First Community-wide Sun-Earth Connection Roadmap Workshop

The first SEC roadmap workshop was held April 10-12 at the Applied Physics Laboratory. Approximately one hundred members of the space physics community attended. The first day of the workshop was devoted to the presentation of concepts for future missions, which ranged from a Mercury orbiter or flyby mission to a small satellite mission for the study of red sprites. On the second day, the participants divided into four subgroups. Each subgroup was assigned one of four broad science themes and tasked with articulating a coherent set of science objectives within its assigned theme. Particular emphasis was to be placed on multidisciplinary objectives that could lead to collaborative undertakings with the astrophysics and planetary science communities. If possible, science objectives were to be formulated in language that would convey to the public and Congress the importance and excitement of the enterprise of space physics and underscore its relevance to humankind's efforts to address fundamental questions about the origins of the solar system, the universe, and life itself. Subgroups were also charged with identifying the technologies needed to achieve the science objectives.

The four science themes, which had been worked out by the core group at its planning meeting on February 29-March 1, were:

- How does the Sun work as a variable, magnetic star? (solar physics)
- How does the Sun interact with other planets and the interstellar medium? (heliospheric physics)
- How does solar variability affect the geospace environment? (magnetospheric physics)
- How does solar variability affect our home in space? (ionospheric-thermospheric-mesospheric physics)

Following the subgroup meetings, the workshop participants re-assembled in plenary session to receive reports from the subgroup chairs on the recommendations developed by each subgroup.

On the final day of the workshop, the participants divided into two teams. Team A was made up of representatives of the ITM and heliospheric physics communities; Team B, of members of the magnetospheric and solar physics communities. Each team was charged with synthesizing the results of the subgroup discussions and developing a first outline of an SEC strategic plan for the period 2000-2020. The recommendations of the two teams were presented to the SEC roadmap core group at the conclusion of the workshop. Together with strategic planning recommendations that will come out of the SECAS meeting scheduled for May 1- 3, these recommendations will serve as the basis for the first draft of the SEC roadmap. A preliminary attempt to integrate the results of the subgroup discussions and the recommendations of Teams A and B is presented in the following section.

The core group met briefly following the end of the workshop to develop a list of possible future Solar Terrestrial Probes. The following were identified as strong candidates for STP missions:

- 1. Mercury Orbiter
- 2. Grand Tour Cluster
- 3. Solar Stereo Mission
- 4. Magnetospheric Stereography Mission
- 5. Global Electrodynamics Mission
- 6. Mesospheric Coupler
- 7. Microsatellite Constellation

The core group also included Solar B in its list of candidate missions for the near term. Solar B is a mission of opportunity rather than an STP mission.

Microsatellite Constellation for Global Magnetospheric Imaging

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 will be achieved with a new tool for magnetospheric research that will give the ability to obtain continuous sequences of magnetospheric images simultaneously in 3-D with spatial coverage broad enough to encompass the main magnetospheric 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 are rendered with tailored software. A key strategic element in the implementation of this global in-situ imaging concept is deployment over time of groups of microsats in planned stages, each self-justified, each building on its predecessors, and each moving the accumulating constellation directly toward a global imaging capability.

Contents

1 The Next Leap in Magnetospheric Physics

The magnetosphere is the fourth geosphere, the other three being the lithosphere, the hydrosphere, and the atmosphere. 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 whose occasional visible flames produce the northern lights. Then came the Age of Reason, during which William Gilbert declared Earth to be a "great magnet," and the fourth geosphere became a magnetic field reaching into space. Three hundred years later, after the discovery of subatomic particles, a modern-age fourth geosphere appeared. Chapman and Ferraro envisioned sporadic ionized streams from the Sun that squeeze Gilbert's magnetic geosphere into a bubble. In the present age, which might be called the Age of Space Realization, the picture of the fourth geosphere unites Aristotle's plasma-fire, Gilbert's magnetic field, and Chapman-Ferraro's solar streams and adds internal structure: a continuous solar wind confines the geomagnetic field to a cavity with a long tail 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 essentially arrived at the answer with the present age of space realization. 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 and create images against which the present picture will seem as out of date as Chapman and Ferraro's empty bubble seems now. This next age, which might be called the Age of Space Utilization and Habitability, will replace the present static picture of the magnetosphere with a dynamic, moving picture of the global magnetosphere responding to real solar wind conditions and performing its own internal modes of behavior. The present age populated the Chapman-Ferraro bubble with plasma to reveal internal structures. The next age will animate these structures to reveal global behavior.

