The Impacts of Lightning Beyond the Troposphere

A White Paper for the NAS Solar and Space Physics (Heliophysics) Decadal Survey

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Synopsis:
We propose that the upcoming Decadal Survey on Solar and Space Physics describe prominent contributions of lightning and its impacts beyond the troposphere, particularly within the NASA Heliophysics portfolio. We present a brief review of several topics highly relevant to NSF and NASA. We opt to unify these topics into one white paper, with longer reviews/references included.

High Level Recommendations:

1. Lightning should be viewed by NASA as an ‘antidisciplinary’ topic, given its impacts on Earth Science, Heliophysics, Planetary Science, and even Astronomy.

2. NASA Heliophysics division should provide more robust support to study the impact of lightning beyond the troposphere and should bolster efforts to develop joint programs with Earth and Planetary Science around lightning impacts beyond the troposphere.

3. NASA and NSF should jointly establish a new program to explore the coupling between lightning/thunderstorms and space science. This program should include collection and/or correspondence of ground-based and satellite data together.

4. NASA Heliophysics division should fund more in situ measurements to quantify lightning/thunderstorm effects in the upper atmosphere, including sounding rockets, short-duration balloon campaigns and gliders, as well as projects engaging citizen science community around TLE detection.

Introduction

Our paper includes four key sections: (1) An overview of two lightning detection regimes, (2) A discussion of two ways in which lightning allows diagnostics of the heliophysics system, (3) A description of three ways lightning directly impact the heliophysics system, (4) Antidisciplinary connections to planetary science and astrophysics. We then conclude with a discussion and recommendation section.

The science of lightning is highly interdisciplinary and involves a mix of paradigm-breaking measurements, modern data science, and high-performance computing and modeling.

1 Lightning Detection

Existing ground networks can be powerful tools for detecting and characterizing lightning on a global level. But in more recent years, the potential for detection from airborne and space-based platforms has begun to mature.

1.1 Lightning Detection from Space

Since 1995, NASA has maintained nearly-continuous monitoring of lightning from space [*Cecil et al.*, 2014; *Blakeslee et al.*, 2020], focusing on total lightning (intracloud and cloud-to-ground). The detection capability is spatially uniform, unlike ground-based networks which have uneven sensitivity based on sensor locations. NASA thus has provided a multi-decadal record that enables detailed investigations into interactions between tropospheric lightning and several phenomena described herein. While missions such as the Lightning Imaging Sensor (LIS) are associated with the NASA Earth Science Division, these observations are highly relevant to NASA Heliophysics.

Currently, most lightning observations from space detect the oxygen band at 777 nm during day and night. Multi-spectral observations of lightning tell us about the coupling of lightning with the upper atmosphere [*Frey et al.*, 2016; *Pérez-Invernón et al.*, 2022; *Neubert et al.*, 2020, 2021], but these measurements are currently limited to nighttime and lack high spatial and temporal resolution. A future satellite missions to study lightning should include fast multi-spectral imagers capable of detecting optical emissions from lightning and TLEs both day and night.

In addition, little is known about the vertical structure of lightning and upper atmospheric electrical discharges on a global scale. A three-dimensional lighting mapping capability from space could provide these observations and unlock new insights about the cause and effects of, e.g., TLEs and TGFs. For example, knowing the vertical altitude of charge layers is critically important for understanding charge moment change and its effects on the production of TLEs [*Lang et al.*, 2011].

Coincident optical and radio measurements of lightning and related electrical phenomena have provided much insight about processes within and composition of Earth's atmosphere [*Light*, 2020; *López et al.*, 2022], and have enabled retrieving information about the vertical structure of lightning [*Peterson et al.*, 2022] and TLEs [*Boggs et al.*, 2022]. Future missions to study lightning should include both broadband RF and multi-spectral optical instruments to comprehensively observe lightning activity. This capability would provide maximum benefit to Heliophysics research.

Many past satellites have been in low-Earth orbit (LIS/OTD) or geostationary orbit (GLM), but accurate satellite measurements at altitudes of 400 km or less can be especially effective at compelementing ground measurements. For example, NASA's Geospace Dynamics Constellation (GDC) mission can address many outstanding lightning/ionospheric science questions.

