Human Adaptation and Plant Use in Highland New Guinea 49,000 to 44,000 Years Ago

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Supporting Online Material
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Human Adaptation and Plant Use in Highland New Guinea 49,000 to 44,000 Years Ago

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After their emergence by 200,000 years before the present in Africa, modern humans colonized the globe, reaching Australia and New Guinea by 40,000 to 50,000 years ago. Understanding how humans lived and adapted to the range of environments in these areas has been difficult because well-preserved settlements are scarce. Data from the New Guinea Highlands (at an elevation of ~2000 meters) demonstrate the exploitation of the endemic nut *Pandanus* and yams in archaeological sites dated to 49,000 to 36,000 years ago, which are among the oldest human sites in this region. The sites also contain stone tools thought to be used to remove trees, which suggests that the early inhabitants cleared forest patches to promote the growth of useful plants.

Sahul, the single Pleistocene continent linking New Guinea, Australia, and Tasmania, is thought to have been colonized by humans some time after 50,000 years ago (*1*). Reaching Sahul required crossing water from Southeast Asia. Most early sites in New Guinea have been found along the coastal margins (Fig. 1, inset; fig S1; and table S2). An exception first documented in the 1960s is an open site [Papua New Guinea (PNG) National Museum site code AER] in the Ivane Valley of the New Guinea Highlands, where excavations at the Kosipe Mission recovered stone artefacts including waisted tools dated then to 26,870 ± 590 ^{14}C years before the present (radiocarbon lab no. ANU-191) (calibrated to 30,350 to 32,580 years ago) (*2*). Kosipe Mission is located at ~2000 m above sea level, on the spur of a hill overlooking a large swamp (Fig. 1). Further excavations in 2005 (*3*) extended known occupation there to 41,000 to 38,000 years ago (table S1). A carbonized kernel of a pandanus nut was recovered in the 36,000- to 34,000-year-old levels.

Subsequent fieldwork in 2007 and 2008 has identified late Pleistocene to Holocene occupation at seven additional locations across the Ivane Valley, with the earliest site dating to between 49,000 and 43,000 calibrated years before the present (table S1). Here we describe the evidence for early occupation of these sites and the subsistence strategies employed by these early colonists.

Sediments in the Ivane valley are dominated by a series of volcanic tephras that are probably derived from Mount Lamington some 140 km to the southeast. All eight highland sites have a basic set of five identified layers: a dark brown topsoil (layer 1), a brown-orange clay (layer 2); a black-brown soil (layers 3a and 3b), and a gray soil (layer 4). These occupation layers overlay culturally sterile orange clay (layer 5). Layer 3 is separated into two distinct units (a and b) at Vilakuav (*2*), representing separate ash falls. We subsequently identified these two layers (3a and 3b) in most sites. At Vilakuav, Joe's Garden, and Kosipe Mission, they are separated by a thin band of charcoal (fig. S2). Accelerator mass spectrometry dates were derived from charcoal collected in situ. We use the calibrated dates (*4*) in our discussion. All dates from Joe's Garden, Vilakuav, South Kov, and Airport Mound are presented here for the first time.

The earliest dates for occupation of the valley are at Vilakuav, between 49,000 and 43,000 years ago; and three sites (Vilakuav, South Kov, and Airport Mound) contain artefacts that yield calibrated ^{14}C dates earlier than 42,500 years ago, at 95.4% confidence levels. Occupation at the Kosipe Mission site is dated to 41,400 to 38,000 years ago, again at a 95.4% confidence level. Layer 3b shows occupation from 38,500 to 30,000 years ago, and layer 3a dates from 30,000 to 26,000 years ago. Layer 2 dates to the Holocene (table S1).

Our radiocarbon ages are some of the oldest dates for any Sahul site (table S2), excluding several contentious 20-year-old claims in Australia (*1*). Together with indirectly dated artefacts from Bobongara on the Huon Peninsula, the oldest occupational layers at the highland sites of Vilakuav, Airport Mound, and South Kov are older than any other known sites in New Guinea or Island Melanesia.

