

1 Supplementary Information for:

# 2 **Anthropogenic Transmitter Networks Reshape Earth's** 3 **Inner Radiation Belt**

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## 12 **Supplementary Notes**

### 13 **Supplementary Note 1: Observational characteristics of NWC and Europe wisps**

14 Complementing the schematic in Fig. 1, we detail here the geometrical and observational characteristics  
15 of NWC and Europe wisps. VLF waves launched from the ground propagate roughly along geomagnetic field  
16 lines and interact resonantly with radiation-belt electrons near the magnetic equator via cyclotron resonance,  
17 scattering them into the drift loss cone<sup>1,2</sup>. Once scattered to lower equatorial pitch angles ( $\alpha_{eq}$ ), these electrons  
18 bounce to altitudes of a few hundred kilometers, appearing as structured flux enhancements.

19 NWC-induced precipitation (NWC wisps) is detected in the conjugate regions of both hemispheres and  
20 drifts eastward toward the SAA. MSS-1 data reveal a pronounced north-south asymmetry near 180° longitude  
21 (Fig. 2), a feature absent in FY-3E observations. We attribute this to the local magnetic topology (Extended  
22 Data Fig. 5): near 180°, the local loss cone broadens. At the lower altitude of MSS-1 (450-500 km), electrons  
23 in the southern hemisphere with  $\alpha_{eq} \lesssim 25^\circ$  become untrapped and precipitate before detection. In the  
24 northern hemisphere, electrons with larger  $\alpha_{eq}$  remain quasi-trapped. At the higher altitude of FY-3E (~837  
25 km), the accessible  $\alpha_{eq}$  range shifts to larger values, rendering wisps observable in both hemispheres.

26 Conversely, the European cluster generates discrete multi-band precipitation structures (Europe wisps).  
These features are confined to the southern African sector because their northern conjugate points lie within

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27 the untrapped zone at satellite altitudes: electrons scattered onto this region mirror into the atmosphere before  
28 they can be sampled. As Europe wisps drift eastward from the SAA, the increasing geomagnetic field strength  
29 raises their mirror points. Consequently, electrons transition from being detectable (quasi-trapped) at MSS-1  
30 altitudes to mirroring above the spacecraft. This evolution limits Europe wisps to a narrow longitudinal range  
31 east of the SAA, consistent with the observed clustering over southern Africa (Fig. 2) and the restricted extent  
32 of Band 1 and Band 2 events (Extended Data Fig. 2).

### 33 **Supplementary Note 2: Dawn and Dusk Asymmetry**

34 The strong preference for dawn over dusk observed in both NWC and Europe wisps (Fig. 3) corresponds  
35 to the magnetic local time (MLT) distribution of VLF wave power. As shown in Extended Data Fig. 3b,d,  
36 electric field power in the 17.8 - 27.4 kHz and 40.2 - 48.7 kHz bands maximizes on the nightside, with a  
37 pronounced dawnside excess (MLT  $\sim 6$ ) relative to dusk (MLT  $\sim 18$ ). This asymmetry arises from D-region  
38 ionospheric attenuation. Solar ionization dominates the D-region; thus, the recently illuminated duskside  
39 ionosphere retains elevated electron densities that suppress VLF transmission<sup>3</sup>. Conversely, after hours of  
40 nightside recombination, the dawnside D-region becomes sufficiently transparent to allow efficient VLF leakage  
41 into the magnetosphere. This ionospheric gating mechanism dictates the occurrence of transmitter-induced  
42 precipitation.

### 43 **Supplementary Note 3: Transmitter Inventory and Station-level Details**

44 Extended Data Table 1 lists major transmitters, operating frequencies, and radiated powers. The Eu-  
45 ropean sector hosts a cluster of moderate-power transmitters in the 18-24 kHz range (Band 1), including  
46 HWU (18.3 kHz), GQD (19.6 kHz), ICV (20.3 kHz), FTA (20.9 kHz), GVT (22.1 kHz), and DHO (23.4  
47 kHz). A distinct higher-frequency group (Band 2) operates near 46 kHz, dominated by NSY (45.9 kHz) and  
48 supported by nearby facilities. While some transmitter powers are undocumented, their signatures are evident  
49 in spaceborne wave spectra.

50 Accordingly, VAP wave power spectra averaged over the nightside European sector display two prominent  
51 peaks at 18-24 kHz and 45-48 kHz (Fig. 3f; Extended Data Fig. 3e). These spectral peaks align with  
52 the discrete precipitation bands observed in Europe wisps (Fig. 3d), with calculated resonant energies for  
53 representative frequencies tracking Band 1 and Band 2. Consistent with these spectral signatures, geographic  
54 maps of wave power in the corresponding bands (Extended Data Fig. 3a,c) show strong enhancements over  
55 Europe and its conjugate region in the southern hemisphere, including southern Africa. Spatially, the near-20  
56 kHz wave power spans a broader longitude than the confined near-40 kHz emissions. This spatial variance  
57 is reflected in the precipitation data, where Band 1 events are more widely distributed than the localized  
58 Band 2 events (Extended Data Fig. 2), confirming the multi-frequency cooperative nature of the European  
59 driver. Although similar wave power enhancements occur over North America, electrons scattered there drift  
60 eastward and encounter the SAA from the west. Because drift shells reach their minimum altitude near the  
61 SAA center, these electrons precipitate rapidly into the atmosphere before they can form quasi-trapped wisps  
62 over southern Africa.

## 63 **References**

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