The following examples illustrate the nature of the next leap in magnetospheric physics. The leap will be from a picture showing the nominal outline of the boundary and plasma sheet–a still life–to a video tape of measurements showing the progression of macro-scale deformations of the boundary and plasma sheet following a sudden change in solar wind conditions as it propagates from nose to tail; we will actually see how the magnetosphere manages to reconfigure its plasma sheet to follow the IMF as it rotates through, say, 180 degrees. The leap will be from a sketch of the magnetosphere's major current systems, which now have uncertain or unknown connections, to a 3-D, rotatable computer graphic showing streamlines of the curl of the simultaneously measured global magnetic field; the global electrical wiring diagram in its multiplicity will simply reveal itself. The leap will be from a line plot showing the magnetic field at point as that point partakes in a global magnetospheric oscillation–a wiggle plot–to images showing global magnetic field lines oscillating; 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 Yohkoh-like images of the magnetosphere erupting in a series of substorms. In summary, with the next leap in magnetospheric physics, magnetospheric depictions will go from static pictures of structures based on data averages and cartoons of dynamical processes under- determined by the data to continuous image sequences based on simultaneous global measurements that spatially resolve 3-D structures and temporally resolve dynamical processes.

To develop a particular but important example, consider substorms. No one need tell members of the substorm community how thoroughly the envisioned leap will revolutionize their discipline. Still, our sister field, meteorology, has an analogy that helps illustrate its importance. The extratropical cyclone is the dominant weather system of the midlatitudes, and in that sense it is analogous to the substorm, the dominant weather system of the 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 large scale in the Earth's geospheres. This is not to say that the substorm shares the same dynamics as the extratropical cyclone. Rather, the point of the analogy is that both are large scale, both are significantly structured, both go through a life cycle of onset, growth, and decay, and both are incomprehensible from the perspective of a point measurement or even from the perspective of a number of point measurements up to a network of sufficient size and density.

Before proceeding with the analogy, however, we should take advantage of the meteorological setting to emphasize a point that has been well established in the disciplines that treat the three lower geospheres. The point is this: large scale dynamical processes in geophysical fluid dynamics–the branch of physics that applies here–are every bit as fundamental as the microphysical processes that ultimately convert ordered energy into disordered energy. Moreover, they are the processes whose effects give a geosphere its characteristic dynamical modes of behavior, for example, mantle convection and plate tectonics for the lithosphere, surface and abyssal ocean currents for the hydrosphere, tropical and extratropical cyclones for the atmosphere, and geomagnetic storms and substorms for the magnetosphere, to name just a few. Accordingly, determining the modes of large scale dynamics is an important priority in a research program that has as its goal the understanding of any geosphere. The leap we are discussing aims at determining the modes of large scale dynamics for the magnetosphere.

In 1743 Benjamin Franklin showed that the storms we now call 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 and then dying away but from its passing through. More than a century elapsed before a network of in-situ observing stations grew large enough to simultaneously encompass a 3-D low-pressure center, spot its onset, follow its growth, track its motion, and record its decay. The pattern of the temperature field that accompanies the storm is the essential piece of information that led to understanding the physical mechanism that drives the storm, the mechanism meteorologists now call the baroclinic instability.

By analogy, substorm research is at the Benjamin Franklin stage. We know that the substorm evolves from a center having a more-or-less fixed location in the magnetosphere, but we have yet to establish a magnetospheric observing network large enough and dense enough to actually encompass a substorm, resolve its onset within a 3-D measuring matrix, follow its growth, and record its decay. There is no reason to think that the substorm is less complex than the extratropical cyclone and, hence, no reason to think that it will yield the secret of its mechanism more readily than did the extratropical cyclone, for example, even before we can describe with empirical, model-independent knowledge what the substorm is as a spatio-temporal physical event.

