

## Global auroral imaging in the ILWS era

E. Donovan<sup>a,\*</sup>, T. Trondsen<sup>a</sup>, J. Spann<sup>b</sup>, W. Liu<sup>c</sup>, E. Spanswick<sup>a</sup>, M. Lester<sup>d</sup>,  
C.-Y. Tu<sup>e</sup>, A. Ridley<sup>f</sup>, M. Henderson<sup>g</sup>, T. Immel<sup>h</sup>, S. Mende<sup>h</sup>, J. Bonnell<sup>h</sup>,  
M. Syrjäsuo<sup>a</sup>, G. Sofko<sup>i</sup>, L. Cogger<sup>a</sup>, J. Murphree<sup>a</sup>, P.T. Jayachandran<sup>j</sup>,  
T. Pulkkinen<sup>k</sup>, R. Rankin<sup>l</sup>, J. Sigwarth<sup>m</sup>

<sup>a</sup> Department of Physics and Astronomy, University of Calgary, Calgary, Canada T2N 1N4

<sup>b</sup> Space Science Branch, NASA Marshall Space Flight Center, Huntsville, AL 35812-0000, USA

<sup>c</sup> Space Science Program, Canadian Space Agency, St. Hubert, Canada J3Y 8Y9

<sup>d</sup> Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, Great Britain, UK

<sup>e</sup> Department of Geophysics, Peking University, Beijing 100871, China

<sup>f</sup> Center For Space Environment Modeling, University of Michigan, Ann Arbor, MI 48109-2143, USA

<sup>g</sup> MS D466, Los Alamos National Laboratories, Los Alamos, NM 87545, USA

<sup>h</sup> Space Science Lab, University of California, Berkeley, CA 94720-7450, USA

<sup>i</sup> Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, Canada S7N 5E2

<sup>j</sup> Department of Physics and Astronomy, University of Western Ontario, London, Canada N6A 3K7

<sup>k</sup> Finnish Meteorological Inst POB 503 Helsinki, FIN 00101, Finland

<sup>l</sup> Department of Physics, University of Alberta, Edmonton, Canada T6G 2J1

<sup>m</sup> Geospace Physics Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771-0000, USA

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### Abstract

The overarching objective of the ILWS Geospace program is to facilitate system level science. This demands synoptic observations such as global auroral imaging. At present, there is no funded mission during ILWS that incorporates a global auroral imager. The imaging community needs to move now to address this important gap. While doing so, it is interesting to take stock of global auroral observations that have not been achieved, or that have been achieved only to a limited extent. These include simultaneous imaging across all relevant scales, spectral resolution of sufficient quality to allow for global maps of characteristic energy and energy flux of precipitating electrons, continuous global auroral imaging for time periods spanning long-duration geomagnetic events, systematic interhemispheric conjugate observations, auroral observations magnetically conjugate to *in situ* measurements, and automatic classification of auroral images. These observations can be achieved within the next decade. If they are, then they will facilitate exciting new science.

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### 1. Introduction

A planetary magnetic field carves a comet-shaped cavity out of the solar wind called a magnetosphere. The otherwise dipolar magnetic field is compressed on the dayside

and stretched to great distances on the nightside. This topology is supported by large scale electric currents flowing on the surface of and throughout the system. The interaction of the solar wind and the magnetosphere provides the power for this current system, as well as the convection of magnetospheric plasma. These currents and the magnetospheric convection, like the solar wind that drives them, are constantly varying. Some of the electromagnetic and

\* Corresponding author. Tel.: +1 403 220 6337.

E-mail address: [eric@phys.ucalgary.ca](mailto:eric@phys.ucalgary.ca) (E. Donovan).

particle energy that has been fed into the magnetosphere finds its way to various sinks that include the radiation belts, plasmasphere, ionosphere, and thermosphere.

