



Ionospheric signatures of a plasmaspheric plume over Europe

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[1] Previously, ionospheric signatures of plasmaspheric plumes were reported only at the North American longitude sector. This led to the hypothesis that the geomagnetic field configuration at those longitudes played a vital role in the observation of plasmaspheric plume signatures only over the American continent. Combining ground-based GPS total electron content (TEC), EISCAT incoherent scattering radar (ISR), and DMSP F15 ion drift meter observations we have observed greatly elevated density over the European continent during storm recovery phase on 12 September 2005. The TEC seen over Europe has a tongue of enhanced ionization extending to higher latitudes, which is identical to the plasmaspheric plume signatures that have been often observed over North America. Therefore, our observations clearly demonstrate that ionospheric signatures of plasmaspheric plumes are not limited to the North American sector and suggest that they may be observed at any longitude as long as a dense array of instruments are available to identify these signatures. **Citation:** Yizengaw, E., M. B. Moldwin, and D. A. Galvan (2006), Ionospheric signatures of a plasmaspheric plume over Europe, *Geophys. Res. Lett.*, *33*, L17103, doi:10.1029/2006GL026597.

1. Introduction

[2] During magnetic storms magnetospheric sunward convection increases, and the plasmasphere undergoes erosion, causing the plasmopause to move closer to the Earth. Previous observations have demonstrated that the plasmasphere can undergo severe depletion even at low L shells [Moldwin *et al.*, 2003; Goldstein and Sandel, 2005]. In recent years, in addition to the new insights of the global plasmasphere provided by the IMAGE satellite mission [Burch, 2000], ground observations of the plasmasphere were revitalized by the advent of new technique and observation. This includes the gradient method that uses ground magnetometer observations of field line resonance (FLR) signatures to infer the magnetospheric density [e.g., Berube *et al.*, 2003; Chi *et al.*, 2005 and references therein]. In addition, the fast-growing array of GPS receivers that can be used to deduce TEC [e.g., Foster *et al.*, 2002; Yizengaw and Moldwin, 2005] also has become an important diagnostic to study ionosphere and plasmasphere configuration from the ground.

[3] Large increases in the midlatitude ionospheric F region electron density TEC are often observed in local dusk sector during magnetic storms and termed dusk effect [Foster, 1993]. The resultant density enhancements at the

equatorward edge of the dusk-sector ionospheric trough were termed storm-enhanced density (SED). Foster *et al.* [2002] have compared measurements of SED with the Millstone Hill radar, the global GPS receiver network, and the DMSP satellites. They found that the SED density enhancements in the dusk sector are associated with the erosion of the outer plasmasphere by subauroral polarization stream (SAPS) electric fields and that the SED plumes can map directly into the plasmaspheric tail (also called “plasmaspheric plume”) observed with the IMAGE spacecraft. Foster *et al.* [2004] used direct radar observations of the sunward $\mathbf{E} \times \mathbf{B}$ plasma convection to quantify the flux of ions carried by the SED plume to the nighttime F-region in the vicinity of the cusp.

[4] The midlatitude ionosphere and overlying plasmasphere are known to respond in dramatic fashion to the electric fields associated with both moderate and severe magnetospheric disturbances. Chi *et al.* [2005], using ground-based observations of field line resonance signals and GPS TEC, observed extraordinary density enhancements in both the magnetosphere and the ionosphere. They conclude that the ionosphere can be an important factor modulating the density variations in a storm-time plasmasphere.

[5] Since Foster *et al.* [2002] demonstrated that the storm enhanced density (SED) and plumes of greatly elevated TEC are associated with the erosion of the outer plasmasphere, the signature of plasmaspheric erosion onto the ionosphere have been reported and well documented [Foster and Rideout, 2005; Chi *et al.*, 2005 and the reference therein]. However, all previous SED/TEC plumes were reported only at longitudes in the North American sector. This led to the hypothesis that the geomagnetic field configuration at those longitudes played a vital role in the observation of plasmaspheric plume signatures only over the American continent (e.g., Rideout *et al.*, 2004). Because of the dipole toward North America, low geographic latitudes are at mid-to-high geomagnetic latitudes in the northern hemisphere and high geographic latitudes are at low geomagnetic latitudes in the south.