All highland sites lack evidence of any occupation during the Last Glacial Maximum (LGM). The mean temperature of the coldest month at Kosipe at the LGM has been estimated to have been between 6.3° to 9.2°C colder than today (*5*, *6*). The climates before the LGM would also have been cooler than those today. Layers 4 and 3b from the Ivane Valley correspond to marine isotope stage (MIS) 3, whereas layer 3a corresponds with the shift to much colder conditions from MIS 3 to MIS 2 (*7*). Other palynological evidence from the Ivane Valley (*6*) also indicates that the tree line was lower during the deposition of layers 4 and 3 and that the vegetation zones were compressed downward during the earliest occupation, which is consistent with a colder climate.

Stone artefacts were recovered from the earliest levels (layer 4) of Kosipe Mission, Airstrip Mound, South Kov, and Vilakuav (Fig. 2). Artefacts are made from a diverse range of raw materials, including basalt, schist, baked siliceous metasediment, dolerite, metabasalt, and quartz. Of these, baked siliceous sediment is the only rock type not found in the Ivane Valley. Samples of this rock were obtained along the Kosipe-Woitape track above Woitape, ~20 km distant. It is valuable for making tools because it flakes easily yet is hard.

Two waisted stone artefacts made from schist and metabasalt were found from layer 4 at South Kov and one from layer 4 at Airstrip Mound (Fig. 2 and fig. S3). This distinctive ar-

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tefact type was also found in layer 3a at South Kov and in layer 3b at Joe's Garden (Fig. 2 and fig. S4) and Vilakuav, but disappears before the LGM. Frequently referred to as waisted axes, they also occur in several other Pleistocene highland and lowland sites of the New Guinea mainland. Waisted axes have been seen as implements used to modify forest environments by opening up patches to sunlight to promote the growth of food and other useful plants (*8*). In the Ivane Valley, other Pleistocene stone artefacts include flaked artefacts, tool blanks, axe-like bifacially flaked implements, and flaking debris. An expanded range of stone artefacts occurs in the Holocene layers at all other sites except for Airstrip Mound.

Onsite stone artefact manufacture at all sites is indicated by the presence of cores and manufacturing debris and the use of local raw materials. River cobble cortex on both igneous and metamorphic artefacts suggests that local waterways were the primary source of raw material. The stone assemblage is consistent with finds from Bobongara, the only other mainland late Pleistocene assemblage older than 35,000 years. At this site, waisted artefacts were recovered below tephra 2 which dates to 38,000 ± 600 years by thermoluminescence (TL) dating (*9*), although the excavators argue for an estimate of 40,000 years or more, based on high moisture levels affecting the TL readings.

Abundant starch grains were extracted from several of the stone artefacts from layer 3a at Joe's Garden and layer 4 at the South Kov site (table S2). Several of these were consistent with starch from yams, specifically *Dioscorea* species. The size and morphology of the tuber-like starch grains (figs. S5 and S6) from the Joe's Garden samples were consistent with *Dioscorea alata* (Fig. 3) comparative reference material. The sample sizes of the yam starch grains from both South Kov artefacts were smaller (n = 7 and n = 8 grains), although two starch grains exceeded 40 µm in size. The shape and surface features of these starches are unlike that of *D. bulbifera* but broadly similar to those of *D. alata* (fig. S6C) and/or *D. pentaphylla* (fig. S6D). There is no clear sculpting of the hilum end of the grain in fig. S6C or S6D, as seen in most grains from *D. pentaphylla*. However, this feature is not present in all *D. pentaphylla* grains, and therefore we cannot exclude a contribution from this species.

Charred *Pandanus* nutshells were identified in Kosipe Mission layer 3, layers 3 and 4 from Joe's Garden, and all layers from South Kov and Vilakuav. All specimens, including fragments, were from single-seeded species of highland *Pandanus* in the section Karuka (*10*), which contain nutritious seeds. Morphometric analysis confirmed that complete specimens from South Kov layers 3 and 4 were not from the economically important *Pandanus brosimos* or *P. julianettii*, being most similar to an unclassified foraged wild species known as *Taip* (see supporting online material). A human source for the archaeological remains is indicated by (i) a close repeated association with charcoal, bone fragments, and tools and (ii) the absence of rodent/cuscus gnaw marks on the seeds. The absence of nuts from some sites and layers may indicate variability in activity areas across the landscape. *Pandanus* was absent at the Airport Mound site and in samples from the swamp sections taken for palynological analysis (*6*).