Numerous plasma processes mediate energy and mass transfer from the solar wind to the magnetosphere, and subsequent transport through the system and deposition in the sinks. These include magnetic reconnection, plasma waves, wave-particle interactions, magnetohydrodynamic (MHD) instabilities, and parallel electric fields. Understanding these geospace processes is important because they are of obvious significance: the Sun–Earth system is the only astrophysical object in which magnetic reconnection and its consequences can be directly observed. These consequences have societal and economic impact: magnetic storms and MHD waves, for example, enhance radiation belt fluxes of charged particles that pose a danger to satellites and astronauts, magnetic storms have knocked out power grids, and there are potential links between geospace phenomena and climate.

Previous satellite and ground-based missions have mapped out the overall magnetospheric topology, and identified interesting plasma physical processes. We are now moving into what can reasonably be called the quantitative era of geospace science. The objectives are to go beyond phenomenology, and now quantify effects of key geospace processes and develop predictive capabilities that both test our understanding against observation, and bring this developing knowledge to real world applications. The International Living With a Star (ILWS) satellite and

ground-based observational programs will be designed to complement each other and facilitate quantitative global studies. Key players in ILWS must build on their historical strengths, and undertake bold new initiatives. The end result will represent a true leap forward in terms of physical understanding and benefit to society. One of the overarching themes of ILWS is to develop the capacity to study geospace as a complex coupled system (Table 1).

The schematic diagram in Fig. 1 illustrates our view of geospace as a complex coupled system. All the energy and much of the mass that populates geospace comes from the Sun, represented by the box on the left (i.e., sources). Ultimately, energy and mass end up in a number of sinks listed in the box on the right. Physical processes affect how energy and mass are transported from the source to the sinks. These operate in geospace, and are numerous (we have listed just a few at the center of the diagram). Many of these processes are understood only empirically, and some are understood only through simulation and theory. As well, we do not know right now which of these processes are dominant in terms of global mass and energy budget. In other words, while some of these processes occur in the system, it may be that if they were excised, there would not be any measurable effect on the global dynamic. For example, Kelvin–Helmholtz and other surface waves certainly exist on the magnetopause, but if the boundary was somehow changed so that it could not support their existence, would the ULF wave power distribution in the magnetosphere be measurably different?

Table 1  
Brief summary of operating parameters of previous global auroral imaging experiments

Platform (Instrument)	Year of launch	Orbit	Wavelengths	Exp. time	Frame rate	Spatial resolution
ISIS 2	1971	1400 km	557.7 nm, 391.4 nm	15 min	2 h	10 km
ISIS 2 (redline)	1971	1400 km	630 nm	15 min	2 h	70 km
DMSP	1971	830 km	400–1100 nm	15 min	1.5 h	0.5, 2.7 km
KYOKKO	1976	650–4000 km	120–140 nm	12 s	2 min	4–21 km
DE-1	1981	675–25,000 km	12 narrow bands from 130 to 630 nm	12 min	12 min	24–130 km
HILAT	1983	830 km	115–200 nm with 2 nm resolution	25 min	100 min	20 × 4 km
Viking	1986	800–13,500 km	125–160, 135–190 nm	1 s	20 s	14–20 km (1 × 1), 27–40 km (2 × 2)
Polar bear	1986	800 km	115–200 nm with 2 nm resolution	25 min	100 min	
AKEBONO	1989	300–8000 km	115–150 nm & 557.7	1 s	8 s	1 km
Freja	1992	650–1700 km	125–180 nm	0.4 s	6 s	5 km (2 × 2)
Interball	1996	475–20,000 km	125–160 nm	6.5 s	120 s	27 km (1 × 1), 55 km (2 × 2)
Polar (VIS)	1996	5100–51,000 km	732.0, 656.3, 630.0, 589.0, 557.7, 391.4, 308.5 nm	12 s	12 s	20 × 4 km
Polar (VIS Earth Camera)	1996	5100–51,000 km	125–150 nm	12 s	12 s	80 km
Polar (UVI)	1996	5100–51,000 km	128–133, 132–139, 140– 158, and 166–174 nm	37 s	37 s	40 km
IMAGE (WIC)	2000	1000–44,500 km	140–190 nm	10 s	120 s	100 km
IMAGE (SI-12)	2000	1000–44,500 km	121.8 nm	5 s	120 s	100 km
IMAGE (SI-13)	2000	1000–44,500 km	121.6, 135.6 nm	5 s	120 s	100 km

Note that we have simplified the information in some cases for clarity. The table is ordered chronologically, from top to bottom. Polar and IMAGE are both still in orbit, and the imagers are still operating.