[6] Combining ground-based GPS TEC, EISCAT ISR, and DMSP F15 ion drift meter observations we have observed greatly elevated density over the European continent during storm recovery phase in the morning sector on 12 September 2005. The GPS TEC seen over Europe between 08:40 and 10:20 UT (between 07:40 and 13:20 LT) has a tongue of enhanced ionization extending to higher latitudes. This is strongly suggestive of plasmaspheric plume signatures that have been often observed over North America [e.g., Foster *et al.*, 2002]. This indicates that plasmaspheric plumes can be formed in the European sector. These are the first reported signatures of apparent plasmaspheric plumes other than in the American longitudinal sector. Usually the plasmaspheric plumes occur at the dusk side, however, in some cases a wrapped plasmaspheric

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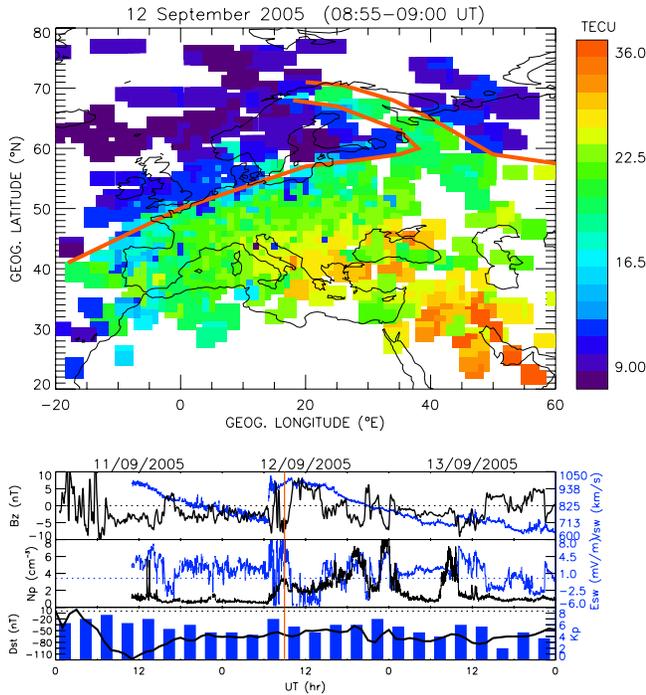


Figure 1. (first panel) The 2-D map of a GPS TEC snapshot of a SED/TEC plume. (second panel) IMF Bz (black curve) and solar wind velocity (blue curve). (third panel) contains the solar wind density (black curve) and magnetospheric dawn-dusk electric field (blue curve). (fourth panel) Dst index (black curve) and Kp index. The vertical red line in the bottom three panels shows the corresponding time of the 2-D map of GPS TEC.

plume can occur in the morning sector. The evolution of wrapped plasmaspheric plumes will be discussed in detail later. Unfortunately, IMAGE EUV images between 08:40 and 10:20 UT on September 12 were not of sufficient quality to identify any plasmaspheric features. However, we present a similar morning sector plume observation from earlier EUV image to demonstrate that morning sector plumes are possible. Although EUV images from the IMAGE spacecraft revealed the wrapping of a plasmaspheric plume to form a morning side plume [e.g., Spasojevic *et al.*, 2003], the morning sector SED/TEC plume has not been reported before.

2. Observations

2.1. GPS TEC Maps

[7] The GPS constellation currently consists of 29 satellites in 12-hr circular orbits (~ 20200 km altitude or $\sim 4.2L$) with orbital inclination $\sim 55^\circ$. Owing to the dispersive nature of the ionosphere, dual frequency GPS measurements are used to determine the GPS TEC along the paths from each receiver to the GPS satellites in view (typically 6–12 satellites). It is quite clear that ground-based GPS TEC includes both plasmaspheric and ionospheric plasma contributions [Foster *et al.*, 2002].

[8] For this study we have calculated vertical TEC from more than 140 GPS sites in Europe using the standard TEC calculation technique [Yizengaw *et al.*, 2004, and the reference therein]. All GPS TECs have been calibrated from instrumental biases and 2-D (latitude versus longitude) maps

of GPS TEC over Europe were prepared for every 5 minute interval. Figure 1 (top) shows the maps of GPS TEC for 08:55 UT (between 08:00 and 13:25 LT) on 12 September 2005. The vertical TECs have been binned in $2^\circ \times 3^\circ$ latitude/longitude bins and no interpolation has been used to produce each map. As can be seen in the figure the map of GPS TEC produces a high level of detail, and a pronounced band of storm enhanced density (marked by red lines) extends from Eastern Europe. About 30 minute later this SED/TEC plume channel extended further west across Northern Scandinavia as shown in Figure 2. This extended TEC plume shows similar characteristics with the one observed quite often over North America [e.g., Foster *et al.*, 2002].

