A Constellation Mission to Understand the Thermospheric Reaction to Energy Input Across Scales

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1 Abstract

The thermosphere and ionosphere are tightly coupled, overlapping regions of the atmosphere that are forced from above and below. The system has no horizontal boundaries and therefore waves and winds can advect mass, momentum and energy easily from one place to another. Therefore the system is extremely dynamic. Utilizing single satellites to examine the dynamics of such a complex environment is extremely difficult because of the space/time ambiguities that exist with all satellites. Therefore, it is suggested that the ionosphere/thermosphere system instead be studied with a constellation of low mass Nano-Satellites that are complimented with miniaturized instruments that are capable of measuring the in situ state of the system (i.e., density, temperature and winds of the neutrals and ions). It is suggested that having four planes that contain six spacecraft is roughly the minimum that will allow the dynamics of the system to be adequately studied.

2 Description

The thermosphere is a crucial boundary between the Earth's atmosphere and space. Orbiting satellites and debris are strongly affected by the lifting of the atmosphere that results from thermospheric weather [*Bruinsma et al.*, 2006; *Fuller-Rowell et al.*, 1994; *Prölss*, 2004]. On March 12, 2009, International Space Station astronauts had to take shelter because a piece of debris passed too close to the ISS. On February 10, 2009, an Iridium cell phone satellite was destroyed in a collision with a defunct Russian satellite. These types of events can be mitigated with better understanding of the upper atmospheric conditions, which leads to more accurate orbit determination [e.g., *Bowman et al.*, 2008]. While current empirical models of the thermosphere can describe the general trends, they can not capture the true dynamics of the system [e.g., *Roble et al.*, 1988; *Fuller-Rowell and Rees*, 1980]. For an accurate specification of the density, an understanding of the thermospheric response to energy input is required.

There have been few satellites that have measured the parameters needed for a detailed understanding of what controls the thermospheric density structure. The CHAMP and GRACE satellites have accelerometers, inferring the mass density by assuming that the in-track wind speed is zero and that the exact orientation and drag coefficients of the satellites are known [e.g., *Lühr et al.*, 2004]. While this has provided a wealth of information on the global thermospheric distribution of density, there are still many unanswered questions on the energization of the thermosphere that can not be addressed by this type of measurement alone.

Further, single satellites assist us in our understanding of the climate of the system, but they are greatly hampered when an understanding of the dynamics is desired. For example, Figure 1 shows thermospheric density measurements from five consecutive ascending nodes. There are many interesting things occuring during this time including: (1) the density in the Southern hemisphere increases dramatically at the highest latitudes; (2) the density in the midlatitudes in the southern hemisphere barely increases; (3) the density at the highest latitudes in the northern hemisphere actually decreases; (4) The density in the equatorial region has the strongest reaction to the energy input; and (5) there is evidence of large-amplitude wave structure in the northern hemisphere midlatitudes.

From this figure it is clear that the thermospheric density can change by a factor of two in less than 90 minutes, which is the approximate orbital period of the CHAMP satellite. In between these orbits, there is no clear indication of what is occuring. While there is an indication of wave structure, it is almost impossible to determine whether the waves are travelling north or south. The waves also gain in amplitude from the high latitudes to the equatorial region, which is opposite from simple geometrical considerations, given that the equatorial region encompasses a larger area than the mid- or high-latitudes.

The example is illustrative of the fundamental problem of single-satellite in situ measurement missions - they can not unravel the dynamics of the system due to the fact that the orbital period is typically longer than the inherent time-scales in the system and that they can not determine whether something is propagating into the field-of-view or is created where it is measured.