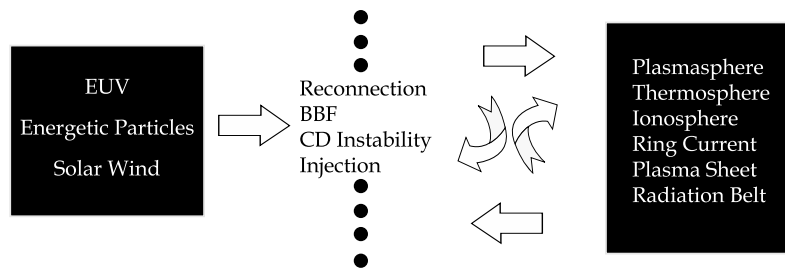


Fig. 1. Energy and mass enters geospace from the Sun and the solar wind. Various physical processes affect mass and energy transport through geospace, and how it is ultimately divided up and deposited in various sinks. Moreover, these geospace physical processes interact with each other, as do the sinks. The ILWS geospace program seeks to identify energy and mass pathways that are important, to quantify their effects, and understand the underlying physics at work.

Would the radiation belt evolution be different? Would the MI coupling be different? Moreover, these processes interact, and there is interaction between the sinks. So it is not as simple as source, process, and sink. Geospace is a complex coupled system that is a more than a passive recipient of solar energy – it is an active participant and source of much of the dynamics that are observed.

This “systems level approach” to geospace science is the natural next step in the evolution of our field. Key missions under the ILWS banner will target physical process such as reconnection (i.e., Magnetospheric Multiscale), wave-particle interactions (i.e., the LWS Radiation Belt Storm Probes and ORBITALS), ionospheric–thermospheric variability (LWS Ionosphere Thermosphere Storm Probes), or Alfvénic acceleration (i.e., Geospace Electrodynamics Connections and Swarm), with the objective of physics-based understanding. At the same time, greatly enhanced and ever more integrated global networks of ground-based instruments, and contemporaneous global imaging of the ring current, plasmasphere, aurora, and even the CPS (see e.g., Ergun et al., 2000) will provide the quantitative observations of the source and sinks necessary for complete specification of the geospace system.

The upcoming NASA Time History of Events and Macroscale Interactions During Substorms (THEMIS) mission is a microcosm of this systems level approach. THEMIS will involve five satellites in a constellation on the nightside magnetosphere, arranged to provide observations of current disruption, mid-tail reconnection, and communication between those two processes via bursty bulk flows and rarefaction waves. THEMIS also includes a ground-based network of all-sky imagers and fluxgate magnetometers which will specify the azimuthal evolution of the substorm disturbance via its effect on the aurora and ionosphere (Frey et al., 2004; Donovan et al., 2006). This combination of targeted *in situ* and coordinated ground-based observations is necessary to close the question of what causes substorm expansive phase onset.

Although it has not always been so strategically targeted as it is in the case of THEMIS, the idea of monitoring the global spatio-temporal evolution of geospace via its impact on the above-mentioned sinks has been the driver behind

SuperDARN (Greenwald et al., 1995, MIRACLE Syrjäsoo et al., 1998), Canadian Geospace Monitoring (see cgs.m.ca), and global imaging of the aurora, ring current, and plasmasphere (Williams et al., 1992). It is the motivation for current activities designed to create virtual observatory networks of magnetometers, riometers, and all-sky imagers that span the globe. This includes the planned United States Distributed Arrays of Small Instruments (DASI) initiative, which if it goes forward will involve the deployment of a worldwide array of ground-based geospace instrumentation, with the stated objective being to facilitate system level science (Foster, 2004). It was certainly the motivation for the Geospace component of the proposed Chinese KuaFu satellite program (Tu et al., 2005).