[9] The bottom three panels in Figures 1 and 2 illustrate the characteristics of magnetic activity between 11 and 13 September 2005. From top to bottom the panels display the solar wind speed (V_{sw}) and the IMF BZ component in GSM coordinates, the solar wind proton density (N_p), and Dst and K_p indices. The red vertical line indicates the corresponding time of the GPS TEC map (Figures 1 and 2, top). As can be seen when this pronounced TEC plume occurred, the solar wind velocity rose from 700 km s^{-1} to over 950 km s^{-1} , Bz turned south, and the solar wind density also rose from 0.55 cm^{-3} to over 3.5 cm^{-3} . Since it is the electric field that directly drives convection of cold $\mathbf{E} \times \mathbf{B}$ drifting plasma in the inner magnetosphere, we have calculated the interplanetary electric field and plotted in the third panel in Figures 1 and 2. The interplanetary electric field shown in the figure is defined as $E_{SW} = V_x \times B_z$, and negative and positive signs indicate westward and eastward direction of the electric field. When IMF Bz turned south, the dawnward (duskward) magnetospheric electric field causes antisunward (sunward) $\mathbf{E} \times \mathbf{B}$ convection in the dayside.

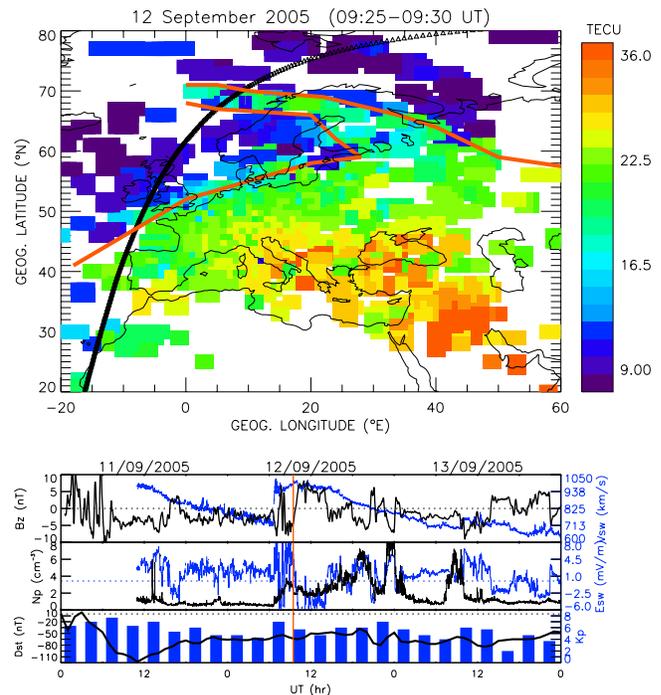


Figure 2. As for Figure 1 but for different time snapshot of the SED/TEC plume. The open triangle curve in the top panel shows the ground track of DMSP F15.