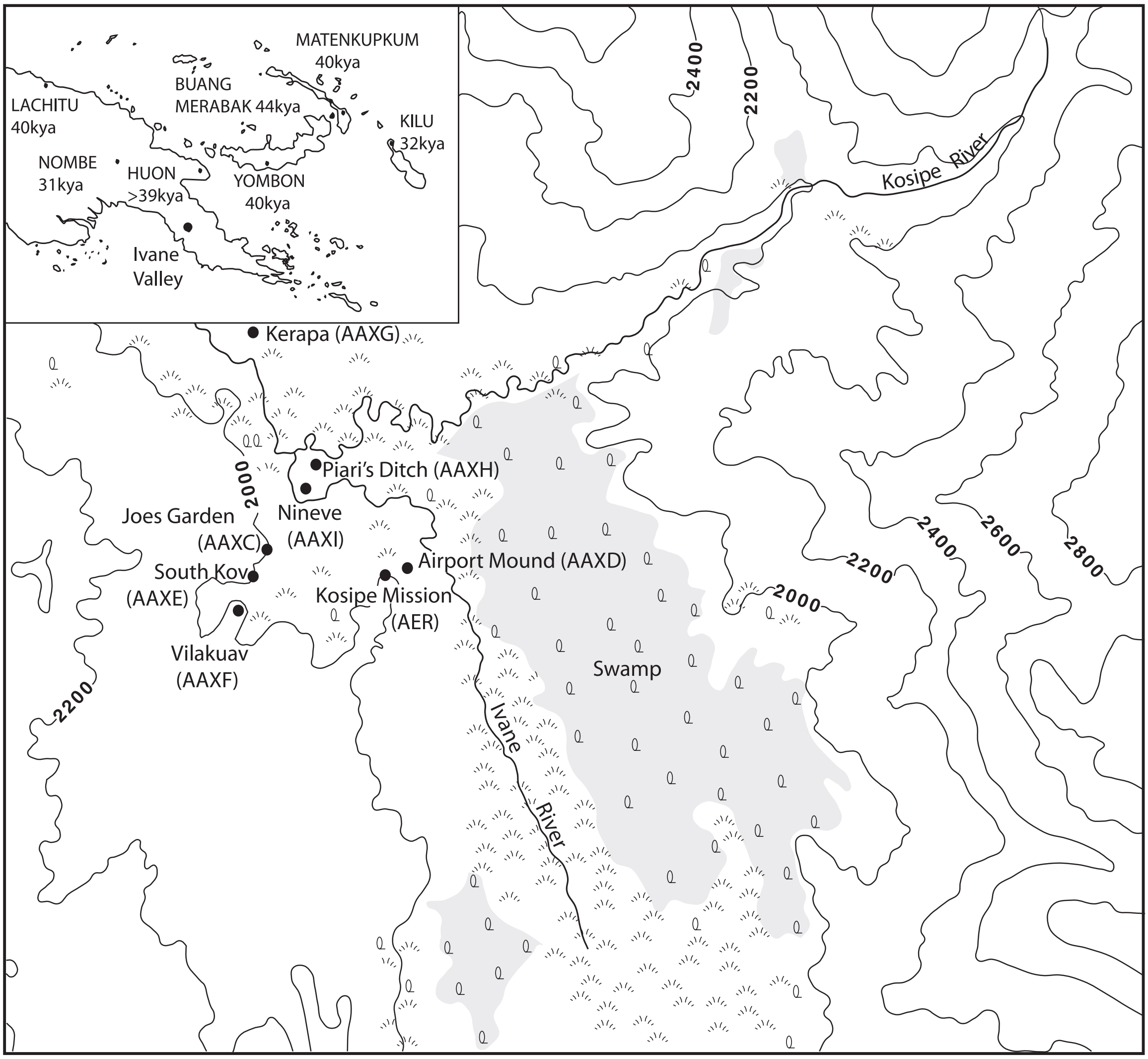


Fig. 1. Map of the Ivane valley with archaeological sites. Seven new late Pleistocene occupation sites were identified. Five are situated on spurs above the valley floor, ranging in altitude from 2020 to 1940 m: Joe's Garden, South Kov, Airport Mound, Kerapa, and Vilakuav. Two sites were located on the western valley floor: Piari's Ditch and Nineve.