ILWS must promote space missions and ground-based observations that target the solar energy and mass sources, that explore the physics of and interrelationship between geospace processes that affect energy and mass transfer, and finally that provide quantitative synoptic observations of every mass and energy sink in the Geospace system. This is a grand challenge, by any means. It is also, however, the logical next step in the over forty year exploration of geospace. Furthermore, it is fitting of an international effort that draws on the collective experiences of the last 40 years and more.

Our objective is to present a high-level view of what we might do, as an international community, in future global auroral imaging projects, particularly within the framework of ILWS. In order to do this, we start with a brief review of the technical accomplishments of the imaging community, woven together with a very brief review of how those technical accomplishments have facilitated ground-breaking science. We then review observations that have either not been carried out, or have been carried out to only a limited extent. Examples include long-term continuous (i.e., “24X7”) global auroral imaging, simultaneous imaging across all relevant spatial scales, and systematic interhemispheric imaging. If we were to carry out these new observations, then we would facilitate exciting new science. Within the constraints of our space limitations, we outline the new science that these new observations would facilitate.

## 2. A brief history of global auroral imaging

Global auroral imaging began in the early 1970s with the Auroral Scanning Photometer (ASP) on ISIS2 satellite (launched April 1, 1971). ASP used the satellite spin and its orbital motion to provide the very first global auroral images (obtained in both 557.7 and 391.4 nm once per orbit). The ISIS2 system was operated for almost 10 years and yielded a number of discoveries, including the diffuse auroral oval (Lui et al., 1975).

Since ISIS2, global auroral imaging has evolved significantly. Imagers on *Kyokko*, *Dynamics Explorer* (DE), *HILAT*, and *Polar Bear* operated in the UV, allowing for the first time imaging of the aurora on the dayside. Global imagers on DE and *Viking* allowed more than one image per pass, with the *Viking* UV instrument providing an impressive cadence of one image every 20 s. In fact, the *Viking* UV imager utilized a novel combination of filters, reflective coatings, and UV-sensitive photocathodes to obtain short-exposure (1.2 s) simultaneous global UV images on two 256 by 256 pixel CCDs in two passbands: 135–190 nm, responding mainly to Lyman–Birge–Hopfield (LBH) N<sub>2</sub>, and 125–160 nm, responding mainly to the 130.4 nm OI line. The *Viking* imager was the first instrument that simultaneously exposed the entire image, hence obtaining the first-ever true global images of auroral activity. *Viking* provided an exciting new picture of the global time-evolving auroral distribution and new insights into the substorm dynamic (Henderson et al., 1998). Images from the two filters could be used to estimate energy deposition and the mean electron energy, although resonant scattering and a requirement of knowing the O/N<sub>2</sub> ratio seriously limited the accuracy of these derived quantities.

The next significant leap forward in global imaging came with the *ISTP Polar* satellite, which carried three imaging packages: the Visible Imaging System (VIS), the Ultraviolet Imager (UVI) and the Polar Ionospheric X-ray Imaging Experiment (PIXIE). The VIS was designed to achieve high time and spatial resolution images of the nighttime polar and auroral emissions at visible wavelengths (Frank et al., 1995). The package consisted of three low-light-level cameras: two auroral cameras which viewed

the aurora at visible wavelengths in narrow passbands as selected by a filter wheel, and one ancillary camera equipped with broad-band filters for FUV wavelengths in the range 124–149 nm. The two visible-light cameras had a spatial resolution of 10 and 20 km, respectively, from a spacecraft altitude of 8 RE. The FUV camera included in the VIS package was used as an Earth-monitoring camera used for verifying the proper pointing of the two-axis targeting mirror of the two primary visible-wavelength auroral cameras. The VIS FUV imager provided full images of the Earth from radial distances of 6 RE and had a spatial resolution of no more than 100 km.

