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Exploring the Earth's Atmosphere-Space Transition Region with Direct Measurements

A White Paper for the 2024-2033 Decadal Survey for Solar and Space Physics (Heliophysics)

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7 September 2022

Synopsis

The Earth's atmosphere-space transition region is a poorly understood yet vital region of Geospace -- it is here where the Earth's atmosphere and the ionized gases of space interact within a "boundary layer" at the base of the ionosphere between 100-250 km altitude. The interactions of these co-existing gases within this region and their consequences are profound. It is here where magnetospheric currents close, where ions and electrons drift at different speeds and directions due to the influence of ion-neutral collisions, where frictional heating between the gases is significant, where neutral wind "jets" are set up in concert with enhanced auroral conductivity, and where gravity waves propagating from below break and deposit energy. Furthermore, at high latitudes, this region is at the end of the line of the sun-upper atmosphere chain, and thus harbors the critical missing link in our knowledge of the transfer, dissipation, and regulation of energy and momentum from the Sun to the upper atmosphere.

Understanding the Earth's transition region is highly synergistic with NASA and NSF goals that seek to understand not only ion-neutral coupling processes but also how solar wind driven sources of energy and momentum couple with the upper atmospheres of the Earth and those of other planets. Indeed, low altitude measurements on NASA's MAVEN satellite have revolutionized our understanding of the Martian ionosphere-thermosphere system and we can expect equally groundbreaking results from future measurements within the Earth's transition region as well.

To make progress with our understanding, direct, high-resolution measurements of key parameters are required in order to reveal the characteristics and energy exchange within the atmosphere-space transition region. This white paper discusses the science motivation for gathering this fundamental knowledge which ultimately leads to new mission designs with both satellites and sounding rockets to gather the necessary measurements.

Atmosphere-Space Transition Region -- Overview

The interaction, coupling, and momentum and energy exchange between coexisting ionized and neutral gases are fundamental and universal processes inherent to vast regions of the cosmos, including such diverse regimes as planetary atmospheres and the Sun’s chromosphere. When threaded by a magnetic field, such “partially ionized” gases not only are influenced by external electric fields and magnetic field-aligned currents, but also feed back on these external energy and momentum sources.

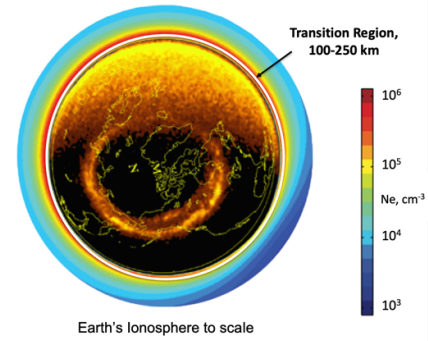


Figure 1

This physical picture is particularly germane for the transition region between the Earth’s neutral atmospheric gases and the ionized gases of space. This transition region is an atmosphere-space “boundary layer” that represents the region that exists between the atmosphere-dominated region below and the plasma dominated region above (Figures 1 and 2). Although the atmosphere-space transition region exists within a very limited altitude range, its importance and effects on the entire ionosphere-thermosphere region are profound.

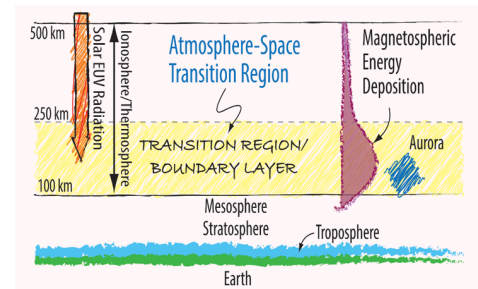


Figure 2

In terms of energy and momentum input from above, this region may be considered the “end of the line” for processes that begin in the Sun. It is where solar EUV and solar wind-derived energy from the magnetosphere are deposited — changing the state of the neutral and ionized gases — stored, and transformed in ways that can feedback on and alter the source region in the magnetosphere. In terms of input from below, this region is where tidal and gravity waves deposit energy and momentum from below and where upwards propagating thunderstorm deposit electrical energy. Despite the fact that the transition region is of such fundamental importance to the Earth and is the seat of so many fundamental and unique physical processes that are only manifest in this region, the transition region is very poorly explored. This situation can be remedied with space-based platforms with comprehensive instrumentation sampling within the atmosphere-space transition region.