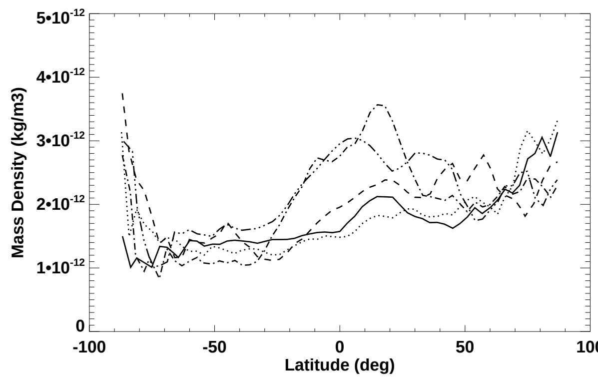

Figure 1: The thermospheric mass density measured by the CHAMP satellite during five consecutive ascending nodes. The order of the orbits in terms of line-style is: solid, dotted, dashed, dash-dot and dash-dot-dot-dot.

Typical satellites that are launched are very large for a few reasons, one of which has been that the size of the electronics has been quite large and heavy. Advances in commercial industry has pushed towards miniaturization of electronics, as clearly indicated by the progression from large desktop computers to laptops to iPads and smart phones. This technology has been embraced by many researchers in Heliophysics, and has resulted in many miniature instruments that, ten years ago, would have had a mass of over 10 kg, but now are under one. This miniaturization of instruments fundamentally changes how satellites can be designed, due to the instrument's decreased mass, volume and energy needs. Satellite busses take advantage of miniaturization also - on board computers and memory banks become smaller, radios become smaller, power systems become smaller, etc.

Practically this miniaturization means that satellites can become smaller and smaller or can be complemented with more and more instrumentation. In many ways, both paths are good for science in general. More instruments on one satellite provides more measurements of the relevant quantities that may be important for a physical understanding of the local processes. Smaller spacecraft may allow for more of them to be launched, providing multipoint measurments of the system. This is the path that we are advocating.

There have been two NASA Heliophysics missions that have utilized more than two satellites: Cluster and Themis. Both of these satellite missions have been magnetospheric oriented, studying very different processes in different ways. Cluster is a mission in which the satellites are flown relatively close together in order to understand gradients and meso-scale processes in the magnetosphere. The five Themis satellites are widely separated, allowing for large-scale processes to be examined. Each mission has been wildly successful.

We are advocating the use of constellation missions in the study of the ionosphere and thermosphere in order to understand the dynamics of the system after energy has been deposited at high latitudes. We suggest the use of relatively simple, miniature instrumentation mounted on Micro-Satellites or Nano-Satellites for such a constellation. Such a constellation of satellites deployed in the thermosphere/ionosphere could address many science questions, such as:

• **What are the scale sizes of thermospheric gradients in the auroral zone?** It has often been thought that the thermosphere has large scales and long time constants [e.g., *Innis and Conde*, 2001; *Guo and McEwen*, 2003]. While this may be true in some regions of the thermosphere when there is little activity, there is strong evidence that the thermosphere in the auroral zone is quite dynamic with strong gradients that can evolve rapidly [e.g., *Conde and Smith*, 1998; *Lühr et al.*, 2004; *Liu et al.*, 2010]. One of the primary science drivers of such a constellation mission could be to examine the spatial scales within the auroral zone thermosphere as energy is deposited into the system on a wide variety of scales.

• **How correlated are the neutral winds and ion flows on different temporal/spatial scales, and what controls that correlation?** A constellation mission that measures both the ion drifts and neutral winds could easily correlate them across many different spatial scales within the high latitudes.

• **On what scales do upwellings occur due to heating?** Results from Fabry Perot Interferometer data have shown that strong vertical winds can result in the auroral zone [e.g., *Spencer et al.*, 1982; *Crickmore et al.*, 1991; *Conde and Dyson*, 1995; *Price et al.*, 1995; *Guo and McEwen*, 2003]. Very little information is known about these vertical winds. It is unclear whether they are highly localized, resulting in significant horizontal shears in the vertical flow, or whether they occur over much larger scales. A constellation mission could provide direct measurements of these winds, allowing a quantification of the scale sizes, magnitudes and correlations with activity level.