There is a second and crucial aspect of the analogy–a lesson from meteorology that applies with full force to magnetospheric physics. The only known way to obtain simultaneous, spatially comprehensive information on data fields of invisible parameters, such as pressure and temperature in meteorology and magnetic fields and currents in magnetospheric physics, is through simultaneous multi-point in-situ observations. One cannot remotely sense pressure fields, and one cannot remotely sense magnetic fields and currents. Yet these are the physical quantities that provide the force that drives the dynamics in the two geospheres. The distributed force fields are defined in these quantities. They are the quantities that must be imaged to understand the dynamics. To obtain such images requires taking simultaneous, multipoint in-situ observations with sufficient spatial coverage to encompass the phenomena and high enough station density to resolve their features.

The leap from static pictures of averaged structures and cartoon sequences of processes to continuous sequences of global, 3-D, synoptic images of the magnetosphere is widely recognized to be the logical next move in magnetospheric science. For example, the 1995 publication of the Space Studies Board of the National Research Council, A Science Strategy for Space Physics, states under its section on magnetospheric physics that, after completing ISTP, "Global imaging of the magnetosphere [is the] highest priority for magnetospheric investigation. Its importance has long been recognized and it should be the next observational thrust in the field." But we need not belabor this point farther. It is obvious by analogy with the experience of meteorology, and it is obvious in its own right. Magnetospheric physics, the discipline, has reached the point where it knows that the domain for which it has assumed responsibility has numerous globally coherent dynamical modes, both driven and inherent, but it does not know what many of them are, including some that are the most salient. The need to find out what they are is critical to its central mission of finding out how the magnetosphere works as a global geosphere. For this, continuous sequences of global, 3-D, synoptic images of the magnetosphere are essential.

2 Science objectives: Examples

In talking about executing a "leap" in magnetospheric science, we mean bringing about a major increase in the power of the tools that magnetospheric physicists use to advance their science, an increase in power great enough to solve major, long-standing problems and great enough to open up major new areas of research. For the leap to be successful, it must transform the field, rid it of stagnating conflicts that hold back any field whose central paradigms are grossly under-determined by the data, 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, this section were to list a delimited set of science objectives, even a long one, it would reveal a 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 the leap's success.

For instance, questions about the magnetospheric site of the onset of magnetospheric substorms, 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 geophysics. At the time of the advent of plate tectonics, who imagined that nearly all textbooks then existing on geophysics would be antiquarian novelties within two decades? The power of paleomagnetism to make global maps of magnetic anomalies made possible the transformation of a field. The present day questions in geophysics simply could not have been formulated before the advent of plate tectonics. The power of continuous sequences of global, 3-D, synoptic images of the magnetosphere has the potential to similarly transform magnetospheric physics. Still, it is useful to name some long-standing problems that the envisioned leap will likely make obsolete and to imagine examples of new types of problems that might occupy the post-leap magnetospheric community. Continuous sequences of global, 3-D, synoptic images of the magnetosphere have the potential to answer most if not all questions unanswered during the last three decades on mesoscale and macroscale structures and dynamics of the magnetosphere in terms of explicit, complete spatio-temporal physical descriptions. These include such major long-standing questions (MLSQs) as the following.

2.1 Major Long-standing Questions

The following are major unresolved questions in the field of space physics that can be answered through continuous sequences of global, 3-D, synoptic images of the magnetosphere:

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.

What is the geometry of the plasma sheet for all IMFs? The classical butterfly cross-sectional shape based on averages for all IMF directions is grossly inconsistent with data binned on unidirectional IMF. This holds especially for the usual Parker spiral orientation and for northward IMF. Thus, we do not know what the plasma sheet looks like at any instant most of the time.

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, NDC, cusp, and mantle, are mostly at high latitudes where field lines mapping from the ionosphere to the magnetosphere is highly uncertain. Some carry as much current as flows in the major structural currents of the magnetosphere: the Chapman-Ferraro current, the storm-time ring current, and the tail current. They obviously carry major 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.

What is the spatio-temporal evolution of a substorm seen in its entirety? As indicated in the previous section, the importance of answering this question cannot be overstated.

What is the spatio-temporal 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. Without empirically knowing how a storm develops, we cannot understand the operation of the physical mechanisms that cause it.