The *Polar UVI* provides sequential spectrally resolved images in the far ultraviolet of the entire auroral oval for roughly half of the 18 h *Polar* orbit (Torr et al., 1995). *Polar UVI* has been widely used in studies of global magnetospheric dynamics (Sergeev et al., 1999). The innovative all-dielectric UV filters developed for UVI enabled the first qualitative estimates of large scale auroral energetics (Lummerzheim et al., 1997). The nominal UVI spatial resolution is 50 km at apogee, with an integration time of 30 s and sensitivity of 50 R. This sensitivity is still the best ever achieved with a global imager. From 1996 to 2002 the X-ray imager on *Polar* (PIXIE) provided global X-ray images of the auroral region, the first to do so (Imhof et al., 1995). PIXIE is a multiple-pinhole X-ray ‘camera’ designed to obtain images in 128 X-ray energy intervals in the range between 2 and 60 keV. The spatial resolution of the images is about 50–1100 km at apogee and 50–250 km at perigee. Integration times for an image depend on the source brightness but typically range from 1 to 30 min.

In 2000, NASA launched the *IMAGE* satellite. This was the first space science satellite with an instrument complement entirely devoted to remote sensing via optical and radio means. *IMAGE* carried with it a global imaging Far Ultraviolet (FUV) package consisting of three instruments. One of the FUV instruments onboard *IMAGE* is the Spectrographic Imager, one channel of which (the SI-12 channel) provides global proton auroral images every 2 min, which is the satellite spin period (Mende et al., 2000). *IMAGE* thus provides the first global picture of the proton aurora and thus certainly the first simultaneous

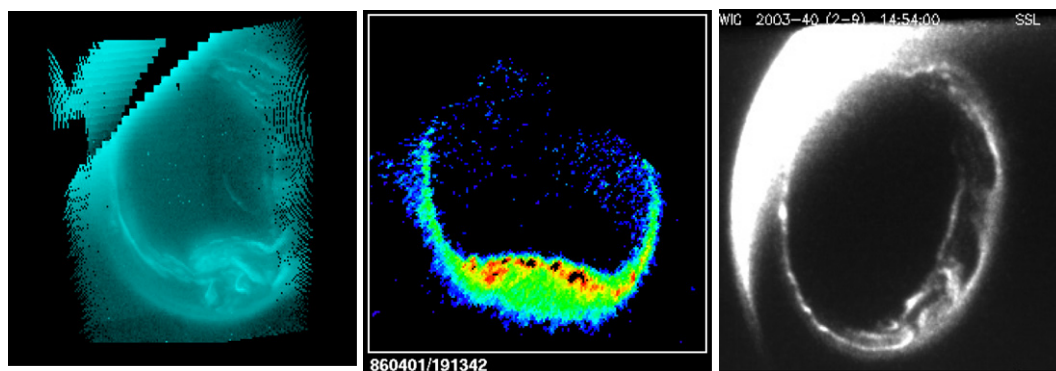


Fig. 2. Images from three satellite-borne imagers. From left to right: ISIS 2; Viking; IMAGE-WIC.

global images of the electron and proton aurora. Global auroral images from three generations of imagers are shown in Fig. 2.

### 3. Technical objectives for global auroral imaging in ILWS

By the time IMAGE was flown, there had been great advances, and great achievements, in global auroral imaging. Still, after 35 years of global imaging from space, there is a surprising list of technical challenges that have either not been met, or have been done to a degree that could be improved upon. Surpassing previous accomplishments, or striking out in new ways would facilitate new science. This must be the primary motivation in developing future missions. Within the context of ILWS, this should be *system level science*, as discussed above. Before we discuss the science that global imaging missions would attack dur-

ing ILWS, we first outline significant measurements that have either not been achieved, or have been achieved only in part. In each case we also point out, in broad-brush terms, what will be necessary to achieve these objectives.

