Constellation Mission and the Next Leap in Magnetospheric Physics

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Abstract. Magnetospheric physics has reached a threshold from which a new leap can be launched that will solve major, long-standing problems and open up major new areas of research. The leap can be achieved with a new tool for magnetospheric research that will give the field the ability to obtain continuous sequences of magnetospheric images simultaneously in 3-D with spatial coverage broad enough to encompass the magnetosphere's main dynamical process and with resolution great enough to see the associated movements and transformations of the relevant magnetospheric structures. The new tool comprises a constellation of autonomous micro-satellites with advanced detectors that provide pixels out of which magnetospheric images can be rendered with tailored software.

1. The Next Leap in Magnetospheric Physics

Above the lithosphere, the hydrosphere, and the atmosphere extends the magnetosphere, the fourth and final physical geosphere. Distinct ages mark the way humankind has thought about this fourth geosphere. First came the "classical age," dating to Aristotle, which saw the fourth geosphere as a sphere of fire, a pyrosphere, whose occasional visible flames produce the northern lights. Then after the demise of Aristotelian cosmology and the ascendance of the "age of reason," William Gilbert declared Earth to be a "great magnet," and the fourth geosphere was thought of as an inert magnetic field reaching into the vacuum of space (as it was, for example, much later by Birkeland and Störmer). Three hundred years after Gilbert, a "modern-age" fourth geosphere appeared. Chapman and Ferraro envisioned sporadic ionized streams from the sun that squeeze Gilbert's magnetic geosphere into the form of an elongated bubble. Now, the present "age of space exploration" has given us a picture of the fourth geosphere that unites Aristotle's elemental fire as plasma, Gilbert's great magnet as a space filling dipole field, and Chapman-Ferraro's solar streams as a continuously blowing solar wind. The new feature that the space-age view adds is internal structure. The magnetosphere has a plasmasphere, radiation belts, a ring current, a plasma sheet, and an associated family of electrical currents. A continuous solar wind confines the geomagnetic dipole field to a cavity with a long tail, which is supported internally from collapse under magnetic tension by hot plasma that makes, as a by-product, the polar lights. Viewed as a project to determine what the fourth geosphere is as a physical object, the progression of ages has arrived at a reasonably complete answer. It seems unlikely that another conceptual leap will add a new category of substance, field, or structure requiring the space age picture of the magnetosphere to be substantially revised.

Nonetheless, a future, fifth age is in the offing that will redraw the way we depict the magnetosphere. The new age will create images against which the present picture will seem as barren of information as the Chapman-Ferraro structureless bubble seems now. It will replace the present static picture of the magnetosphere with a dynamic, moving picture of the actual magnetosphere responding to real solar wind conditions. The age of space exploration populated the Chapman-Ferraro bubble with plasma structures. The new age—which for the purpose here I will dub the age of space domestication—will animate these structures to reveal how the magnetosphere behaves as a global geophysical system. Then our view of the magnetosphere will comprise an unbroken, diachronic series of 3-D, global images. We will see the magnetosphere constantly performing selections from a repertoire of dynamical modes. The dramatis personae—calms, pulsations, bursty bulk flows, substorms, continuous magnetospheric convection, magnetic storms, etc. and their entourages—will repeatedly enact variations on standard scenes. We will watch as external and internal dynamical modes vie to express themselves while the vicissitudes of an indifferent external world, played by the solar wind and the IMF, determine their fates. We will become as at home in the magnetosphere as we are at home in a play of Hamlet. The new view will render the magnetosphere familiar and domesticated. Despite its familiarity, the detail and variety of the drama it enacts will make it more interesting than our present magnetosphere to both lay and scientific observers. Most importantly, it will provide the information needed to launch the next leap in magnetospheric physics.

In talking about executing a "leap" in magnetospheric physics, I mean bringing about a major increase in the power of the tools that we, as magnetospheric physicists, use to advance our science, an increase in power great enough to solve major, long-standing problems and to replace them (finally) with new ones by opening up major new areas of research. For the leap to be successful, it must transform the field, rid it of stagnating conflicts that arise when available data grossly under determine central paradigms, and lift it to a level where it can describe with authority the physical nature of the processes that characterize its domain and that make it a special branch of science. If, therefore, I were to list a delimited set of the leap's scientific objectives, however long, it would reveal my failure to understand the concept of a leap. A leap should take us to where we cannot know from here the questions that will be asked. This is the criterion that defines a successful leap. To see this, consider the leap from the Chapman-Ferraro magnetosphere to the current one. Questions about where and how magnetospheric substorms start—which now consume the field—would be incomprehensible in the context of the Chapman-Ferraro featureless magnetic bubble. For an example from another field, consider solid-earth geophysics. At the advent of plate tectonics, who imagined that nearly all textbooks then existing on traditional geophysics would become antiquarian novelties within two decades? The power of in situ paleomagnetic measurements to make global maps of magnetic anomalies enabled the transformation of a field. Before this happened, questions central to present-day geophysics simply could not have been formulated. The power of continuous sequences of global, 3-D, synoptic images of the magnetosphere has the potential similarly to transform magnetospheric physics.