High Latitude Processes in the Atmosphere-Space Transition Region

Within the atmosphere-space transition region on Earth, the strongest exchanges of heat and momentum between the neutral and ionized gases occur at high latitudes. This is the primary regime where ion-neutral collisions radically alter the ambient plasma and electrodynamic properties, as well as the neutral gas itself. The high-latitude transition region is the seat of a number of fundamental, intrinsic physical processes that only exist in this altitude region (Fig 3).

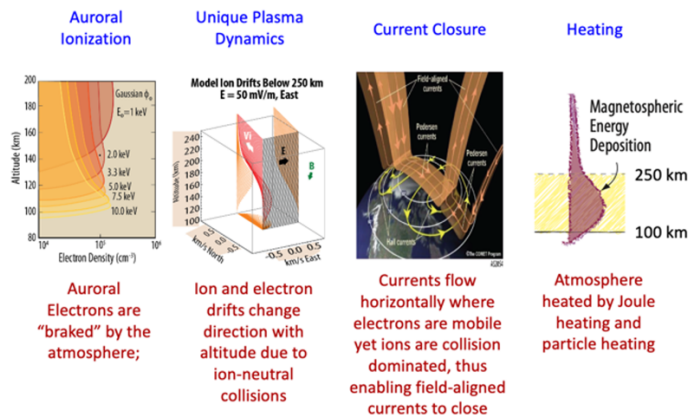


Figure 3

- **Auroral Ionization.** At high latitudes between 100-250 km, energetic, precipitating auroral particles are “braked” by the atmosphere via collisions, where they create thermal plasma and heat the atmosphere (Figure 4, Pfaff 2012). Indeed, the familiar auroral optical emissions are a visible manifestation of the interaction of the incoming energetic particles and atmospheric gases that primarily occur here.

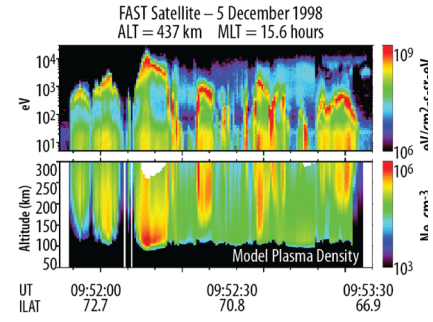


Figure 4

- **Heating.** Energy is deposited in the transition region in the form of electromagnetic Poynting Flux which creates Joule heating. The Joule heating per unit volume maximizes at low altitudes where the Pedersen conductivity is highest. Heating of the upper atmosphere also occurs here due to impacting auroral particle energy. Joule heating calculations using simultaneous measurements of electric fields, neutral winds, and plasma density have been carried out on sounding rockets and show large variations with altitude (Fig 5, Pfaff et al., 2003).

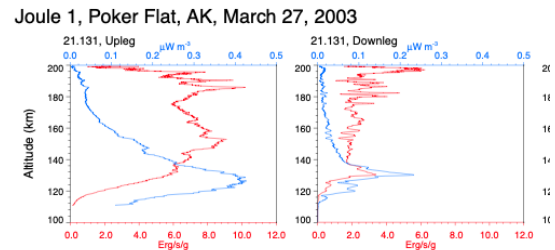


Figure 5

- **Current Closure.** Field aligned currents associated with the aurora close in the transition region as the electrons are mobile (due to their very small mass compared to that of the ions) and hence permit horizontal currents to flow. This current closure is a fundamental process that occurs in the high latitude atmosphere-space transition region with critical importance for models of dissipation and heating in the upper atmosphere, as well as feedback mechanisms that help to regulate magnetosphere-ionosphere coupling.