1.2 Lightning Detection from Sub-Orbital Platforms

Measurements of electromagnetic fields and atmospheric conductivity in the upper stratosphere, mesosphere, and D-region ionosphere above thunderstorms are crucial to quantify thunderstorm to ionosphere coupling [*Holzworth et al.*, 2005; *Thomas et al.*, 2008]. TLEs occur in a relatively inaccessible region of the atmosphere (30-100 km altitude) which is barely reached by high-altitude balloons and sparsely sampled by sounding rockets. With a lack of in situ observations, models and extrapolations have been used to estimate the electrical environment where and when TLEs form [*Gamerota et al.*, 2011]. Electromagnetic field observations are crucial to tie together high-speed video recordings of TLEs, properties of their parent lightning flashes, and numerical models. Beyond TLE research, in situ measurements are important for quantifying how lightning ElectroMagnetic Pulses (EMPs) propagate to and through the D-region to the E/F regions and the magnetosphere and, in turn, change the ionospheric conductivity [*Shao et al.*, 2013].

NASA and NSF currently support high-altitude balloons and sounding rockets. However, targeted lightning related solicitations have been absent for decades. NASA balloon support have been directed towards a few large payloads per year. This policy excludes smaller, cheaper, or faster research projects, which are typically needed for over-thunderstorm balloon experiments. We also advocate for the application of non-conventional mission technology to study the 30-100 km region. Such technology includes drones and gliding platforms from lower altitudes to reach this region. Another option is to fund short-duration (6-12 months) low-altitude mini-CubeSat constellations. Applying these new technologies to study the upper stratosphere, mesosphere, and D-region ionosphere altitudes constitutes a new category of high-risk high-return missions, especially for such a high value region of the atmosphere. Such innovative research platforms can also be applied to study other lightning-related phenomena (TLEs) occurring in these regions.

2 Lightning as a Space Weather Probe

The thermosphere and ionosphere (60-1000 km) affects satellite-ground communication, LEO satellite orbital drag, GPS accuracy, and over-the-horizon communications for the aviation sector. It responds to space weather including solar flares, geomagnetic storms and electron precipitation, as well as cosmic gamma-ray bursts. But it is also driven by thunderstorms and other atmospheric phenomena from below. We now describe two methods by which lightning leads to an effective diagnostic tool for space weather and even astrophysics phenomena.

2.1 Ionospheric Imaging

The D-region ionosphere (60-90 km) lies at altitudes too high for balloons but too low for satellites, but the highly collisional plasma decouples it from the rest of the ionosphere above, and makes

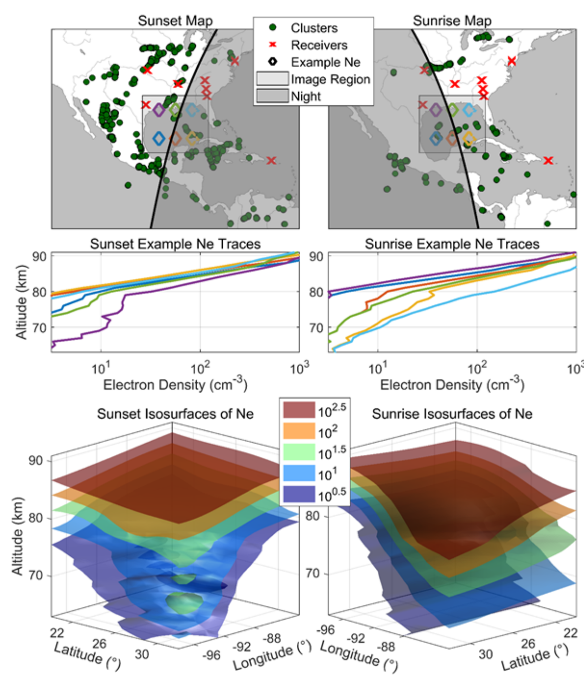

Figure 1: D-region electron densities during sunset (left) and sunrise (right) using VLF observations of lightning emissions

it more directly responsive to solar output and electron precipitation. Lightning disturbs the ionosphere via three mechanisms: (1) Direct heating from electromagnetic pulse and the quasi-static field change from lightning flashes, (2) Electron precipitation from the radiation belts triggered by lightning-released radio energy in the Very Low Frequency (VLF, 3−30 kHz) range, and (3) Atmospheric waves from thunderstorm updrafts. When these three sources are decoupled, radio measurements can turn the ionosphere into a big detector.