The following examples illustrate the nature of the next leap for the magnetosphere. The leap will be from a static outline depicting the nominal shapes of the magnetopause and the plasma sheet to a video showing their surfaces progressively deforming and twisting as a sudden change in solar wind pressure or IMF direction washes over them. The leap will be from sketches of the magnetosphere's major current systems, which now have uncertain or unknown connections, to a 3-D computer graphic showing streamlines of the instantaneous curl of the global magnetic field; the global electrical wiring diagram in its

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multiplicity will simply reveal itself. The leap will be from a "wiggle plot" showing the magnetic field at point partaking in a magnetic pulsation to images showing entire magnetic field lines oscillating everywhere; magnetospheric seismology will have come of age. And the leap will be from a dozen cartoons showing a dozen ideas of what a substorm is to a spectator's view of actual substorms igniting, exploding, and fading; think of Yoko-like images of the magnetosphere erupting in a series of substorms. These examples illustrate different scales of magnetospheric phenomena from the global (whole magnetosphere) to the synoptic (current systems and substorms) to the mesoscale (pulsations and bursty bulk flows). To distinguish these scales from the microscale (kinetic processes), I refer to them collectively as macroscale. Then I may describe the next leap in magnetospheric physics as taking us from statistically derived diagrams of structures and conceptual sketches of dynamical processes to continuous sequences of global images of the actual, "living" magnetosphere that adequately resolve its macroscale structures in space and its macroscale dynamics in time.

2. Analogies and Lessons from Meteorology

The magnetosphere bears a family resemblance to the other geospheres, especially to the atmosphere. The atmosphere is a fluid that manifests many types of 3-D, nonlinear dynamical modes. These modes exhibit organization over different characteristic scale lengths from the global scale to the mesoscale. In magnetospheric parlance, they exhibit cross-scale coupling. These couplings result in discrete storm systems such as tropical and extratropical cyclones. The aspect of coupled, multiscale dynamics resulting in discrete storm systems makes the resemblance between the atmosphere and the magnetosphere particularly striking. Enough so to motivate an interest in seeing how the scientists who work to understand atmospheric dynamics have managed. First it should be noted that there are many more of them than of us, that they have been at it far longer, and that they are no less bright. Hence atmospheric dynamicists, who have problems very similar to ours, have evolved farther in dealing with theirs. They have already made a leap analogous to the one under discussion here. Theirs was a leap from a stage that had developed a highly serviceable climatology (an understanding of the average atmosphere) to a stage that was able to develop a highly serviceable understanding of storm systems (an understanding of the dynamic atmosphere).

In meteorological parlance, the leap we are describing will take us from climatological models of the magnetosphere to continuous global views of the magnetosphere's actual, ongoing weather systems. (See Figure 1 for an example of the distinction between weather and climate in the magnetosphere.) At present we have highly developed climatological models of the magnetosphere but relatively primitive models of the magnetosphere's weather systems. This is because we are in a transitional stage that occurs in the normal history of a geoscience. Climatological models naturally develop before weather models, for they are statistical. Scientists build them by accumulating measurements over time from relatively few stations. For example in 1686, Edmond Halley published the first climatological map showing prevailing winds over the world's oceans. Such climatological knowledge was immensely useful for sea trade, but a mariner facing a hurricane or a squall would prefer detailed weather information. Since knowledge to provide this kind of information requires repeated, simultaneous, mesoscale-resolution, synoptic-scale observations, it took longer to develop. Now such knowledge exists and the detailed weather information it provides is readily available and widely distributed, for example, on the Weather Channel. To speak figuratively and loosely to make a point, magnetospheric physics has its trade winds but not yet its Weather Channel.