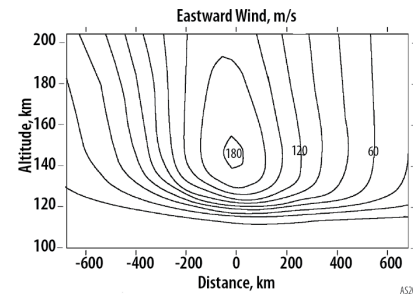


Figure 6

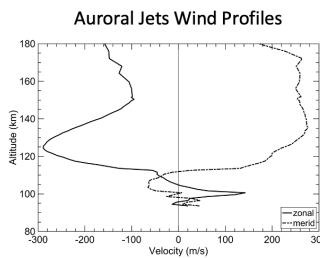


Figure 7

- **Dynamics.** In addition to the large-scale neutral wind circulation patterns which are virtually unknown in the transition region at high latitudes, smaller-scale, intense, neutral wind “jets”, associated with auroral formations, may also form at low altitudes. Brinkman et al., [1995] show the predicted formation of “jet streams” peaking at ~150 km within the aurora near where the ion-drag force per unit mass peaks (Figure 6). These neutral jets have been observed with sounding rockets on limited occasions, such as NASA’s Auroral Jets experiment (Figure 7, Larsen et al. 2021).

- **Ion Drift Deceleration Below 200 km and Instabilities.** DC electric fields associated with magnetospheric processes set the high-latitude plasma in motion via $\mathbf{E} \times \mathbf{B}$ drifts. At lower altitudes (below 200 km), however, the ion motion is appreciably affected by ion-neutral collisions such that the ion plasma drift is noticeably slowed and undergoes a change in direction. The electrons, on the other hand, remain fully “magnetized” and continue to execute $\mathbf{E} \times \mathbf{B}$ drifts at altitudes as low as 80–90 km (Figure 8, Pfaff, 2012).

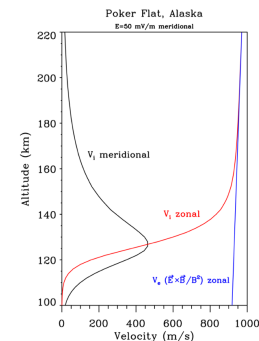


Figure 8

The collisional two-stream instability results when the $\mathbf{E} \times \mathbf{B}$ driven electrons “stream” through the ions that are collisionally bound to the neutral gas. This instability occurs when the relative ion-electron velocity exceeds a threshold given approximately by the ion acoustic velocity. In the auroral electrojet, such relative ion-electron drifts occur at altitudes between 95 and 125 km. The instability threshold is met for DC electric fields of approximately 20–25 mV/m, since the ion acoustic velocity here is typically about 350–400 m/sec (Figures 9, 10, Pfaff, 2012).

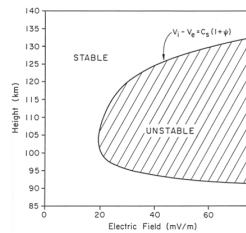


Figure 9

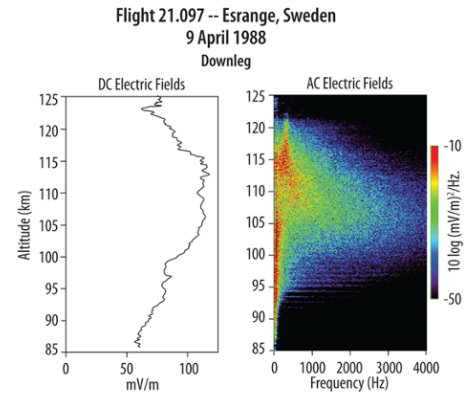


Figure 10

Key Mid/Low Latitude Processes in the Atmosphere-Space Transition Region

At mid and low latitudes, where the Earth’s dipole magnetic field lines are closed, the lower ionosphere/thermosphere reveals a different set of prominent features than at high latitudes (Fig. 11). Here, the influence of winds as well as tidal and gravity wave forcing from below dominate during quiet times. During disturbed conditions, penetration electric fields and other disturbance currents are expected to dominate but have never been studied systematically.

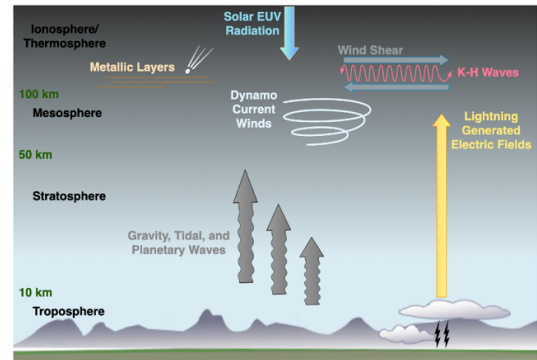


Figure 11

The most salient electrodynamic feature of the transition region at mid/low latitudes is the Earth’s atmospheric dynamo (Figure 12) which is a system of global, largely horizontal ionospheric currents (Figure 12). Neutral winds, driven by solar heating drag plasma across magnetic field lines which produce currents as the ions and electrons drift in different directions [e.g., Rishbeth and Garriott, 1969].