Lightning provides a valuable method of tracking the D-region through the release of VLF energy by millions of lightning flashes each day. VLF energy reflects from the D-region and is guided to global distances, therefore providing a diagnostic of the D-region conditions between any lightning location and receiver [*Cummer et al.*, 1998; *Lay et al.*, 2014; *McCormick and Cohen*, 2021]. A network of VLF receivers detecting lightning over a wide region therefore can be used to map or 'image' the D-region the electron density profile [*McCormick*, 2019]. An example is shown in Figure 1.

Accurate spatial tracking of the D-region enables us to quantify the ionosphere's response to space weather including electron precipitation, solar flares, cosmic gamma-ray bursts, and more. Reviews of these impacts can be found in *Inan et al.* [2010]; *Silber and Price* [2017]. As such, investments in stable, long-term ground-based networks to track lightning and ionospheric propagation directly benefit heliophysics missions, and could be pursued by joint NASA/NSF funding programs.

2.2 Leveraging The Global Electric Circuit

The highly resistive troposphere sandwiched between the conductive Earth and the conductive ionosphere provides the medium for the two global electrical circuits. The traditional DC global circuit is characterized by an "ionospheric potential" between the two conductors on the order of 250 kilovolts. The AC global circuit (aka, Schumann resonances) is contained in the same medium which serves as a giant electromagnetic waveguide. Tropospheric lightning is a source term for both global circuits, a partial one for the DC global circuit [*Wormell*, 1930, 1953] and a nearly complete one for Schumann resonances.

The integrated upward current from thunderstorms and electrified shower clouds (ESCs) [*Wilson*, 1920] provide for the nominal kiloampere of return current in fair weather regions. The traditional altitude limit for this current flow is the 'equilibration layer' near 60 km [*Israel and Kasemir*, 1949]. However, it has been suggested [*Kasemir*, 1971; *Tuomi*, 1984] that some of these current lines leave the ionosphere and follow magnetic field lines into the Earth's magnetosphere in their ultimate return to Earth. The main dissipation region for Schumann resonances is comprised of two layers [*Madden and Thompson*, 1965] in the range of 50 to 150 km, well above the global tropopause height. As such, the combined effect of charge transfer in global lightning may, like TLEs, be contributing significantly to magnetosphere-ionopshere-thermosphere coupling. But more powerful Schumann resonance excitations known as Q-bursts [*OGAWA et al.*, 1966; *Ogawa and Komatsu*, 2007] may have an even larger impact.

Schumann resonances can be effectively exploited to study space-weather effects of solar X-radiation and solar proton events [*Schlegel and Füllekrug*, 1999; *Satori et al.*, 2016] on the background Schumann resonances. In this way, the Q-bursts from lightning serve as a natural ELF radar for probing changes in the ionosphere that may arise from space weather. So while lightning and its energy release occur in the troposphere, its potential use in space physics missions has not yet been fully realized.

3 Direct Impacts of Lightning in the Space Environment

Whereas the previous sections described lightning as a diagnostic tool, lighting also directly impacts the space environment in at least three ways, as described here.

3.1 Transient Luminous Events

Transient Luminous Events (TLEs) are an optical phenomena associated with thunderstorms that occur in the stratosphere, mesosphere and lower ionosphere [*Pasko*, 2010]. TLEs take on many different shapes and sizes: "elves", which are laterally expansive (300 km) luminous rings that occur at 80-90 km altitude [*Inan et al.*, 1997; *Barrington-Leigh and Inan*, 1999; *Cheng et al.*, 2007; *Kuo et al.*, 2007]; "sprites" (Figure 2), which initiate around 80 km altitude and propagate downward with speeds around 10^7 m s^{-1} [*Sentman et al.*, 1995; *Stanley et al.*, 1999]; "halos", pancake-shaped glows (50 km) often associated with sprites" [*Barrington-Leigh et al.*, 2001; *Frey et al.*, 2007]; "blue starters and blue jets", which begin at cloud top and propagate upward in the stratosphere [*Wescott et al.*, 1995, 1996]; "gigantic jets", which escape the cloud top and discharge storms to the ionosphere [*Pasko et al.*, 2002; *Su*, 2003; *Cummer et al.*, 2009].