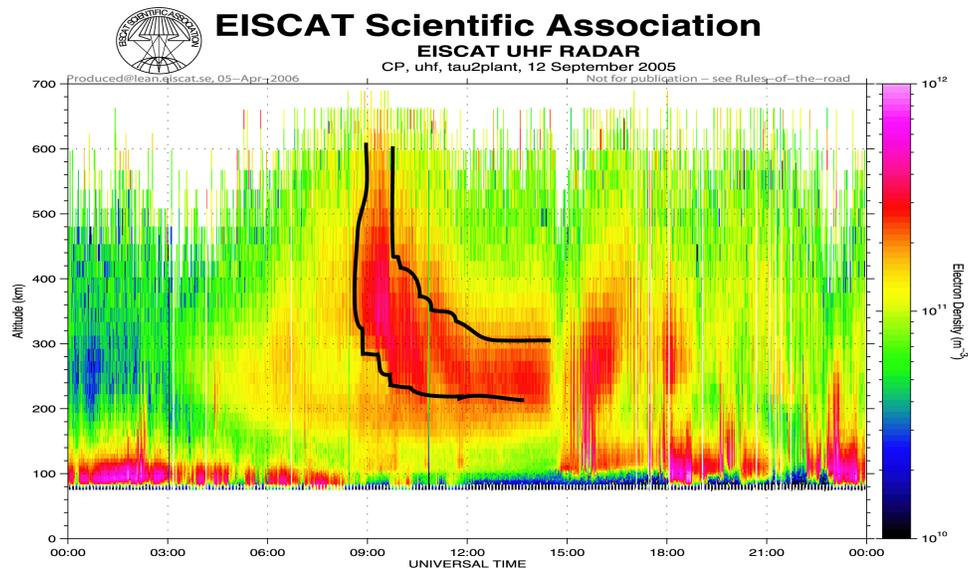


Figure 3. The 2-D maps of electron density obtained by the EISCAT radar. The curved black line illustrates the orientation of the enhanced density from the dayside to the morning sector.

2.2. EISCAT Radar Observation

[10] The EISCAT (European Incoherent SCATter) radar observed a significant density enhancement, extending to higher altitude. In Figure 3 we present a 2-D map of radar observations of the density enhancement, which is oriented towards the morning side, indicated by the black lines, at the same time when the SED/TEC observed by ground-based GPS TEC on 12 September 2005. The density scale reaches up to $8 \times 10^{11} \text{ m}^{-3}$ in the center of the flux channel. The tilted density enhancement detected by EISCAT radar also shows that the SED plume was rotating to the morning side, which is consistent with GPS TEC observation shown in Figures 1 and 2. This suggests the existence of a plasmaspheric plume in the morning sector.

2.3. DMSP Satellite Observation

[11] The DMSP F15 satellite flew over the region of SED/TEC plume near 09:40 UT as indicated by its ground track (indicated by open triangles) shown in Figure 2. The DMSP ion drift meter observations shown in Figure 4 identify both antisunward and sunward ion velocities. While the ion meter observes antisunward ion velocity $\sim 1000 \text{ m/s}$ the density at the DMSP orbit altitude increases from about $2.5 \times 10^4 \text{ cm}^{-3}$ at 60°N to about $7.8 \times 10^4 \text{ cm}^{-3}$ at 69°N . This region is the region where the GPS TEC observed the SED/TEC plume shown in Figure 2. Similarly, the density shows fluctuations at the cusp region (between 70°N and 80°N or poleward of the SED/TEC plume region) at the same time the ion velocity turned sunward and reached $\sim 800 \text{ m/s}$ at about 74°N . The vertical velocity more or less shows upward flows with a maximum upward velocity reaching in excess of 1000 m/s at about 72°N , which is outside of the SED/TEC plume region.

3. Discussion and Conclusion

[12] In this specific event ground-based GPS TEC measurements detected a flux channel of enhanced density structure, oriented toward the morning side, over Europe.

The EISCAT radar and DMSP ion drift measurement also show similar density enhancement features. The DMSP ion drift meter indicates the antisunward plasma convection between 60°N and 70°N latitudes. In the vicinity of the same region the ground-based GPS TEC observed a SED/TEC plume channel was located on the morning sector with its base on the dayside. This clearly indicates that the plasmaspheric plume was observed over Europe. The question is how the morning sector plasmaspheric tail can be formed? Here we summarize the evolution of morning side plasmaspheric plumes.