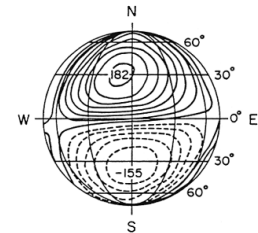


Figure 12

The dynamo region is found in the lower E-region (90–150 km), since here the Hall and Pedersen conductivities are greatest, as are the influences of the neutral wind. When magnetic disturbances are introduced, the influence of disturbance winds and heating as well as large external DC electric fields alter the patterns of E-region currents and fields, creating the *disturbance dynamo* which could develop additional current cells or loops [Figure 13, Blanc and Richmond, 1980].

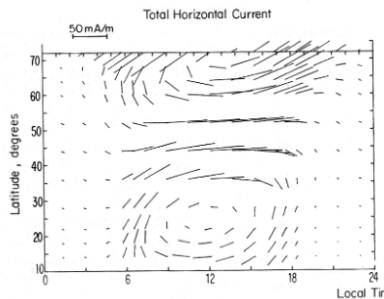


Figure 13

Sounding rocket observations during quiet times have revealed the winds, electric fields, and currents associated with the dynamo at mid-latitudes and that the winds and currents display a spiral pattern indicative that they are driven by tidal forcing from below (Figures 14a,b Pfaff et al. 2020).

Recent observations from ICON have revealed that the daytime winds are highly variable and intense, with large variations in the 100-150 km region (Figure 15 Harding et al., 2020).

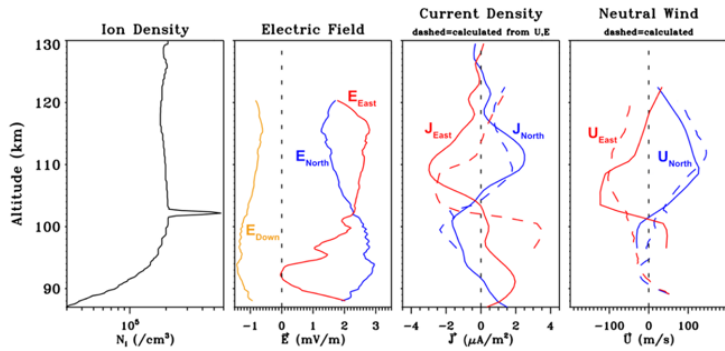


Figure 14a

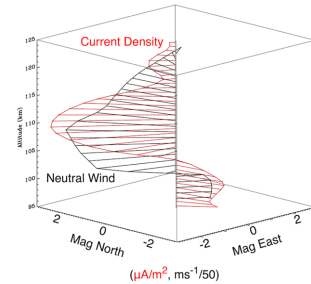


Figure 14b

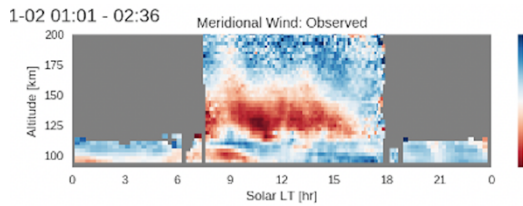


Figure 15

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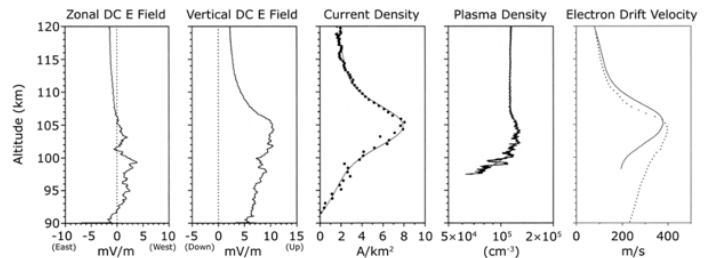


Figure 16

An important feature of the dynamo current pattern is the equatorial electrojet that flows along the magnetic equator and gives rise to intrinsic, enhanced vertical electric fields due to the Cowling conductivity enhancement (Figure 16 Pfaff et al. 1997). The response of the equatorial electrojet to wind shears as well as nighttime effects have not been measured. The equatorial electrojet plasma is often supersonic in which case it gives rise to two-stream instabilities in a similar manner as for the auroral two-stream data.