TLEs electrically couple the troposphere to the ionosphere and can also be used to probe the lower ionosphere-mesosphere system [*Gordillo-Vázquez et al.*, 2018]. Gigantic jets can greatly alter the conductivity of the lower ionosphere [*van der Velde et al.*, 2010]. Sprites may affect mesospheric chemistry [*Sentman et al.*, 2008; *Gordillo-Vázquez*, 2008]. Blue jets and gigantic jets have in-situ effects in stratospheric ozone chemistry [*Da Silva and Pasko*, 2013; *Winkler and Notholt*, 2015; *Xu et al.*, 2020]. Gigantic jets could have a large impact on the Global Electric Circuit (GEC) due to the long sustained current flow associated with the events [*Siingh et al.*, 2007].

We advocate for: (1) support to expand the number of, and resolution of, TLE detections, to quantify how TLEs affect the ionosphere. Future observation capabilities should increase from regional-scale to continental-scale, (2) increased engagement with citizen scientists who, with off-the-shelf cameras, can observe TLEs in large numbers, (3) more expansive all-sky camera networks to detect TLEs, and (4) use of lightning detectors in orbit to detect TLEs [*Boggs et al.*, 2019]. Better sensitivity to the ultraviolet (UV)/blue wavelengths, higher pixel resolutions (tens of megapixels), and time resolutions of sub-millisecond will allow us to detect filamentary streamers associated with many TLEs. Spectral measurements from UV to near-infrared (IR) with sub-nanonmeter spectral resolution are needed to ascertain plasma properties of TLEs. In-situ measurements of the upper atmosphere are also needed. Parameters such as ambient electric field can help understand TLE initiation and formation from stratospheric balloon measurements, as models suggest sprites can initiate at subbreakdown electric fields [*Kosar et al.*, 2013]. Finally, future research studies of TLEs should utilize the International Space Station (ISS) and scientific aircrafts, which unlike ground measurements are not limited by optical scattering and clouds.

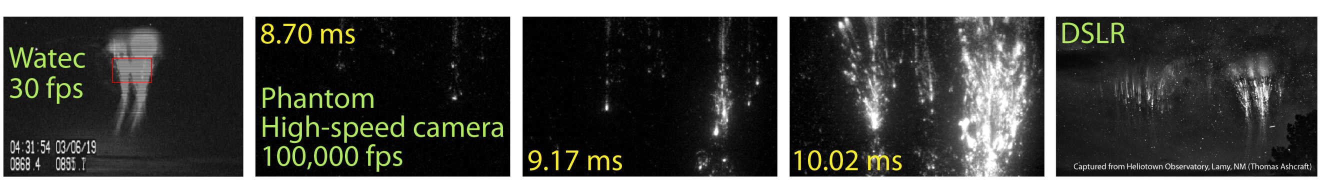

Figure 2: A sprite observed observed at 100,000 fps from Langmuir Lab in NM, adapted from *Contreras-Vidal et al.* [2021]. The visual morphology is a proxy for the energetic impacts of sprites.

3.2 Terrestrial Gamma-Ray Flashes

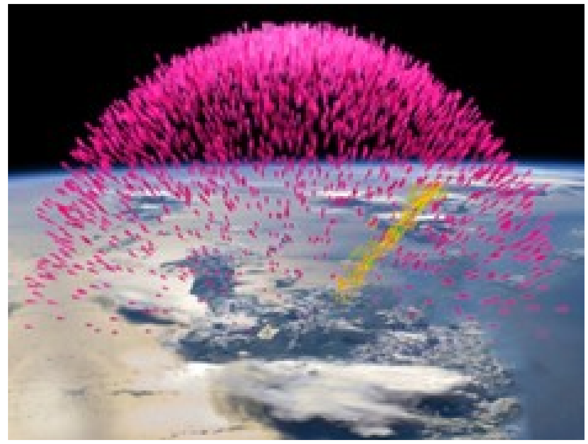

Figure 3: Depiction of a TGF (pink) and resulting electron-positron beam (yellow and green). Courtesy NASA.

Terrestrial gamma-ray flashes (TGFs) are powerful bursts of gamma rays, usually observed from space, that originate inside thunderstorms. They have durations ranging from 10s-1000s of μs and have energies up to 10s of MeV. The gamma rays are thought to be produced via bremsstrahlung interactions of energetic runaway electrons with air, accelerated by the strong electric fields inside storms. TGFs were first discovered by the Compton Gamma Ray Observatory (CGRO) in 1994 and have since been measured by the RHESSI, Fermi, AGILE and ASIM, all of which were funded as astrophysics platforms. Modeling suggests that up to 10^{19} high-energy electrons are being produced by the thunderstorms during a TGF. Observations and modeling have also shown that TGFs launch beams of energetic electrons and positrons into the inner magnetosphere in the form of terrestrial electron beam (TEBs).