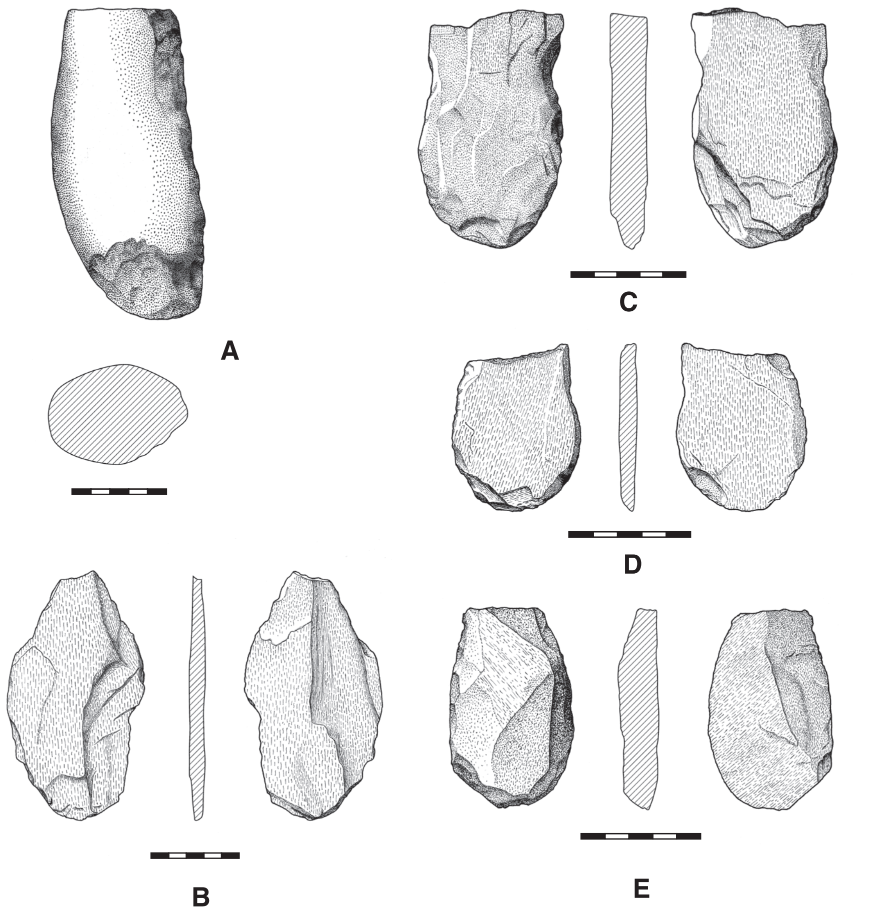
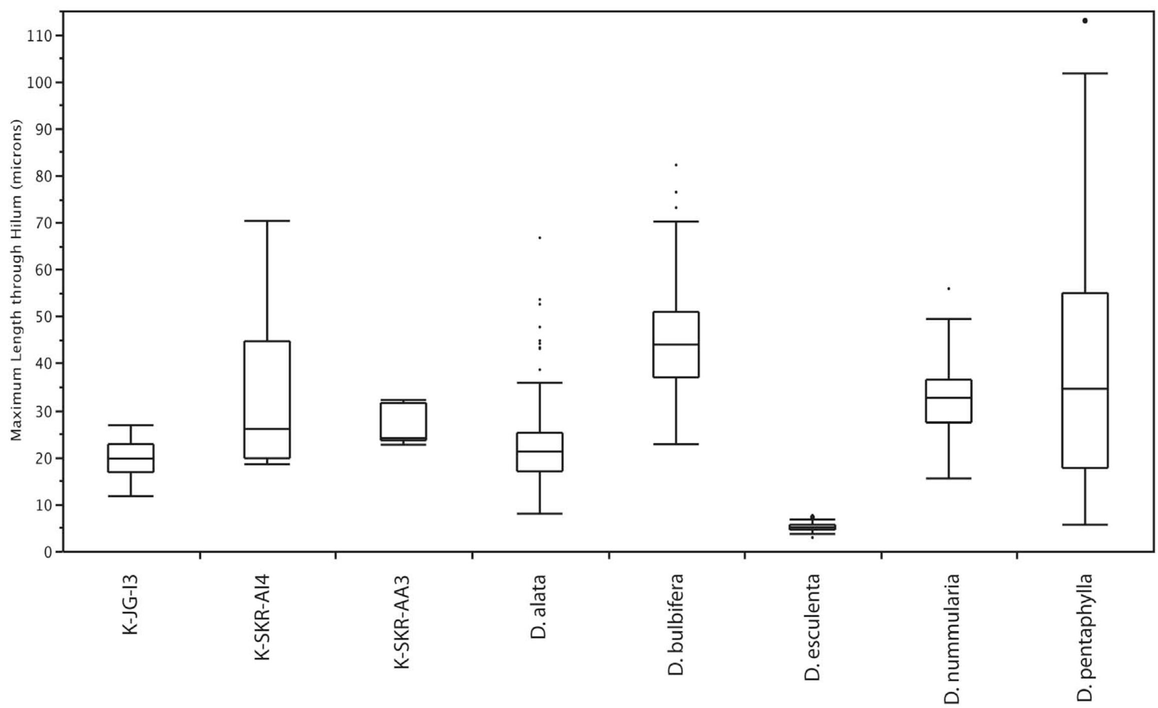