During the nighttime low altitude mid-latitude ionosphere, the wind shears associated with sporadic-E layers have been shown to generate Kelvin-Helmholtz instabilities that drive large scale structures. Such a process has been shown by Larsen (2000) to account for the quasi-periodic (QP) radar echoes that have been regularly reported in backscatter radar data associated with sporadic-E layers (e.g., Yamamoto et al. 1991; Hysell et al. 2004). Rocket measurements reveal electric field waveforms with pronounced km-scale structuring and evidence for steepening (Figure 17a Pfaff et al., 2005). The data appear associated with the mechanism responsible for a well-defined pattern of “whorls” in the neutral wind data that were revealed in a chemical trail released by a second sounding rocket launched 15 minutes later (Figure 17b, Larsen et al. 2005).

The lower edge of the ionosphere is the conductive upper layer of the ionospheric waveguide. To investigate how thunderstorm electrical energy penetrates this layer, Kelley et al. (1985) reported observations gathered by a pair of sounding rockets launched simultaneously to apogees in the mesosphere and ionosphere over an active thunderstorm at a mid-latitude location (Figure 18). The data clearly demonstrated that the DC electric field “pulse” associated with lightning spherics penetrated into the ionosphere, depositing energy in the ionosphere. These researchers also reported a significant component of the DC electric field pulse oriented parallel to the magnetic field direction

in the lower ionosphere. Such an electric field would be expected to contribute to localized plasma heating.

The effects of tropospheric storms on the ionosphere include other consequences. Burke et al. (1992) reported Dynamics Explorer- 2 observations of Alfvén waves over a hurricane that show a DC electric field pulse of more than 40 mV/m with an associated plasma density depletion and strong magnetic signature. Similarly, using data from the San Marco satellite, Farrell et al. (1994) reported large, localized DC electric field “structures” in the ionosphere over tropical storms, providing further evidence that DC-coupled electric fields associated with tropospheric storms propagate upwards and penetrate into and through the atmosphere-space transition region.

Gravity waves represent another key process that is particularly important to the lower ionosphere/thermosphere, as these waves propagate from the lower atmosphere and break and deposit energy in the transition region. In particular, gravity waves are a possible trigger for medium-scale travelling ionospheric disturbances (e.g., Tsugawa et al., 2007), which permeate through the ionosphere at higher altitudes.

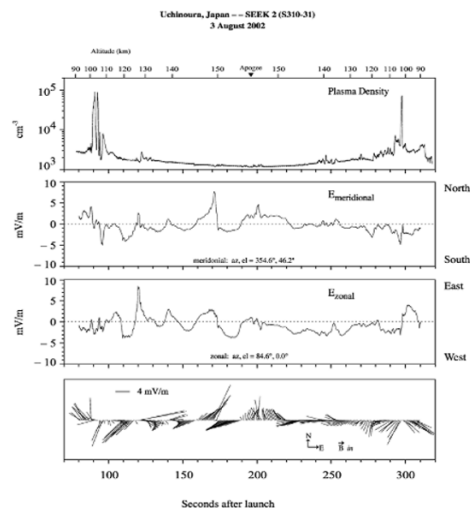


Figure 17a

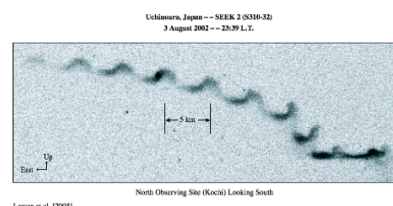


Figure 17b

The dynamics of the lower ionosphere/thermosphere at low latitudes is particularly challenging to understand without the aid of low altitude measurements. In particular, because the magnetic field lines are essentially horizontal, electric fields do not “map” in the vertical direction along the magnetic field lines as they do at high latitudes. Neutral dynamics are also affected by the lack of Coriolis forces at the geographic equator. Vertical profiles provided by vapor trails released by sounding rockets have shown significant and surprising gradients with altitudes in the E-region and lower F-region [Kiene et al., 2015]. In the dual rocket experiment from Kwajalein at sunset, plasma drifts are shown to exhibit large shears below 250 km and evidence of a vortex pattern, as predicted by Haerendel et al. [1992], which are not observed in a simultaneous satellite overpass near 400 km [Pfaff et al., 2022a].

