the teens [24], indicating very high ambient UV. At high elevations in Bolivia and northern Chile (15°–22°S), UVI values above 20 have been observed [26], and the world-record UVI of 43 was measured atop a Bolivian mountain [27]. These extreme values were historically attributed to altitude, clear skies, and in some cases proximity to the edge of the Antarctic ozone hole in spring. The question is whether the SAA's effects on ozone are already measurably enhancing surface UV beyond this natural high baseline.

Direct ground measurements focused on the SAA region are still relatively sparse, but there are intriguing indications. In 2025, researchers in Paraguay conducted a dedicated study to measure the full spectrum of solar UV (UV-A, UV-B, and UV-C) in the SAA zone [28]. They developed a specialized optical receiver and spectrometer system to detect even the shorter UV wavelengths. **Their measurements confirmed the presence of UV-B and even UV-C radiation at ground level in the Paraguayan SAA region** [29] **.** UV-C (<280 nm) is normally completely absorbed by the ozone layer and should be virtually zero at Earth's surface. Detecting any UV-C suggests an unusual transparency of the atmosphere at those wavelengths, likely due to ozone deficits. It's possible that momentary ozone thinning (for instance, during a solar storm or due to chronically lower ozone column over the SAA) allowed trace amounts of UV-C to reach the ground [29]. While the intensity of this UV-C is undoubtedly very low compared to UV-A/B, its mere detection is a sign of a perturbed UV shielding. The same study also performed nighttime measurements looking for atmospheric glow from recombining ionospheric ions, reflecting the ionization conditions in the upper atmosphere [29].

Satellite data and surface UV networks can also be examined for regional anomalies. A long-term analysis (45 years) of total ozone over southeastern South America showed that ozone levels have largely followed global trends (depletion in the 1980s–90s and slow recovery post-2000) [30]. The average total ozone column in the subtropics of South America is about 260–300 Dobson Units, which is comparable to other subtropical regions [31]. This suggests there isn't a large persistent "ozone hole" over the SAA – any SAA-related ozone dips may be subtle or transient. However, short-term anomaly studies have noted that on rare occasions, **mid-latitude South America sees sudden drops in ozone** (and spikes in UV) when stratospheric conditions align, such as the November 2009 incident over the Southern Cone [32]. The SAA's role in such cases is not yet clear, but improved monitoring could identify whether space weather contributes to these anomalies.

In summary, Paraguay and the broader SAA-influenced region already face very high solar UV exposure as a baseline. Any additional increase in UV-B due to ozone depletion aloft would further elevate the risk to the population. Given that **observations have linked SAA geomagnetic disturbances to ozone loss aloft and even the leakage of UV-C to the surface** [14] [29], it is plausible that the SAA exacerbates surface UV levels during certain periods. Continued UV monitoring in SAA-affected areas is warranted to quantify this effect. Notably, a recent European-backed project (EURAMET BIOSPHERE) has established campaigns to measure cosmic radiation, total ozone, and surface UV concurrently [33]. Such efforts will help disentangle natural UV variability from any space-weather-induced spikes.

Human Health Implications: Skin Cancer Risk and Other Effects

Ultraviolet radiation is a well-established environmental carcinogen. Excessive UV-B exposure induces DNA damage in skin cells (particularly the formation of thymine dimers), overwhelming the body's ability to repair genetic damage. Over time, this leads to mutations that cause skin cancers – including basal cell carcinoma, squamous cell carcinoma, and melanoma. Epidemiological studies show a clear dose-response relationship between cumulative UV exposure and skin cancer incidence [34]. In light-skinned populations, the highest skin cancer rates are found in regions with intense sunlight and high UV indices. In South America, for example, fair-skinned individuals in southern Brazil, Uruguay, and Argentina have significant rates of skin cancer, and **in Brazil about 25% of all cancers diagnosed are non-melanoma skin cancers** – a huge public health burden [35]. Paraguay's population has mixed ancestry, but with enough susceptible individuals that UV-related skin damage is a concern in the medical community.