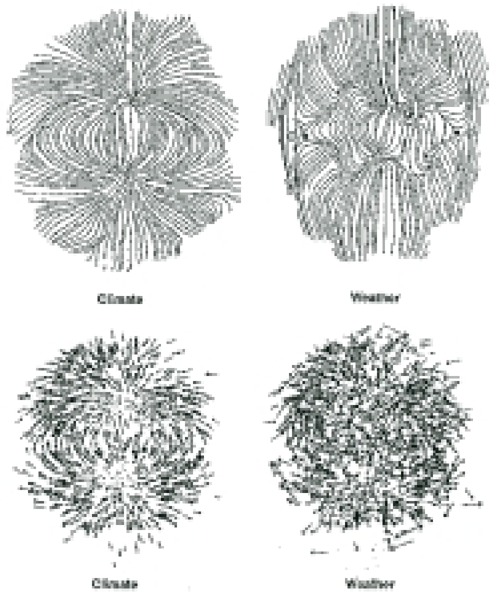

Figure 1. Illustrating the difference between "weather" and "climate" for the magnetosphere. The upper pair of figures shows streamlines of the magnetic field in the cross-sectional plane of the magnetotail at about 30 Re from Earth. The nearly symmetrical left pattern is an average over 16 years of measurements taken with the IMP 8 satellite. It shows climatology. This pattern is constant in time. The unsymmetrical right pattern gives magnetic streamlines at one instant computed with the Lyon-Fedder global MHD code. It shows weather. This pattern undergoes "synoptic" scale changes in time. [The upper pair of figures are taken from Kaymaz et al., 1995.] The lower pair of figures shows magnetic field vectors projected onto the cross-sectional plane of the magnetotail at about 30 Re from Earth. The symmetrical left pattern corresponds to the upper left pattern. It represents an average over 16 years of all measurements made in a 5 Re square centered on the vector. The chaotic right pattern shows randomly selected vectors from the averaging volumes before averaging [from Kaymaz, 1993].

Of course the goal of the next leap is not to provide data to feed a Space-Weather Channel (though that would be nice). Instead it is to provide data to feed magnetospheric physics for the purpose of developing deep knowledge of the magnetosphere's weather systems. From such knowledge a future Space-Weather Channel would be possible if warranted. But the leap itself is a leap in science. The science in this case is the macroscale dynamics of the magnetosphere. To amplify this remark, I will appeal again to comparative geoscience to emphasize a point that is well known in the disciplines that treat the three lower geospheres, which is this: Macroscale dynamical processes in geophysical fluid dynamics—the branch of physics that applies here—are as fundamental, interesting, and intellectually challenging as the microphysical processes that ultimately convert ordered macroscale energy into disordered thermal energy. Moreover, they are the processes whose effects give a geosphere its characteristic dynamical modes. For the lithosphere, these include mantle convection and plate tectonics; for the hydrosphere, surface and abyssal ocean currents; for the atmosphere, tropical and extratropical cyclones; and for the magnetosphere, geomagnetic storms and substorms. From a geophysical perspective, determining the modes of macroscale dynamics is a top priority; arguably it is *the* top priority. The leap I am discussing will let us fully describe at least the magnetosphere's major modes of macroscale dynamics, and beyond that, it will give us the data we need to understand these modes as natural solutions of the governing equations of motion.

Take substorms, a specific but important example of one of the magnetosphere's dynamical modes. Our sister field, meteorology, has an analogy that shows how important it is to be able to resolve the full range of spatial and temporal scales over which a particular dynamical mode, like the substorm, operates. The extratropical cyclone is the dominant weather system of the troposphere at midlatitudes. In that sense it is analogous to the substorm, the dominant weather system of the leeward magnetosphere. Its characteristic pattern of warm and cold fronts radiating out from a migrating low pressure center which forms, deepens, then dissipates as the fronts fold and collapse on each other epitomizes the complex, basic fluid dynamics that operates on the macroscale in the earth's geospheres. This is not to say that the substorm works by the same dynamics as the extratropical cyclone. It doesn't. Instead, the point of the analogy is that both are macroscale phenomena in which mesoscale structures are organized on a synoptic scale, both go through a life cycle of onset, growth, and decay, and both are incomprehensible from the perspective of climatology, or even from the perspective of a number of simultaneous point measurements up to a network of sufficient size and density.