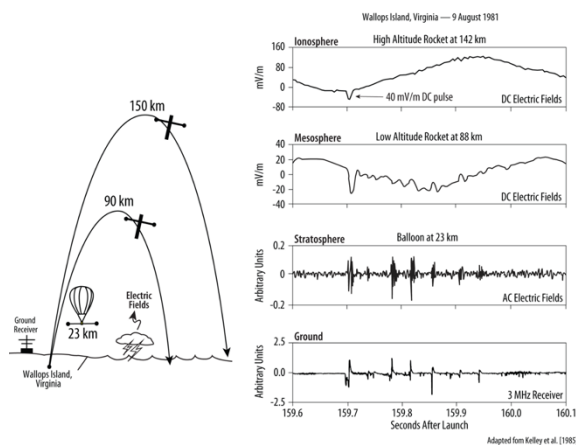


Figure 18

Gathering Comprehensive Measurements with Low Perigee Satellites

Although the Earth’s atmosphere-space transition region has been explored with radars and remote sensing observations, there are very few in situ observations of this region with comprehensive

measurements except from sounding rockets. Researchers must rely on idealized models driven by idealized inputs, and those models are clearly data starved. As a consequence, the fundamental unknowns in the transition region include (1) neutral wind circulation patterns in the transition region, (2) the location, intensity, or consequences of frictional heating, (3) the causes of global-scale composition changes observed remotely, (4) unknown electrodynamics including how magnetospheric currents close in the lower ionosphere, (5) how tidal and planetary waves deposit energy and momentum in this region from below and (6) how dynamo currents are set up including associated DC electric fields that then influence the higher altitudes.

These major observational gaps block our path to understanding the flow of energy into and out of the atmosphere-space transition region. To study this coupled system, we must measure simultaneously:

- The **drivers** – the energy coming into the system, including electric fields, winds, currents, and precipitating energetic particles
- The **response** of the system, including upper atmospheric winds and neutral density, currents and electric fields, ions, electron, and neutrals temperatures, and ion and neutral composition
- The **coupling** strength including collision frequencies between the neutral and ionized densities as a function of altitude, composition, and temperature.

To fully understand these plasma-atmosphere interactions, we must journey to the region where the exchange of energy and momentum between the solar wind and the atmosphere, and from the lower and middle atmosphere and the upper atmosphere, primarily occurs. For the Earth, this boundary layer occupies the altitude range from 100–250 km. This region is inaccessible to direct, sustained study by spacecraft that lack onboard propulsion, and has never been systematically explored with instrumentation to investigate simultaneously the electrodynamics and the neutral atmosphere response.

Future missions are needed with a comprehensive suite of well proven, high heritage scientific instruments, to gather the necessary, direct measurements of plasma-atmosphere coupling phenomena in the transition region. Such a series of dedicated low perigee satellites will dramatically improve our understanding of the mechanisms that drive the upper atmosphere in response to solar wind forcing from above and tidal/gravity wave forcing from below, dissipate this energy via heating and other processes, and regulate and modify the near-Earth space environment.

Previous Low Perigee Missions at the Earth and Other Planets

Fortunately, there is a solid legacy of exploration from NASA's Atmosphere Explorer (AE) satellites that journeyed into the atmosphere-space transition in 1973–1976 (Figure 19). Although AE-C and AE-E each included about one year of operations to perigees between 130 and 150 km, these missions did not include the comprehensive instrumentation or the sufficiently high inclinations to cover the critical high latitude region. AE nonetheless served as an important scientific and technological pathfinder by revealing the immense variability of the region and by demonstrating the feasibility of low-perigee operations.