Fig. 2. Ivane Valley late Pleistocene stone tools. (**A** and **B**) Airstrip Mound (PNG National Museum site code AAXD) from layer 4. (**C**) Joe's Garden (AAXC) from layer 3b. (**D** and **E**) South Kov (AAXE) from layer 4. Scale bars are in centimeters.

The preservation of food plant species in open sites of this age is remarkable, and the analysis confirms that *Pandanus* and yams were used for subsistence in this valley from the time that the earliest colonists arrived. Although *Pandanus* would have grown abundantly in the local environment, yams would have been found at lower altitudes, indicating that gathering territories included lower altitudinal zones beyond the Ivane Valley. The gathering of food plants was accompanied by hunting of small animals. Burnt highly fragmented bone was recovered from the lowest levels at Vilakuav (1.1 g from layer 4 and 0.3 g from layer 3b), although it has been impossible to identify the species hunted. The acidic soil ensures that only the highly fragmented burnt bone survives. Although we have little evidence for the nature of hunted animals in the Ivane Valley diet, the range of potential high-altitude game in New Guinea is wide and well documented from later Highlands sites farther to the west (*11*).

The nature of human impact on the local environment is difficult to assess. In the Ivane Valley, Hope (*6*) noted an increase in microscopic charcoal between 41,000 and 38,000 calibrated years before the present, soon after the Kosipe Zone-2 stage (KOS-2) (at 42,000 years ago). Hope argued that the early humans burned the wet montane vegetation. The activities of people were probably a contributing factor to the physical changes to the Ivane basin. The base of layer 4 is indicative of the presence of a swampy lake (Hope's KOS-4 phase), which slowly developed into a peat swamp that extended to the south by the time of occupation in layer 3b (*6*). A human presence, increased fire, and changes in the lake hydrology are likely to be related.

Fig. 3. Box plots of the maximum dimensions of starch grains through the hilum in micrometers. The box includes 50% of the population, and the horizontal line represents the median value. The tuber grains presented from each archaeological preparation are only a small portion of the total counts from each artefact. The K-JG-I3 sample matches entirely with the *D. alata* sample. For the K-SKR-AI4 sample, the variation in grain length indicates that it is likely to represent more than one type of yam. The third artefact, K-SKR-AA3, comprises only seven grains, and these overlap with all samples except the *D. esculenta* sample.



Our data show that people occupied a New Guinea valley at 2000 m above sea level soon after their arrival in Sahul (*1*). As the climate cooled, the optimal growing conditions for yams would have occurred at lower altitudes. This may indicate that *Pandanus* was the most important staple at this time and help explain the late Pleistocene abandonment of the highland sites. Foraging into this high-altitude environment would guarantee a high return in plant fat and protein to complement local animal foods, the starch-rich yams from lower altitudes, and those foods not preserved in the archaeological record.