• **What are the scale-sizes of neutrals away from the auroral zone after a heating event?** It can be speculated that the thermosphere may have small scales in the auroral zone, where the Joule and auroral heating may be quite localized [e.g., *Innis et al.*, 2001]. As the increased densities and temperatures propagate away from the source location of the heating, it is unclear how much structure will remain. One of the primary goals of Armada is to quantify the scale-sizes of the density, temperature and neutral winds as a function of distance away from the auroral zone, activity level, and amount of time after a heating event (e.g., time after a sudden increase in the auroral electrojet index, hemispheric power or cross polar cap potential).

• **What is the influence of the background temperature, density and wind structure on the propagation away from the heating location?** In order to quantify how the thermosphere reacts to energy input, the dissipation of the energy needs to be examined. One of the primary dissipation mechanisms within the thermosphere is the advection of the energy to different locations [e.g. *Sutton et al.*, 2005]. Modeling results have shown that after a solar flare, the increased dayside temperature and density cause a wave to propagate to the nightside, where the reconvergence of the wave causes a significant peak in density near the equatorial region around midnight [*Pawlowski and Ridley*, 2008]. The wave then begins to propagate towards the dayside again, but it is propagating against the bulk day-to-night neutral wind flow, which causes the wave to propagate more slowly and to dissipate almost completely before reconverging on the dayside. It is clear that the sound speed will be different on the dayside and nightside, which should result in an asymmetric propagation of gradients away from the high latitudes, possibly allowing the waves to dissipate at different rates. Further, nitric oxide, which is a significant radiative cooler in the thermosphere [*Kockarts*, 1980; *Barth*, 1992], has an asymmetric day to night distribution [e.g., *Cravens and Stewart*, 1978; *Gerard and Roble*, 1988; *Siskind et al.*, 1997; *Ridley et al.*, 1999], which may strongly influence the dissipation rate of the enhanced temperature wave.

• **How do different sized fronts lose coherence as they propagate away from the source?** The CHAMP satellite has shown that high latitude heating events cause perturbations that propagate towards the equator [e.g., *Sutton et al.*, 2005]. Modeling shows that these perturbations should pass through the equatorial region, into the other hemisphere and reconverge at the other pole. This has not been clearly observed in satellite data. Therefore, there is a clear lack of understanding in why disturbances lose coherence as they propagate through the equatorial region and into the opposite hemisphere. Having both ion and neutral measurements on a constellation mission, researchers could investigate whether the coupling between the two influences the dissipation mechanisms.

• **What are the interhemispheric asymmetries in the response of the thermosphere to energy input?** Studies have examined how the magnetic pole offset, the interplanetary magnetic field B_y component and the seasons affect the response of the thermosphere and ionosphere to energy input [e.g., *Thayer et al.*, 1987; *Newell and Meng*, 1988; *Crowley et al.*, 1999; *Lu et al.*, 1994; *Rodger et al.*, 1994; *Gasda and Richmond*, 1998]. Each of the studies that we have described above will include an interhemispheric component to it, where the northern and southern hemispheres are considered separately and together as a system. This will allow the examination of any hemispheric, seasonal, or magnetic differences in the scale-sizes and response of the thermosphere to energy input.

3 Objectives

This white paper advocates the use of a constellation of satellites to radically improve our understanding of the **dynamics** of the coupled thermosphere/ionosphere system. In order to acheive this goal the following top level requirements must be met:

1. Each satellite needs to be complemented with instrumentation that is capable of measuring both the neutral and ion state variables, such as density, temperature and winds. There are a few different instrument packages that are capable of achieving this requirement, with many of them small enough to fit on very small spacecraft. We specifically advocate the use of the Wind Ion Neutral Composition Suite (WINCS) [*Herrero et al.*, 2009] that is composed of four electrostatic analyzers (two for ions and two for neutrals, each mounted perpendicularly to each other) and two mass spectrometers (one for ions and one for neutrals). This suite of instruments contained in a single enclosure that is extremely small (less than 10cm x 10cm x 10cm) and is less than 1 kg in mass.