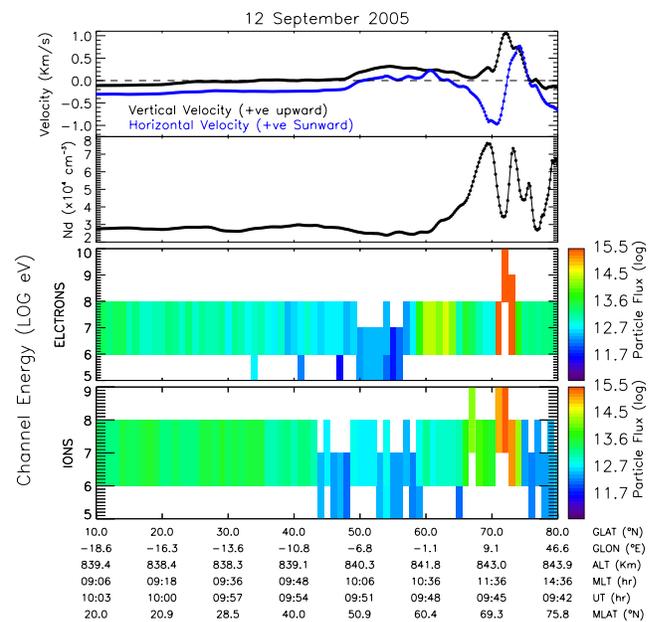


Figure 4. (first panel) DMPS F15 ion drift meter vertical (black) and horizontal (blue) velocity. (second panel) the density at the DMSP orbiting altitude and (third panel) electron and (fourth panel) ion channel energy.

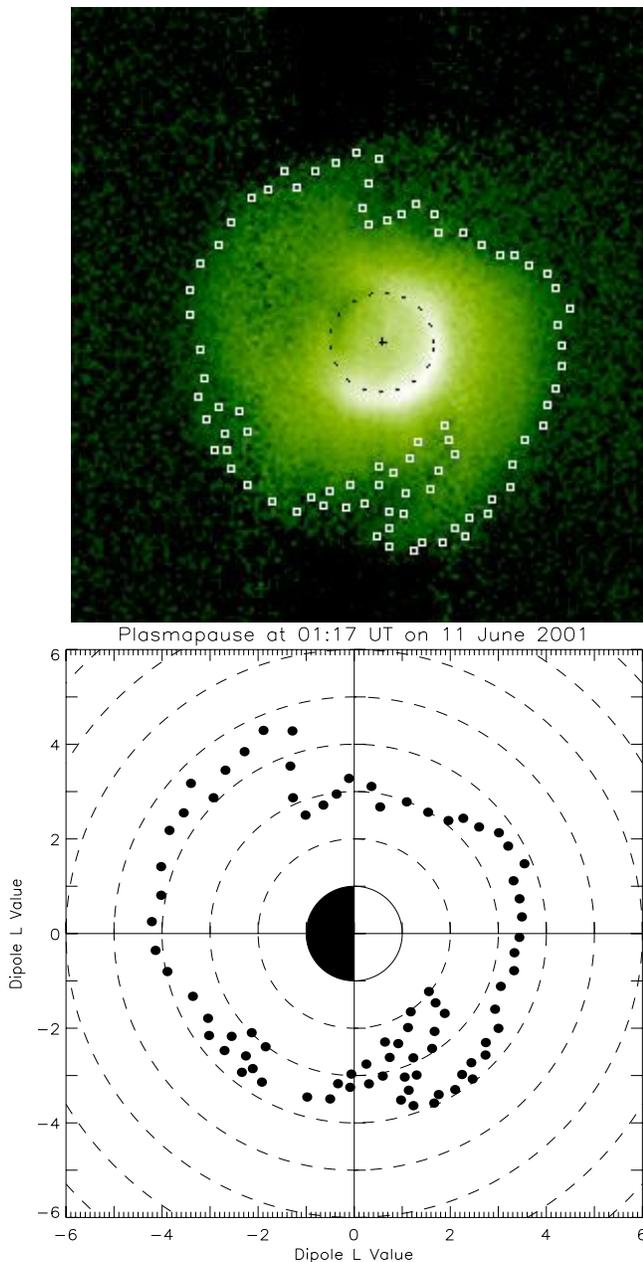


Figure 5. Example of a plasmaspheric image, which is mapped to the magnetic equator (Earth at the center and Sun to the right), as seen by IMAGE EUV at the time and date given at the bottom of the panel, and the filled black circles in the bottom panel show manually extracted points along the plasmopause from the EUV IMAGE in the top panel.

[13] The evolution of a plasmaspheric plume is discussed by *Spasojević et al.* [2003] and later in detail by *Goldstein and Sandel* [2005]. Generally, plumes form after a period of quiet geomagnetic activity ($K_p < \sim 4$) followed by an increase in activity, which causes the boundary between open and closed $\mathbf{E} \times \mathbf{B}$ drift path (separatrix), to move inward due to stronger convection electric fields. This increase in the geomagnetic K_p index is typically caused by a southward turning of the interplanetary magnetic field (IMF), which leads to increased dayside magnetic recon-

nection and therefore increased magnetospheric convection. Cold plasma that was part of the plasmasphere now finds itself outside the separatrix, and begins to drift sunward on open drift paths.