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Identifying the Driver of Pulsating Aurora

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Pulsating aurora, a spectacular emission that appears as blinking of the upper atmosphere in the polar regions, is known to be excited by modulated, downward-streaming electrons. Despite its distinctive feature, identifying the driver of the electron precipitation has been a long-standing problem. Using coordinated satellite and ground-based all-sky imager observations from the THEMIS mission, we provide direct evidence that a naturally occurring electromagnetic wave, lower-band chorus, can drive pulsating aurora. Because the waves at a given equatorial location in space correlate with a single pulsating auroral patch in the upper atmosphere, our findings can also be used to constrain magnetic field models with much higher accuracy than has previously been possible.

The aurora is a spectacular natural phenomenon that occurs in Earth's polar regions, exhibiting a range of scale sizes (~1 to 100 km) and characteristic wavelengths (e.g., 427.8, 557.7, and 630.0 nm) (*1*, *2*). Auroral features are a visual display of the patterns of energetic particles from distant regions in Earth's magnetosphere that move along magnetic field lines, causing photon emissions in the upper atmosphere. This process represents an important loss of energetic particles from the magnetosphere, and the energy from these particles causes drastic changes in ionization of the upper atmosphere. One type of aurora, the pulsating aurora (PA), has attracted much attention because of its distinctive luminosity patches at ~100-km altitude, which have a horizontal scale size of ~100 km and switch on and off with recurrence periods of ~5 to 40 s (*3*, *4*).

Rocket and low-altitude spacecraft observations have revealed that auroral pulsations result from a time-varying flux of precipitating electrons with energies exceeding ~10 keV (*3*, *5*). However, the driver of this precipitation has not been uniquely identified. Theoretical investigations have shown that resonant interactions with naturally occurring emissions, known as chorus, could lead to the precipitation of energetic electrons in the appropriate energy range for PA (*4*, *6*), but this suggestion has been difficult to verify experimentally. Chorus consists of discrete bursts of wave power that are confined near the magnetic equator (*7*, *8*) and typically occur in distinct lower- and upper-frequency bands, below and above half of the equatorial electron cyclotron frequency (f_c). Lower- and upper-band chorus can resonate with more than 10 and less than a few keV electrons (*9*), respectively. In addition, chorus may evolve nonlinearly for large amplitudes (*10*) and is frequently associated with electrostatic cyclotron harmonic (ECH) waves, which occur above 1 f_c and can resonate with electrons of energies below a few keV (*11*).

Attempts have been made to test wave theories using low-altitude rocket observations (*12*) and high-altitude, equatorial spacecraft (*13*–*15*). Although a general correspondence between PA and electromagnetic waves has been observed, a one-to-one correlation between individual bursts of chorus and auroral pulses has been elusive. This discrepancy between observation and theoretical prediction has been attributed to the difficulty in finding the exact mapping of a distant spacecraft to a small (~100 km) pulsating auroral patch in the upper atmosphere along magnetic field lines. Such mapping is particularly difficult because adjacent auroral patches typically pulsate independently of each other (*16*). Additionally, the simultaneous existence of multiple magnetospheric plasma waves (*13*, *17*) makes it difficult to identify the specific wave mode responsible for electron scattering leading to PA.

Here, we report observations of PA obtained on 15 February 2009 using one of the ground-based All-Sky Imagers (ASIs) (*18*) of the THEMIS mission (*19*). Their broad latitudinal and longitudinal coverage (~1000 km), as well as high resolution (~1 km spatial and 3 s temporal), allowed us to observe the evolution of localized, individual pulsating auroral patches. We also report on plasma wave observations made in space by THEMIS-A (*20*–*22*). During the period of observation, this spacecraft was located near the magnetic equator in the Southern Hemisphere, and the magnetic field line threading the spacecraft was located close to the center of the imager field of view, which avoids optical distortion.

In the model shown in Fig. 1A, electrons that are initially trapped by Earth's magnetic field encounter chorus propagating away from the equator. The electrons are scattered and precipitate into the upper atmosphere, resulting in

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