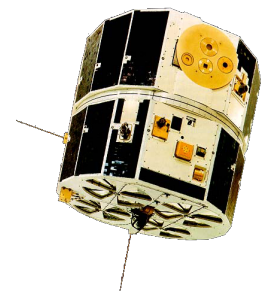
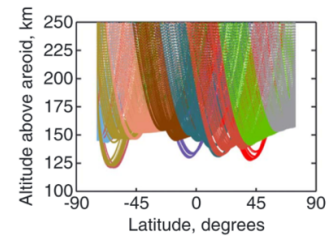


Figure 19

NASA also enjoyed considerable success with the Pioneer Venus mission that included periapsis journeys to ~150 km within the Venusian upper atmosphere, similar to the lowest AE-C perigee altitudes. As NASA continues to implement a vigorous program of exploration of our solar system, and in particular of Mars, NASA's MAVEN mission (Figure 20) focuses on the escape of the Martian atmosphere over time which undoubtedly depends on processes in its atmosphere-space transition region. Indeed, MAVEN's successful "deep dips" to low Martian altitudes (Figure 21) have demonstrated the richness of this region and the success of similar instruments as those which we believe should be carried out on Earth (e.g., Figure 22, Grebowsky et al. 2017).

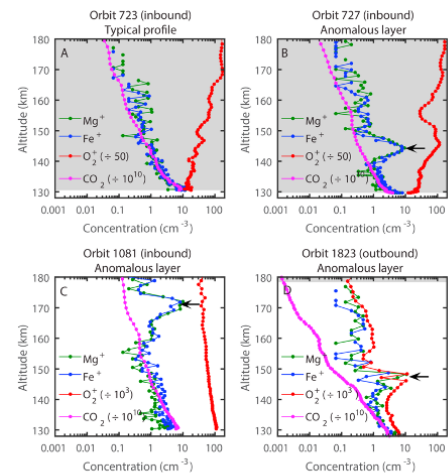


Figure 20



MAVEN "Dipping" Feb 2015 – Mar 2016
Figure 21

In view of the importance of understanding the atmosphere-space transition region, NASA has carried out a number of studies over the past several decades including engineering analyses of satellite missions to directly sample this region with *in situ* probes. These include both the TIMED mission, which originally included two dipper satellites, and the GEC mission, which included 4 dipper satellites. Despite their exceptional scientific importance and proven technical feasibility, these missions were not carried out due to programmatic reasons.



Metal ion profiles from MAVEN deep dives

Figure 22

In addition to these directed missions, NASA has also received a number of Explorer and Small Explorer proposals to carry out this research. These proposals have received very high reviews and, in fact, helped inspire the GEC directed mission. The most recent Explorer proposal, the Atmosphere-Space Transition Region Explorer (ASTRE) submitted by the NASA/Goddard Space Flight Center in 2011 with a detailed Phase A study the following year, was extremely well received but was not chosen in a very competitive selection. An artist conception of the ASTRE mission is shown at the top of this column. Details of the ASTRE mission may be found in Pfaff et al. [2022b]. Finally, a similar low perigee mission, Daedalus, has been proposed to ESA, which also seeks to understand the atmosphere-space transition region. Details may be found in Sarris et al. (2020).

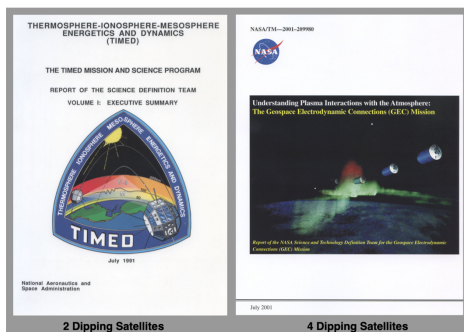
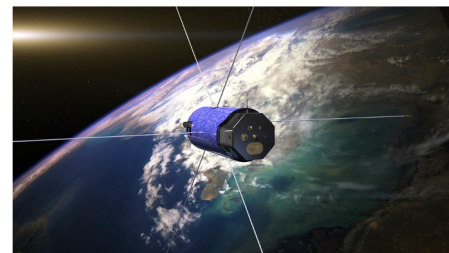


Figure 23



Atmosphere-Space Transition Region Explorer (Proposed)

Figure 24

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