In 1743 Benjamin Franklin showed that the storms now called extratropical cyclones do not form, grow, and die in place but instead move from place to place. The local start-to-finish experience of a storm results not from its building up then dying away locally but from its passing through. More than a century went by before a network of in situ observing stations grew large enough simultaneously to encompass a 3-D low pressure center, spot its onset, follow its growth, track its motion, and record its decay. The mesoscale pattern of the temperature field that accompanies the synoptic scale storm was the crucial piece of information that led to understanding the physical mechanism that drives the storm. Meteorologists now call this mechanism the baroclinic instability. A network of observing stations wide and dense enough to resolve the baroclinic instability's mesoscale structure on a synoptic scale was not achieved until 1919. Now for the analogy with substorms: though the observational branch of substorm research is well beyond the Benjamin Franklin, single-station stage, it is still far from the synoptic stage. We think that a substorm evolves from a center having a more-or-less preferred location in or near the magnetotail. But we have yet to establish a magnetospheric observing network large enough and dense enough actually to encompass a substorm, resolve its onset within a 3-D measuring matrix, follow its growth, and record its decay. There is reason to think that the substorm is as complex as the extratropical cyclone. We should, therefore, expect it to hold on to the secret of its mechanism as tightly as did the extratropical cyclone. In particular, it is unlikely to yield up its secret before we can describe with empirical, model-independent certainty what the substorm is as a fully resolved, spatiotemporal physical event.

There is a second and more general point to the analogy, which concerns applying another lesson from meteorology to magnetospheric physics. It is this: the only known way to obtain instantaneous information on the data fields that govern macroscale dynamics—these data fields are pressure and temperature in meteorology and pressure and magnetic fields in magnetospheric physics—is through simultaneous, multi-point, in situ observations. The measurements must be in situ because these data fields are otherwise invisible. Except for model-dependent inversions of spatially limited energetic neutral atom (ENA) imaging (which are nonetheless highly valuable), one can remotely sense neither the magnetosphere's pressure fields nor its magnetic fields. Yet these are the physical quantities that provide the forces that drive magnetospheric dynamics. They define the distributed force fields that enter the equations of motion. It should therefore be a high-priority undertaking for our discipline to image these quantities in order that magnetospheric physics might engage in the dialog between macroscale theory and observation on which progress in geoscience depends.

3. Strategic Principles and Implementation Issues

Among the strategic principles by which NASA might move under its Sun-Earth Connections theme to reach a capability of obtaining continuous sequences of global, 3-D, synoptic images of the magnetosphere's dynamical parameters, I suggest these. 1. Build on existing and future program elements. The Sun-Earth Connections theme and its partners in other national and international agencies already have satellites that can be integrated into the service of developing a global magnetospheric imaging capability. These include IMP 8, Wind, POLAR, Geotail, Equator S, Interball, SAMPEX, FAST, ACE, Cluster, TIMED, IMAGE, Multiscale, DMSP, GPS and other DOD, DOE, and NOAA satellites. 2. Make clear and sharp distinctions between the goals of these missions and the goals of the global magnetospheric imaging mission. 3. Build over time in planned phases. Although most versions of constellation missions propose to launch all satellites in the constellation at once, a phased approach has strategic advantages. A phased approach can reduce and control the cost per unit time and allow the project to integrate the experience gained from earlier phases into implementing later phases. Each phase should have self-justifying scientific objectives. Each phase can use the full satellite constellation that has evolved up to its time to set its mission goals. 4. Compose each phase (beyond the initial one) out of groups of autonomous microsats with advanced detector capabilities. Such satellites might be dubbed pixies since they provide the pixels for the global magnetospheric images. As a top priority, constantly evolve pixie configuration to increase global imaging capability. 5. Design pixies for minimum instrument complement, duty cycle, and data rate consistent with the overriding global imaging objective. Let no other objective compromise this principle. Its enforcement is critical to keeping the cost per satellite low enough to build a constellation numerous enough to achieve the ultimate global imaging objective. 6. Build an L1 solar wind station into constellation concept. As for any global magnetospheric mission, continuous solar wind data are essential to the success of the project. 7. To the extent possible, build remote sensing imagers into the constellation concept, for example, a high altitude polar imager of auroras and an ENA imager of magnetospheric plasma populations. These expand knowledge of global context and, in conjunction with in situ magnetic field measurements, can give useful macroscale information on particle pressure. 8. Develop software graphics routines, based, for example, on analytic, 3-D, least-squares fitting algorithms, to turn pixilated images into continuous 3-D graphics with full rotating and slicing power. Provide the capability for users to mix, match, and create images of many types using combinations of parameters and features for multipurpose applications, for example, to generate animated images of boundaries, plasma populations, electrical current stream lines, magnetic field lines, pressure contours, and so on. 9. Operate the mission as a facility. A useful analogy might be the Hubble mission, which has no instrument PIs with associated MO&DA. Instead the facility "belongs" to the community, individuals from which can apply for funds to use the facilities' data resources for research and applications. 10. Aggressively develop outreach programs. The project could exploit the existence of many pixies to extend some meaningful form of nominal ownership of individual pixies to educational institutions and other high-profile outreach targets.