[14] When the IMF turns northward, the convection electric fields which caused the separatrix to move inward relax, and the separatrix now moves outward. Plume plasma now finds itself again on closed drift paths, and the part of the plume that is inside the separatrix begins to co-rotate eastward with the rest of the plasmasphere. Because the rate of rotation in the plasmasphere decreases with distance from the Earth in the dusk region, the outer part of the plume rotates more slowly than the inner part, and the plume stretches out in length and can eventually “wrap” around the Earth. Thus in some cases a wrapped plasmaspheric plume can be observed in the morning sector. This is the case for the included EUV image shown in Figure 5, which was taken on 11 June 2001 at 01:17 UT. In this image, the sun is to the lower right, and a remnant plasmaspheric plume is visible in the lower right (post-dawn morning) region. *Spasojević et al.* [2003] have discussed this particular plume in detail. It is under these circumstances that one would expect to observe the TEC signature of a plasmaspheric plume in the morning sector. It is a signature of this type of wrapped up plume that the GPS TEC observed over Europe between 08:40 UT and 10:20 UT (between 07:40 and 13:20 LT) on 12 September 2005. The SED/TEC plume also exhibits the wrapping nature. The comparison between Figures 1 and 2 clearly indicate that the enhanced TEC channel is oriented toward the morning side. Similarly the ground-based scanning radar also shows enhanced density that aligned from the noon to the morning sector. Unfortunately, EUV images during this time interval on 12 September were not of sufficient quality to identify any plasmaspheric features.

[15] It is interesting that the plume presented in Figure 5 extends to L-shells as low as $L \sim 2$ on the interior; lower L-shell values than the SED/TEC plume presented in Figures 1 and 2, which is about $L \sim 2.4$. One might expect that the plume extending to lower L-shells would result from a more intense geomagnetic disturbance. In fact, the plume presented in Figure 5 is visible in the late recovery phase of a disturbance with a maximum K_p of ~ 6 , while the plume observed in GPS/TEC is likely a result of geomagnetic activity surging to $K_p \sim 8$ at around 09:00 UT on 11 September 2005. The details of the situation are, of course, more complex. As *Spasojević et al.* [2003] explained in their discussion of the plume shown in our Figure 5, that plume was modified by a second surge in geomagnetic activity and recurring substorm activity throughout the recovery phase, the combination of which brought the westward interior edge of the plume to its low value of $L \sim 2$. While the 2005 plume was created by a more intense storm, there were no major secondary surges in geomagnetic activity until a few hours before the SED/TEC plume was observed. In Figures 1 and 2, lower panels, there is a clear rise in K_p just before the TEC observation. This rise may cause the westward interior edge of the plume to move to lower L-shells at a later time, but just a few hours is not enough time for the plasma that is newly outside the separatrix to convect away. Thus, our plume probably spans higher L-shell values than the one in Figure 5 due to the detailed differences in geomagnetic

activity during the recovery phase of the storms from which the plumes were formed. Of course, no two plumes have the exact same geomagnetic history.

[16] Though this paper clearly demonstrates the occurrence of a TEC SED event over Europe, it should be noted that these signatures should be more infrequent than the same signatures over North America. This is due to the Earth's magnetic dipole tilt making most of the European continent at low geomagnetic latitudes. To observe a TEC SED/Plasmaspheric plume over Europe requires deep erosion of the plasmasphere to $L \sim 2$. In the North America sector, the dense GPS array covers a good range of mid-latitude L-shells allowing observation of the TEC SED/plume interval even for moderate activity levels.

[17] In conclusion, for the first time we observed ionospheric signatures of plasmaspheric plumes over Europe. Previously, these signatures were only observed over North America, which led to the hypothesis that the equatorward offset of the geomagnetic pole at those longitudes play a major role for the SED formation in this region. On the other hand, at the European longitudes the magnetic equator shifts to the north. This demonstrates that the signature of the plasmaspheric plume can be observed over Europe and strongly suggests that they can be observed at any longitude as long as there are space- and ground-based instruments available to detect them.

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