Title: Advancing Ultraviolet Remote Sensing for Thermosphere - Ionosphere Forecasting in 2030 and Beyond

Brief Summary: Far Ultraviolet (FUV) remote sensing has shown potential for providing critical information to make better forecasts of the upper atmosphere system, an important region for space weather responses. This document suggests needed advances for future use of FUV remote sensing.

Motivation:

The Earth's thermosphere and ionosphere (T-I) constitute a dynamic system that varies rapidly in response to energy inputs from the Sun, the Earth's magnetosphere and the lower altitude regions. Within the T-I system plasma and fluid processes compete to control its temperature, composition, and structure. It is where energetic radiation from the Sun and charged particles from the magnetosphere are absorbed, and where waves propagating from the lower atmosphere finally dissipate. *Determining how the thermosphere-ionosphere (T-I) system responds to these drivers on a global-scale is essential to our physical understanding of the system's behavior, and to our capabilities to meet current and future space weather forecasting requirements*.

Better ionosphere and thermosphere forecasts are necessary to meet civilian requirements for navigation, orbit prediction and communications. The need for advances in orbit prediction, for example, which depends on neutral density changes, is increasing rapidly due to the burgeoning number of low-earth-orbiting satellites. While there are operational needs for each, the neutral atmosphere and the ionosphere are intricately coupled, so they must be studied as a coupled system.

Similarly, the changes that occur in the T-I system are not independent of changes that occur elsewhere in the system. Any measurements must not only address the coupled nature of the thermosphere and ionosphere, they must also address the spatial and temporal coupling of the system as a whole. To do this, it is necessary to both develop a system that makes relatively small-scale observations of the coupled T-I environment, and to develop a capability to gain a global-scale view of the entire system.

In the last 20 years, pathfinding observations using FUV remote sensing have shown its potential both for many local observations, and especially for providing the necessary global-scale description of the T-I system. However, much more can be achieved using this capability; it is the purpose of this document to suggest ways to greatly improve understanding of the T-I system using FUV remote sensing.

Consequently, future development of measurement, sensing and interpretation capabilities using FUV observations should be studied to determine both how to better use current capabilities but also how to build on and expand such capabilities. Important considerations include:

1. Advancing interpretation of measurements (e.g., using FUV observations to develop a global perspective on composition and temperature).
2. Advancing model capabilities for using measurements (e.g., data assimilation, high spatial and temporal resolution, coupling to adjacent geophysical regimes).
3. Advancing capabilities for and approaches to measurements (e.g., direct use of radiances rather than quantities derived from radiances, particularly in data assimilation models).

Description:

The first extensive use of FUV remote sensing for Earth's upper atmosphere in non-auroral regions was in 2001 with the GUVI (Global UltraViolet Imager) instrument on board the TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) satellite. TIMED provided the first comprehensive, lower latitude observations of thermospheric composition and the Equatorial Ionization Anomaly. The success of GUVI is evidenced by the large number of papers that have been associated with it. As TIMED aged, it was recognized that new techniques and more extensive use of FUV emissions could provide new insight into the thermosphere and the ionosphere. The Ionosphere CONnection Explorer (ICON) mission was designed to more comprehensively study the vertical structure and connections in the T-I system. It was launched in 2019. In addition to the FUV, thermosphere and ionosphere measurements are also made by other instruments on ICON. The other FUV instrument currently flying is for the Global-scale Observations of the Limb and Disk (GOLD) mission. It is hosted on a communication satellite in geostationary orbit, and takes full disk images of the thermospheric composition and temperature during the day, and O+ density at the F2 peak during the night. The combination of the two approaches promises to multiply the science of both missions. However, some steps to achieving that and expanding the potential capabilities for these and future missions are needed:

1. Analysis of data for consistency between measurements and measurement techniques for a quantity (e.g., cross compare with ICON and GUVI, reach consensus on algorithms used to analyze the data).
2. Test against models over wide ranges of conditions and advance model capabilities (continuing efforts with GOLD and TGCMs - TIEGCM, WACCM-X, CTIPe).
3. Expand Capabilities for assimilation (e.g., needs for memory, processing speed, numerical techniques, assimilation efforts at NOAA, Utah State, JPL etc.) and test assimilations against data.
4. Further testing and development of instrumentation capabilities for future missions (on small and large satellites, both cubesats and larger, including geostationary).

Future FUV Observations:

While measurements by a variety of instruments will be needed to understand and predict the effects of space weather in the T-I system, an expansion of existing FUV observational capabilities and their integration into a wider observational and modeling effort must be considered. Space only permits discussion of other capabilities in passing.

GOLD's geostationary perspective should be used to provide context for other observations and to provide a test for models by requiring them to replicate the observations, not just at one location, but at many locations simultaneously. This capability is also required to provide sufficient information for assimilation models to run successfully. But there are limitations of the GOLD approach. The first one is that composition and temperature can only be measured in the daytime. This limitation cannot be readily addressed, so we will not discuss it further here, although flying mass spectrometers on other satellites would supplement GOLD-type observations. The second is that GOLD provides little vertical information. The third is that GOLD disk observations effectively cover about 120 degrees of longitude. The fourth is that coverage of the critical high geomagnetic latitude region is limited.

In the rest of this document we will describe some of the ways that these issues can be addressed. The second issue can be addressed by using geostationary (GEO) observations combined with low-Earth-orbit (LEO) observations supplemented with ground-based data. The orbits of LEO satellites can be optimized to maximize the vertical information within the GEO satellites field-of-regard. Complimentary configurations, such as 4 polar orbiting LEO satellites at constant local-times separated by six hours, and use of FUV observations from LEO satellites should be examined. Additional instrumentation may be needed to provide the high latitude information mentioned in the fourth point. The final issue is that GOLD only observes a third of the world in the daytime and less at night. Constant monitoring of plasma bubbles, particularly in the evening equatorial region, is critical for space weather application at night. In the daytime, studies of waves, and other global phenomena such as geomagnetic storms, require a whole globe view of the thermosphere. The latter need can be addressed by 3 FUV instruments on GEO spacecraft, separated by 120 degrees longitude. Given that GOLD cost only $55M in 2011 dollars, this represents a cost-effective way to provide both the global perspective and constant monitoring of plasma bubbles. These data will also provide a platform to test and improve models and provide a good basis for data assimilation. They will also provide a much better perspective for more local observations by low Earth orbit satellites and ground based measurements.

30 Year Perspective:

The satellite, ground based observational and modeling efforts described here provide a basis for space weather activities in the thermosphere and ionosphere system for the next 30 years. This satellite configuration and the other observations and modeling can form the basis of a space weather effects monitoring network similar to current weather monitoring networks in the lower atmosphere. It is certain that presently unforseen technological and scientific developments will vastly improve the structure of this network. One such possibility is a network of cubesats that can complement this network. The nature of scientific research is such that we cannot fully anticipate the scientific enquiries that will be needed and undertaken 30 years from now. However, more extensive sampling of the ionosphere-thermosphere system, which continues to be severely under-sampled, and more effective use of current measurements can make essential contributions to all future scientific enquiries.