Besides strategic principles, there are many implementation issues that must be resolved during a mission concept study phase. Among these are the following. 1. Design the optimum mission. This is a most critical task. Under-design will frustrate science objectives, because of limited science capability, and over-design will compromise mission objectives, because of excessive cost. To the end of finding an optimum mission, it might be useful to adopt a functionalist perspective. Think of the constellation mission as a new tool for magnetospheric research whose function it is to achieve the next leap in magnetospheric science. Then the question is: What is the minimum power the tool needs to solve major, long-standing problems in magnetospheric science and to open up major new areas of research? The problem has two parts: defining the minimum pixie and defining the minimum satellite constellation. 2. Consider first defining the minimum pixie, for which I suggest a zero-base approach. Start with an instrument complement consisting of nothing but a vector magnetometer and build from there. Specifying the global magnetic field gives the global electrical currents by taking the curl. In regions of subsonic plasmas—which includes most of the magnetosphere most of the time—one then gets the pressure from the static force balance equation. The information thus acquired already goes a long way in the direction of obtaining continuous sequences of global, 3-D, synoptic images of the magnetosphere. Then ask: How much new information is added for what price with each additional instrument? Select instruments on the basis of most dynamical information (pressures, velocities) added for least cost until a cost ceiling is reached or until an obvious point of diminishing return is reached. In this exercise, it is essential to weigh the value of information added by how well it provides a pixel for global images of dynamical quantities. After instrument definition, determine the minimum duty cycle and data rate. There is no point, for example, in a duty cycle faster than needed to resolve the propagation time of information in the global system. 3. Define the minimum satellite constellation. The constellation ultimately must be able to resolve the spatial structures of interest and their movements and transformations. The zero-base approach can be applied here as well. The phased approach also helps by building up to the minimum constellation in phases, each stage justified in part by information obtained in the previous phases. We will know enough at each phase to be able to specify a lower limit on a constellation size needed to achieve the objectives for that phase. 4. Define position and attitude requirements. Not only is there a minimum constellation size, there is an optimal constellation distribution that gets the most useful global images out of the minimum constellation. In this case, optimization should also consider the delivery costs associated with achieving the distribution. Moreover, the satellite density must be great enough and the attitude determination accurate enough to give reliable determinations of derived quantities, such as the vector electric current density. 5. Define telemetering requirements. The problem of retrieving information from a large constellation of microsats must be addressed in the concept definition phase. There are opportunities here for groundbreaking innovations. Low data rates will help reduce the receiver requirements. The degree of success will set the horizon for exploiting multipoint microsatellite projects in general. 6. Define a data-handling system. How centralized and how distributed should be the data acquisition, processing, distribution, and storage tasks? There is an obvious role for strong centralization of primary functions. But there might be advantages in performing some tasks in a distributed mode. There is also an opportunity here to extend nominal ownership to outreach targets. 7. Develop imaging software. This project opens up a new arena for graphics software development. The software should create continuous images out of multiple point measurements as the points move. It should also create images of many parameters, both directly measured and derived, for example, images of magnetic field lines and electric current streamlines. It should also create images of user-specified quantities, for example, images out of contours of scalar quantities, images out of stream lines of vector quantities, combinations of images, 3-D images from arbitrary viewing positions, and 2-D images in arbitrary planes.