Figure 3 shows an artist's impression of a TGF and the accompanying TEB, produced by a thunderstorm. Because the high-energy particles are being accelerated in the mid-to-high levels of the storms (e.g., 12 km), at the altitudes where commercial aircraft fly, research suggests that TGFs could be a radiation hazard for individuals in aircraft. The exact mechanism for producing TGFs is uncertain but may involve x-ray emissions from lightning leaders or a new kind of electric discharge involving a feedback effect from positrons created by pair-production within the storms. Because the gamma rays are produced in the highest field regions inside the thunderclouds close to the times that lightning is initiated, the gamma-ray emissions serve as a remote probe for studying thunderstorm electrification and lightning initiation. To date, most TGF observations have been carried out by space instrumentation that was designed to measure astrophysical or solar emissions and is not particularly well suited for measuring short and bright TGFs. In a few cases, TGFs have also been detected by aircraft and ground-based sensors. At present, our understanding of TGFs is very rudimentary. Therefore, more space-based, ground-based, and in situ observations are still needed to better understand this fascinating and fundamentally important phenomenon. A review of TGFs and other lightning-related phenomena can be found in *Dwyer and Uman* [2014].

3.3 Radiation Belt and Magnetospheric Impacts

Lightning return strokes generate intense electromagnetic radiation in the frequency band spanning from tens of Hz to tens of kHz [*Helliwell*, 1965]. These radio waves propagate radially outwards from the lightning location, within the Earth-Ionosphere waveguide, and leak through the partially conductive ionosphere into the near-Earth space environment. Here, they couple into the whistler-mode of plasma wave propagation, allowing them to be steered and guided by gradients in the plasma density and background magnetic field, to disperse (spatially) and to interact with the high-energy electrons (tens of keV and above) that comprise the Earth's radiation belts (see [*Ripoll et al.*, 2020] for a review). The Van Allen Probes yielded new statistics from lightning-generated whistlers, but the rarity of the most intense lightning [*Ripoll et al.*, 2021] makes full statistics, particularly at mid latitudes, still incomplete.

Numerous studies [*Johnson et al.*, 1999; *Blake et al.*, 2001; *Rodger and Clilverd*, 2002; *Bortnik et al.*, 2002, 2006a,b; *Peter and Inan*, 2007; *Inan et al.*, 2007; *Green et al.*, 2020] have shown that intense lightning discharges often cause electron precipitation into the upper atmosphere (observed with both ground-based and space-borne sensors), and theoretical estimates of its long-term impacts [*Abel and Thorne*, 1998] indicate that lightning-generated whistlers (LGWs) dominantly control the electron lifetimes of the inner portion of outer radiation belt electrons. Magnetospherically reflected whistlers can also trigger plasmaspheric hiss emissions [*Draganov et al.*, 1993].

However, many problems remain outstanding, including quantification of the efficacy of the lightning-generated whistler wave-particle interactions, the time dependent nature of those interactions, coupling into the ducted or nonducted modes, latitudinal propagation and damping, as well as the waves' potential to be naturally amplified and trigger secondary emissions.

4 Antidiscplinary topics

Lightning science crosses boundaries to both the planetary science and astrophysics realms.

4.1 Planetary Lightning

Lightning also occurs on other planets, most notably Jupiter [*Kolmasova et al.*, 2018], Saturn, Uranus, and possibly also Venus and Neptune. The basics of lightning formation is similar on other planets - charge separation leads to a high electric field, which promotes gas breakdown and propagating streamers and leaders. But there are key differences. For instance, lightning on Jupiter can release 10x more electromagnetic energy and is more mid and high latitude leaning than Earth's land and tropical-focused lightning.