What is the relation between the magnetic storm and the substorm? 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 of substorms in storm phenomenology and on determining whether they are central to storm development rather than on the cause of magnetic storms, substorms being one possibility. Thus, the answer that substorms play a minor role in storm development would be a celebrated finding here, but it would not answer the previous 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 quasi-simultaneous activations of day-side and night-side processes as seen in various auroral and ionospheric-electrodynamic data.

Consider next possible major new question types (MNQTs) that might be asked in the post-leap era of magnetospheric physics, questions such as the following.

2.2 Major New Question Types

The following questions exemplify the new types of questions that space physicists might ask in the new "post-leap" era made possible by the availability of continuous sequences of global, 3-D, synoptic images of the magnetosphere.

What are the time-dependent, global magnetospheric responses to changes in solar wind conditions of all kinds, including IMF changes? This question type is rich in examples, but we will pick three and discuss them here and in the next two MNQTs. Recall the example given earlier of a sudden change in solar wind conditions washing over the magnetosphere. Take a case where the IMF rotates from an away sector northward into a toward sector faster than open field line reconnection can transfer much flux. According to one model, generally endorsed and supported by available data, the point where the plasma sheet meets the magnetopause will try to follow the IMF in its excursion. But it cannot negotiate the transition across straight north without flipping over, which is not an option. What happens then? Is there a snapping back? A sudden flip of the attachment geometry by 180 degrees? Probably not, but that our ignorance could suggest such an option shows how open to discovery and new knowledge this question type is.

What are the global responses to IMF changes that trigger substorms? It is known that a high percentage, perhaps over 50%, of substorms are triggered by sudden changes in solar wind conditions, often by northward turnings of the IMF. What are the corresponding changes in magnetospheric conditions that trigger the substorms?

What are the global magnetospheric responses to interplanetary shock waves and vice versa? We know that strong shocks can create new radiation belts in a matter of minutes. Obviously they also make sudden, dramatic changes in other magnetospheric properties. In turn, they are strongly refracted within the magnetosphere and reflected off the ionosphere. These processes of magnetospheric transformation and reconfiguration and of shock refraction and reflection can be documented with continuous sequences of global, 3-D, synoptic images of the magnetosphere. Such data will open up a rich field for magnetospheric model testing.

How well does a given quantitative model of substorm dynamics simulate substorms, in general and in particular? In the postleap era, when the substorm will be comprehended as an empirically described spatio-temporal physical event, cartoon descriptions of the substorm will be obsolete. It will be an era of quantitative physical models in which the data will be capable of testing and guiding model development through detailed spatio-temporal comparisons, both in generic studies and in case studies.

How well does a given quantitative model of magnetic storm dynamics simulate storms, in general and in particular? All comments from the previous MNQT also apply here.

How well does a given quantitative model of any of the other modes of coherent magnetospheric behavior simulate that behavior, in general and in particular? This question adds to the last two MNQTs all the known modes of coherent magnetospheric behavior, including traveling convection vortices, continuous magnetospheric convection, global resonances, and quasi- simultaneous activations of day-side and night-side processes.

How well does a given quantitative model of the new super mode of coherent magnetospheric behavior, discovered in the post-leap era, simulate its behavior, in general and in particular?

3 Strategic Principles

Strategic principles (SPs) by which NASA can move under its Sun-Earth Connections theme to reach a capability of obtaining continuous sequences of global, 3-D, synoptic images of the magnetosphere include the following:

Build on existing and future program elements. The SunEarth Connections theme and its partners in other agencies already have missions that can be integrated into the service of developing a global magnetospheric imaging capability. These missions include ISTP, FAST, ACE, TIMED, IMAGE, DMSP, GPS and other DOD, DOE, and NOAA satellites.

Make clear and sharp distinctions between the goals of these missions and the goals of the global magnetospheric imaging mission. The discussions in the earlier sections, with their descriptions and illustrations of the "next leap" concept and scientific objectives, do this.

Build over time in planned phases. This principle is aimed at reducing and controlling the cost per unit time and at allowing the project to integrate the experience gained from earlier phases into implementing later phases.