4. A View from After the Leap

Though we cannot know from here what will consume the interest of our science in the post-leap era, it is still useful to name some long standing problems that the envisioned leap will likely make obsolete. Continuous sequences of global, 3-D, synoptic images of the magnetosphere's dynamical fields have the potential to answer many questions on macroscale structures and dynamics left unanswered during the last three decades. Ideally, the answers will take the form of explicit, complete spatiotemporal physical descriptions. Among questions that should receive such answers are these. 1. What is the origin of the plasma sheet? The images will show how it recovers after substorms: from the front, from the sides, or from behind. 2. What is the geometry of the plasma sheet for all IMF orientations? The classical butterfly cross-sectional shape based on averages for all IMF directions is not fully consistent with IMP-8 data binned on unidirectional IMF. We really do not know what the plasma sheet looks like at any instant most of the time. 3. Where do the field-aligned currents that are known from maps at the ionospheric level go in the magnetosphere? These currents, named region 0, region 1, region 2, NBZ, cusp, and mantle, are mostly at high latitudes where field-line mapping from the ionosphere to the magnetosphere is highly uncertain. Some carry as much current as flows in the magnetosphere's major structural currents: the Chapman-Ferraro current, the storm-time ring current, and the tail current. So field-aligned currents evidently carry significant amounts of energy and information between the magnetosphere and the ionosphere, in both directions. Though some models exist that connect some of the field-aligned currents at the ionospheric level to magnetospheric sources and loads, none is verified and most are controversial. 4. What is the spatiotemporal evolution of a substorm seen in its entirety? As indicated earlier, the importance of answering this question cannot be overstated. 5. What is the spatiotemporal evolution of a magnetic storm seen in its entirety? The standard picture of a geomagnetic storm features a symmetrical ring current. Yet during the growth of this ring current, the asymmetry in the disturbance field exceeds or equals the symmetrical disturbance, up to and including the maximum disturbance. Evidently the process of creating the symmetrical ring current entails the action of an asymmetric current system as powerful as the ultimate symmetrical ring current. There is virtually everything to be learned in an empirical sense about the global, 3-D asymmetrical development of the magnetic storm. 6. What is the relation between magnetic storms and substorms? Though this is part of the previous question, it has a history and an interest of its own. Here the emphasis is on the role that substorms play in storm phenomenology and on whether they are central to storm development. The answer that substorms play a minor role in storm development—which recent work in this field suggests—would be a major finding. 7. As a final question, what are the modes of coherent magnetospheric behavior? All previous questions are subsumed under this one. They epitomize global modes of coherent behavior but do not exhaust them. Other known modes include traveling convection vortices, continuous magnetospheric convection, global resonances, and substorm triggering by sudden changes in solar wind or IMF parameters.

5. Summary

The magnetosphere is Earth's fourth and ultimate physical geosphere, encompassing the lithosphere, hydrosphere, and atmosphere. The history of humankind's understanding of this fourth geosphere has gone through four great ages: a pyrosphere age, a great-magnet age, a stream-confined-magnetic-bubble age, and a space-age age that combines the earlier ages into a synthesis incorporating internal structure. The conceptual distance between ages illustrates what is meant by a leap in the history of science: the big, central questions at one age cannot be formulated at previous ages. Each age opens up a world of new questions. In the course of answering these new questions the science becomes more general and more powerful. We seem to be at a stage of advancement within the fourth age of magnetospheric science that we can deliberately engineer a leap to a fifth age.

Courage so to leap can be mustered by recognizing that an analogous leap has occurred in a related field—atmospheric science—and that it worked. The analogous leap in atmospheric science was from descriptive climatology to dynamical meteorology. The key to the leap in this case was developing the ability to make in situ observations of the dynamics-governing quantities over a wide enough spatial domain to encompass synoptic phenomena, with close enough station spacing within the domain to resolve mesoscale structure, and with fast enough cadence across the domain to follow macroscale evolution. This ability allowed meteorologists to engage in a bootstrapping dialog between the observations and theory of macroscale phenomena. The concept is simple but difficult to implement since it requires many stations operating continuously over an extended area. So, implementation naturally comes late in the history of a geoscience. Magnetospheric science has developed mature climatological models, but its dynamical models lack adequate data on the behavior of macroscale dynamical modes, adequate in the sense of being commensurate with the scale and intricacy of these modes. Such data would allow magnetospheric science to move (in meteorological terms) from an age descriptive climatology to an age of dynamical "magnetospherology." The goal of a constellation mission is to provide such data.

To achieve this goal, a constellation mission should follow certain strategic principles and tackle particular implementation issues. Chief among these is optimizing the trade-off between instrumentation, data rate, and fleet size. To succeed in providing data needed for macroscale dynamics, fleet size should generally win trade-off contests against instrument and data-rate challenges, consistent with achieving the mission's prime goal (achieve simultaneous, diachronic data on dynamics-governing parameters with synoptic-scale coverage and mesoscale resolution). One way to maximize fleet size is to apply a zero-base strategy in building the instrument complement and in setting the data rate. Start with the absolute minimum, then add instruments and data rate while keeping track of the cost in the form of diminished fleet size. Then ask, does the increase in information on dynamics-governing quantities that the added instrument or data rate provides balance the loss of information on the magnetospheres dynamical modes that the consequent diminished spatial coverage or resolution entails? Err on the side of coverage and resolution, since this side leads to the new age.

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