2. Each satellite needs to pass through the auroral zone, since this is the primary science zone.

3. There must be enough satellites in a single orbital plane that the return time to a location is less than dynamical time-scales within the system. Because our understanding of the dynamics of the system is quite weak at this point, it would be best to have to return times be variable. This means that the "pearls on a string" satellites within a single plane should have slightly different orbital periods, allowing them to catch up to and pass each other, giving return times between 0 minutes and the orbital period of the fastest satellite. Because of ground-based instrumentation, we understand that the inherent time-scale in the large-scale ionospheric convection is roughly 15 minutes [*Ridley et al.*, 1998], we should have more than six satellites within each plane (i.e., six satellites provides an average of 15 minutes return times to the same place).

4. Multiple planes of satellites should be utilized to provide information on the longitudinal structure and the dynamics of system. The scale-sizes of the thermosphere/ionosphere in longitude are poorly understood, and so it would, once again, be good to have variable spacing in longitude, allowing systematic studies of the longitudinal and local time variability in the the system. The number of orbital planes is quite difficult to specify, because our understanding is so limited. Four planes at equal spacing would allow for the comparison of many different local time sectors, but may not allow for the dynamics of longitudinally propagating waves to be examined. Therefore, it is suggested that four is the minimum that could be deployed in order to begin to understand the global structure of the thermosphere/ionosphere system.

5. A side-benefit from having different orbital periods for each satellite in an orbital plane is that in order to actually accomplish the different periods, the satellites must be deployed at slightly different altitudes or with slightly different ellipticities. Either way, the satellites will pass over or under each other, providing a view of the vertical structure in the thermosphere and ionosphere on small-scales.

4 Cost

It is suggested above that the minimum number of satellites that should be launched is 24 (four orbital planes containing six satellites). If one were to simply assume that the 24 satellites would cost roughly the same as a Themis satellite (assuming that the Themis mission cost approximately $180M, so each satellite cost 1/5 of this, or $36M), such a mission would cost approximately $864M. This is obviously a simplification, but it may put an upper cap cost on the mission.

There are a few reasons why this cost may be a significant over estimate:

1. The size of the spacecraft could actually be significantly smaller than those within the Themis mission. It is now possible to incorporate sensors such WINCS into NanoSats under 10 kg. Building a smaller spacecraft typically costs less money than a larger spacecraft, due to power, thermal and structural downsizing.

2. Companies exist that build multiple satellites in relatively large quantities. For these types of builds, the companies validate the process of building, and conduct less testing on the individual satellites being produced. A switch to this tye of building requires more non reoccuring expenses, but, overall, a huge savings is gained in the production of many systems.

3. At the level of four or five spacecraft, it is still possible to treat the satellites as individual entities and runs communication systems and such the typical way. As the number of satellites grow beyond a small number, the method for communication and operations needs to change. For example, automated scheduling of downloads needs to be done. While the operations cost for a constellation mission may be larger than a single or double satellite mission, it will be significantly less than the cost for a single satellite multiplied by the number of satellites.

It is suggested that building 24 satellites at 10kg each would cost on the order of $10M each, for a total of $240M for satellites. Considering that operations costs will be significantly larger than typical satellite missions, this could run as large as $24M, or 10% of the cost of the satellites. With costs of management, systems engineering, science, etc., the cost of such a mission is estimated to be on the order of $350M, excluding launch costs.

There are two alternatives to launch 24 10kg spacecraft to relatively high inclinations (above 80°) into four different orbital planes: (1) launch all the satellites on a single large rocket with a bus that is capable of making small orbital changes needed to deploy the spacecraft into the slightly different inclinations; (2) launch two smaller rockets in which the upper stage can perform a single orbital maneuver that can change inclinations by a small amount, and dispence two orbital planes. Each method has different costs and benefits. With a single launch vehicle and a bus to deliver them into orbits, they can be placed more exactly into the orbital planes, and a second rocket is not needed. For two rockets, the orbital insertion may not be as precise, but there is redundancy in the system if one of the rockets were to fail. If the single rocket were a Taurus and the two other rockets were Pegasuses, then the cost of building a deployment bus along with the cost of the Taurus may be comparable to the cost of two Pegususes with simple deployers attached to the upper stage. Either way would cost approximately $100M, bringing the total mission cost up to about $450M.