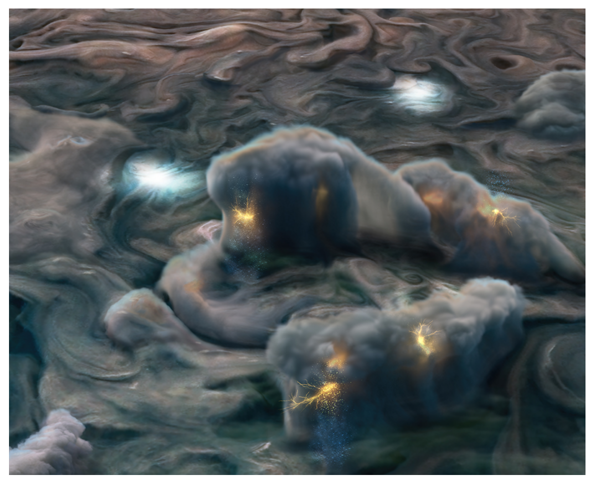

Figure 4: Depiction of Jovian lightning using Juno data. Courtesy NASA/JPL

Lightning characteristics depend on atmospheric composition, and potentially the planet's magnetic field. The occurrence of lightning and its phenomenology yield direct insight into the dynamics of a planet's atmosphere and space environment. As such, the study of lightning on other planets naturally dovetails with the study of lightning on Earth.

4.2 Bolide Detection in Lightning Networks

Bolides are the millions of known asteroids, comets and meteoroids in our solar system, with thousands more discovered each year. While bolides are not an impact of lightning, they are nonetheless another example of a way in which the science of lightning measurements impacts fields way outside tropospheric effects, in this case the response of the ionosphere to bolides. Many bolides have the potential to cause serious damage to life and property. The Near Earth Observations (NEO) program aims to find, track, and characterize at least 90 percent of the >140-m bolides. The occurrence of smaller bolides is frequent and comprised of a variety of meteor species. By studying the spectral characteristics of the emitted light and accurately recording its trajectory we will be able to characterize much larger bolide events.

The Geo-Stationary Lightning Mapper (GLM) on board the Geostationary Operational Environmental Satellite (GOES) spacecraft detects bolide impacts. Each year, approximately 1400 bolide impacts at the Earth's atmosphere are detected by the GLM. GLM covers nearly half of the globe, including location and magnitude data.

5 Discussion and Recommendations

A (virtual) workshop organized by NASA entitled 'Lightning-Related Research Beyond the Troposphere' took place on 2-3 May, 2022. An agenda and full recordings are available at this link.

Historically, research on lightning has been underfunded by NASA's heliophysics directorate, in part because as a tropospheric event, it is seen as Earth Science. However, NASA's Earth Science directorate considers the space-facing impacts of lightning to be outside its scope, since those are no longer atmospheric in nature. As such, the impacts of lightning beyond the troposphere has fallen between the cracks, despite its importance to Heliophysics mission science. NASA's structure, processes and organization have made cross-directorate funding and programs difficult. NASA's funding focus in this area has been largely tied to mission science on few-year frameworks, which has made it difficult to fund long-term observations from ground networks.

Some NSF-NASA programs have emerged recently, providing a potential path forward to fund the fundamental science and mission-based science, for all of ground data, satellite data, and modeling. We suggest expansion of these efforts aimed at lightning beyond the troposphere, given its connection to heliophysics topics. We thus present out overall recommendations in an effort to suggest targeted ways that NASA (and to some extent NSF) can bolster our understanding on Heliophysics through increased visibility for lightning and its effects beyond the troposphere:

1. NASA Heliophysics Directorate should provide more robust support to studying the impact of lightning beyond the troposphere.

2. NASA Heliophysics should bolster efforts to develop joint programs with Earth Science around lightning impacts beyond the troposphere.

3. NASA and NSF should jointly establish a new program to explore the coupling between lightning/thunderstorms, and space science.

4. NASA and NSF should jointly fund ground instrument networks that can complement NASA satellite missions.

5. NASA Heliophysics should develop jointly a funded program with NASA Planetary Science directorate on lightning

6. NASA Heliophysics should fund more in situ measurements in the stratosphere, including short-duration balloon campaigns and gliders.

7. NASA Heliophysics should engage the citizen science community around TLE detection.

8. Lightning should be viewed by NASA as an 'antidisciplinary' topic, given its impacts on Earth Science, Heliophysics, Planetary Science, and even Astronomy.

9. NASA's Geospace Dynamics Constellation (GDC) mission will provide measurements to address many outstanding ionospheric science questions and should be carried out.

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