*Simultaneous imaging across all relevant spatial scales:* Spatial resolution of global images has to date been limited to no better than 50 km. As well, it is only in recent years that ground-based arrays of all-sky imagers (ASIs) are capable of providing continent-scale images with  $\sim$ km resolution. Imagers with resolution significantly better than 1 km (Trondsen and Cogger, 1997; Trondsen et al., 26) have not been operated with larger-scale imagers (i.e., with spatial coverage larger than that of one ASI). Consequently, there has never been a systematic program for simultaneous auroral imaging across all important spatial scales (i.e., from global down to tens of meters). All relevant spatial scales can be observed with existing technologies (see

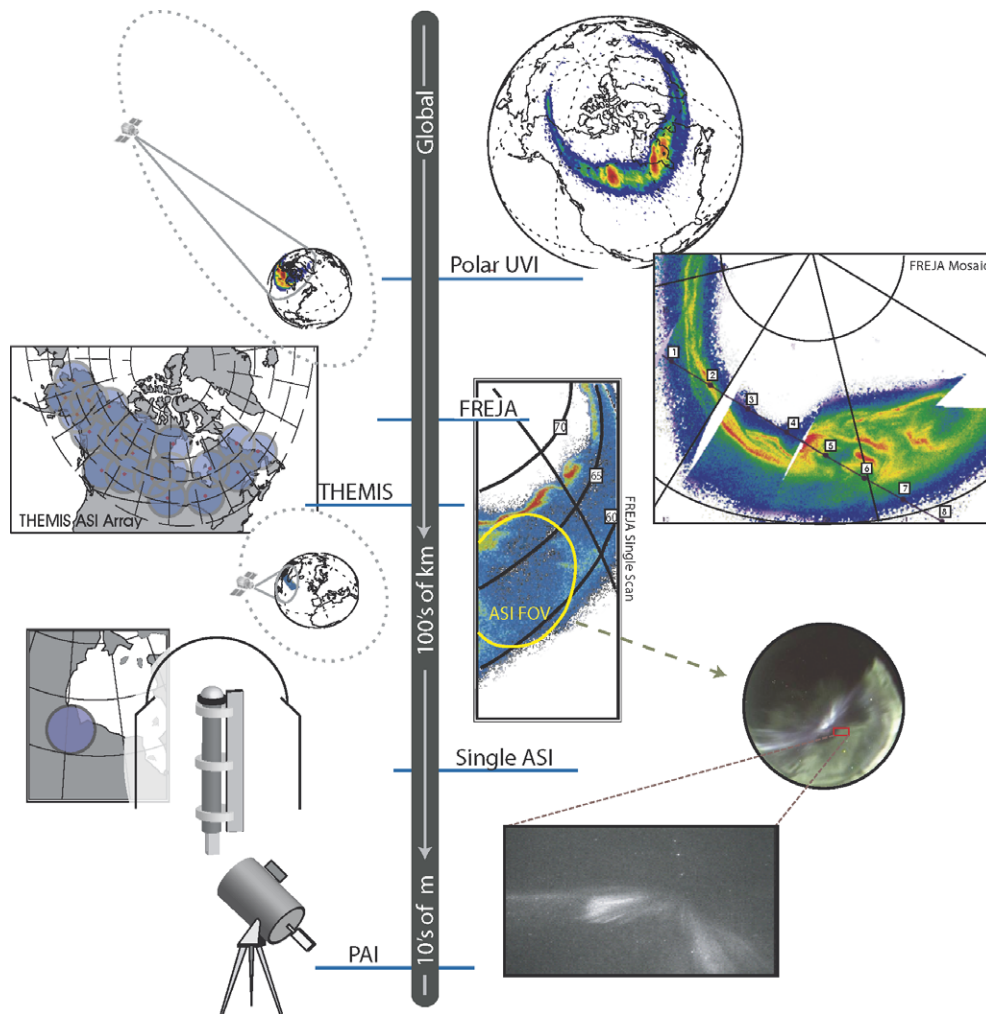


Fig. 3. The scales across which auroral observations are necessary range from tens of meters up to global. Different optical instruments provide observations in different and overlapping parts of the auroral scale size spectrum. Imagers on high altitude satellites such as Polar provide global observations. Imagers on lower altitude satellites such as Freja and ground-based networks such as MIRACLE, the THEMIS ASI-array, and NORSTAR provide mesoscale (continent-scale) observations. Individual ASIs operate with fields of view that span hundreds of km and auroral features such as vortices. Telescopes, such as the Portable Auroral Imager Trondsen and Cogger, 1997; Trondsen et al., 26 provide us with a view down to tens of meters. Simultaneous imaging across these scales has not been achieved. Due to enhancements in the capabilities of ground-based instruments and arrays, and provided that global images are available in the future, simultaneous imaging across these scales will be achieved.