5 Relevance

National Academy of Sciences Decadal Survey for Solar and Space Physics has the following highlights that are specifically addressed by such a thermosphere/ionosphere constellation mission:

• Challenge 3: Understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences.

• Challenge 4: Understanding the basic physical principles manifest in processes observed in solar and space plasmas.

• Challenge 5: Developing a near-real-time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun, in the interplanetary medium, and in Earths magnetosphere and ionosphere.

• Advanced science instrumentation. Highly miniaturized sensors of charged and neutral particles and photons will be essential elements of instruments for new solar and space physics missions. **Recommendation: NASA should continue to assign high priority, through its recently established new instrument development programs, to supporting the development of advanced instrumentation for solar and space physics missions and programs.**

• Gathering and assimilating data from multiple platforms. Future flight missions include multipoint measurements to resolve spatial and temporal scales that dominate the physical processes that operate in solar system plasmas. **Recommendation: NASA should accelerate the development of command-and-control and data acquisition technologies for constellation missions.**

The 2010 Heliophysics Roadmap for Space and Technology has the following highlights that could be specifically addressed by such a constellation mission:

• Origins of Near Earth Plasma (ONEP): Understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.

• Ion-Neutral Coupling in the Atmosphere (INCA): Understand how neutral winds control ionospheric variability.

• Climate Impacts of Space Radiation (CISR): Understand our atmospheres response to auroral, radiation belt, and solar energetic particles, and the associated effects on nitric oxide (NO) and ozone.

• Dynamic Geospace Coupling (DGC): Understand how magnetospheric dynamics provide energy into the coupled ionosphere-magnetosphere system.

In addition, such a constellation could address the following research focus areas: **F2** Particle acceleration and transport; **F3** Ion-neutral coupling; **F4** Creation and variability of magnetic dynamos; **H2** Earths magnetosphere, ionosphere and upper atmosphere; **H3** Role of the Sun in driving change in the Earths atmosphere; **H4** Apply our knowledge to understand other regions; **J1** Variability, extremes and boundary conditions; and **J4** Effects on and within planetary environments.

6 Technical Challenges

In order for NASA to accomplish a constellation mission with 24 or more satellites, three areas should be addressed specificially:

1. NASA should recognize that single satellites launched on single rockets are single points of failure, while a satellite mission with many satellites can lose a certain percentage of them without a serious degradation of the science that can be accomplished. This is not to say that the quality of the satellites should be lowered in any way, but there should be a fundamental shift in validating the build/integrating/testing process instead of a focus of the individual satellites when considering constellations. This will significantly reduce the per spacecraft cost which may enable more satellites to be deployed at the possibility that a slightly higher percentage may fail. For example, if 48 satellites could be built under this scheme instead of 24 under the current scheme, and the failure rate only increases by a few percentage points, then the mission would have significantly more satellites in orbit, even though a small percentage may fail sooner than expected.

2. NASA needs to fund programs focused on the miniaturization of both instruments and subsystems such as attitude determination (e.g., star trackers, horizon sensors, rate gyros, etc.) and communication (e.g., UHF, S-band and X-band radios). By shrinking these critical subsystems, more small instrumentation may have the capability of being put on Micro- and Nano-Sats.

3. NASA needs to upgrade its communication network to enable the possibility of many simultaneous contacts, very fast acquisition of new contacts, and automated handling uplinks and downlinks. With the

current network, it is very hard to envision a large constellation mission that is taking significant amounts of data to succeed using only the NASA near-Earth network.

7 Summary

This white paper advocates a Heliosphysics mission to study the dynamics of the ionosphere/thermosphere system that would be composed of a constellation of 24 Nano-Satellites with a mass of less than 10kg. These satellites would be dispersed with six satellites in four different orbital planes. Giving each satellite a slightly different periodicity would allow the satellites within the plane wto spread out over time, and giving each of the planes a slightly different inclination would allow the planes to spread out over time. The scientific aim that is suggested in this white paper is to examine the response of the thermosphere/ionosphere system to high latitude heating, so each of the planes would need to be at approximately 80°-85° inclination angle.

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