If the SAA contributes to even small increases in ground-level UV, it could amplify these health risks. According to the United Nations Environment Programme, **for every 1% depletion of the ozone layer,**

the incidence of skin cancers can increase by approximately 2% (with some variations by cancer type) [36]. This relationship arises because reduced ozone leads to a roughly proportional increase in biologically harmful UV-B at the surface. For context, the Montreal Protocol's success in phasing out CFCs is estimated to have prevented a huge number of skin cancer cases by averting further ozone loss. However, ozone thinning from phenomena like solar particle events could locally offset some of those gains. One modeling study in *PNAS* projected that under a very weak geomagnetic field (simulating an extreme SAA or magnetic reversal scenario), an extreme solar event could cause global ozone loss on the order of tens of percent, which *"would likely have significant impacts"* on skin cancer rates worldwide [37].

In the specific case of the SAA and Paraguay, we should consider not only UV-B but also the potential contribution of other radiation. The same space radiation that affects ozone can also directly reach aircraft altitudes and produce secondary radiation in the atmosphere. One fascinating finding from the EURAMET BIOSPHERE project was that **human skin cells experience more damage when exposed simultaneously to UV radiation *and* ionizing radiation (cosmic rays), far exceeding the damage from UV alone** [38]. In other words, there appears to be a synergistic effect: cosmic rays can weaken cellular repair mechanisms or immune responses, making the cells more vulnerable to UV-induced mutations (and vice versa). This synergy was demonstrated in radiobiology experiments where cell cultures showed greatly enhanced DNA damage under combined radiation fields [38]. In regions under the SAA, where both cosmic ray flux (slightly enhanced aloft) and UV flux (very high) coexist, such synergistic effects could conceivably elevate health risks.

It is also worth noting that increased UV radiation has health implications beyond skin cancer. High UV exposure can cause eye damage (cataracts and other ocular diseases) and suppress the immune system's function in the skin. Moreover, any perturbation to the ozone layer can alter the UV spectrum that reaches the ground – for instance, a slight increase in UV-B/UV-A ratio or the appearance of normally absent UV-C could have unknown ecological and health consequences, affecting not just humans but also wildlife and ecosystems (e.g. phytoplankton DNA damage, crop yield reductions) [39]. Thus, the SAA-related changes form an intersection of space physics and public health: a reminder that processes hundreds of kilometers above Earth can ultimately influence ground-level conditions for living organisms.

Conclusion

The South Atlantic Magnetic Anomaly represents a regional weakening of Earth's magnetic shield that exposes the atmosphere over Paraguay and nearby countries to higher-than-usual influxes of energetic particles. During strong solar events, this leads to enhanced atmospheric ionization, the production of ozone-depleting NO_x and HO_x, and measurable ozone layer thinning above the region [14] [17]. The resulting increase in harmful UV radiation at the surface – although episodic – adds to an already high-UV environment in subtropical South America. We have outlined the physical mechanism: **geomagnetic weakening → particle precipitation → ozone depletion → increased UV-B and UV-C** at ground level, and we have highlighted supporting evidence from recent observations and models. Importantly, even moderate rises in UV exposure can translate into higher skin cancer incidence over time [36], especially for susceptible populations. There is also emerging evidence that the combination of cosmic radiation and UV can synergistically damage skin cells [38], underscoring the multifaceted health implications of the SAA.

Moving forward, interdisciplinary research is needed in this region. Continuous monitoring of stratospheric ozone and ground UV in SAA-affected countries like Paraguay, coupled with space weather observations, can help quantify the influence of geomagnetic anomalies on surface conditions.

Such data would improve our ability to forecast periods of elevated UV risk linked to solar storms. On the public health front, it may be prudent for authorities in SAA regions to incorporate space weather factors into UV alert systems and cancer prevention strategies – for example, warning the public of unusually high UV days that might occur after major solar flares. The SAA serves as a vivid reminder that Earth's magnetic field is a crucial component of the planetary life support system. Its quirks – like the SAA "dip" – connect the realm of geophysics to everyday issues of environmental health. Protecting and educating communities under the SAA's influence is an emerging challenge that sits at the convergence of space science, atmospheric chemistry, and public health.

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