Evolve in steps from the existing constellation of satellites up to a constellation with full imaging capability. Each step should have a self-justifying scientific objective. Each step can use the full satellite constellation that has evolved up to its time to set its mission goals.

Compose steps out of groups of "autonomous, micro-spacecraft 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 imaging capability.

Design pixies for minimum instrument complement, duty cycle, and data rate consistent with 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.

Build L1 solar wind station into constellation concept. Continuous solar wind data are essential to the success of the project.

To the extent possible, build remote sensing imagers into the constellation concept–for example, a high-altitude polar imager of auroras and an IMAGE-type imager of magnetospheric plasma populations.

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 multi-purpose applications, for example, to generate animated images of boundaries, plasma populations, electrical current stream lines, magnetic field lines, pressure contours, and so on.

Operate imaging constellation as a facility. There should be no instrument PI with associated MO&DA. The facility should belong to the community which can apply for funds to use its data resources for research and applications.

Aggressively develop outreach programs. For example, 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.

4 "To explore, use, and enable the development of space for human enterprise"

Besides its strategic importance in propelling the advance of magnetospheric science into a new era, achieving the capability to obtain continuous sequences of global, 3-D, synoptic images of the magnetosphere is responsive to the goals listed in the current NASA Strategic Plan. The mission statement in the NASA Strategic Plan contains three themes, the second of which is the heading to this section. The goals under this theme that relate to the "Space Science Enterprise," the code name for the Office of Space Science, include demonstrating "a system for reliable space weather forecasting" in the 1996-2002 time frame, and, in the 2003-2009 time frame, achieving a capability to "monitor and predict space weather." While not their direct, primary objective, it is nonetheless true that continuous sequences of global, 3-D, synoptic images of the magnetosphere would, probably more than any other achievable capability, provide the understanding needed to carry out the first goal. If the images were obtained in near real time, they could also facilitate achieving the second goal. Another major aspect of the project described here is responsive to the NASA Strategic Plan. The third theme under the mission statement is "To research, develop, verify, and transfer advanced aeronautics, space and related technologies." The goals under this theme that relate to the "Space Science Enterprise" include developing autonomous, microspacecraft with advanced detector capabilities. Precisely such development will be needed to carry out the project of obtaining continuous sequences of global, 3-D, synoptic images of the magnetosphere. We discuss this topic in the following sections.

5 Implementation Issues

There are many implementation issues that must be resolved during a mission concept study phase. Some of these are the following:

Designing 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 the optimum mission, it is useful to adopt a functionalist perspective. Think of the global magnetospheric imaging mission as a new tool for magnetospheric research whose function 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.

Defining the minimum "pixie"*. A zero-base approach. The following is an example of how one might proceed to define the minimum pixie. 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 information added for least cost until a cost ceiling is reached or until an obvious point of diminishing return is reached, which ever comes first. In this exercise, it is essential to weigh the value of information added by how well it provides a pixel for global images. After instrument definition, determine the minimum duty cycle and data rate. There is no point in a duty cycle faster than needed to resolve the propagation time of information in the global system, for example.

*Pixie = a microsatellite that provides the "pixels" for global magnetospheric images

Defining the minimum satellite constellation. The constellation must ultimately be able to resolve the spatial structures of interest and their movements and transformations. The zero-base approach applies here as well. In this case, it works by building up to the minimum constellation in stages, each stage justified in part by information obtain in the previous stages. Still, there are optimal ways of designing stages which must be considered.

Position and attitude requirements. Not only is there a minimum constellation size, there is an optimal constellation distribution which gets the most useful global images out of the minimum constellation. In this case, optimization must 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. Design specification need to be calculated.

Telemetering requirements. The problem of retrieving information from a large constellation of micro-satellites must be addressed in the concept definition phase. There are opportunities for groundbreaking innovations in this area. Low data rates will help reduce the receiver requirements. The degree of success here will set the horizon for exploiting multi-point micro-satellite projects in general.

Data handling. 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. These issues need to be systematically explored.

Imaging software. This project opens up a new arena for graphics software development. The software must solve the problem of creating continuous images out of multiple point measurements as the points move. It must also create images of all parameters, directly measured and derived, for example, images of magnetic field lines and electric current stream lines. It must also create images of many user specified types, 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.