Fig. 3). Provided that global observations are available in the future, simultaneous imaging across all relevant scales will be a reality. There is an important caveat, however, in that kilometer scale resolution images will be available for only a part of the global auroral distribution, and even higher resolution images for even smaller regions. This scenario will provide a complete picture of the cross-scale distribution only if fine scale structure is not globally organized. While this is a logical assumption, it has not been proven.

*Spectral resolution of sufficient quality to allow for global maps of characteristic energy and total energy flux of incoming electrons:* The most direct way of deriving the auroral energetics is to compare large scale images in two spectral regions of the far-ultraviolet LBH band-system; 140–160 nm (“LBH short” or “LBH 1”) where O<sub>2</sub> absorption at auroral altitudes is significant and 160–190 (“LBH long” or “LBH 2”) where the emissions are relatively free of absorption (Strickland et al., 1983; Germany et al., 1994a; Germany et al., 1994b; Germany et al., 1990). While there are difficulties with this approach due to factors such as O<sub>2</sub> upwelling and other factors that obfuscate atmospheric composition, it is the best technique available. Previous global auroral imaging experiments have obtained nearly simultaneous images from different parts of the electron auroral spectrum (i.e., see Polar UVI above and studies utilizing Polar-PIXIE data (Imhof et al., 1995; Anderson et al., 2000)). The UV data, however, has not yet met the technical requirements necessary to quantify the spatial dynamics of the average energy and total energy flux of precipitating particles on a global scale (these are 5 km/10 s spatial/temporal resolution, 10 counts/kR/s sensitivity, and 10<sup>10</sup> out-of-band spectral rejection), and as such, time evolving maps of the global distribution of both characteristic energy and total energy flux have not been obtained. Instrument development programs are currently underway in several institutions to achieve the technical requirements stated here. Strategies that are being explored include the use of newly developed materials for reflective coatings and filters for better out of bandpass rejection.

*Long-duration continuous global auroral imaging:* Previous global imaging experiments have been flown on single satellite missions, and hence have provided continuous imaging (at whatever cadence the imager is working at) for only a fraction of the satellite orbit. The UV imagers on Polar, for example, provide continuous complete hemispheric auroral coverage for less than half of Polar’s 18 h orbit. As a consequence, there are no unbroken sequences of images that span the relatively long time-scale geospace processes such as magnetic storms. Continuous global auroral imaging of one hemisphere can be obtained with two satellites on elliptical polar orbits, relatively phased on those orbits so that when one satellite is at apogee the other is at perigee (see the discussion of “KuaFu-B” in Tu et al., 2005). As is pointed out in Tu et al. (2005), it is straightforward to generate several years or more of con-

tinuous imaging with such an orbital configuration (i.e., this is subject to precession of the line of apsides).

*Simultaneous global imaging of both hemispheres:* The northern and southern hemisphere auroral ovals have been simultaneously imaged during serendipitous events when two UV imaging satellites had a clear view of the two hemispheres (see, e.g., Craven et al., 2001; Østgaard et al., 2004; Stubbs et al., 2005), or when one satellite had an oblique view of the two hemispheres (see e.g., NASA EPO material on Polar and DE-1 observations of conjugate aurora, <http://www.gsfc.nasa.gov/topstory/20011025aurora.html>). To date, there has never been a systematic program for interhemispheric conjugate auroral observation on the global scale. As in the case of continuous global auroral observations, interhemispheric conjugate observations can be achieved with well-planned orbital configurations in multi-satellite missions. In a KuaFu-B type scenario, in which two satellites are used to provide continuous global observations in one hemisphere, a “perigee-imager” on the satellites would provide some conjugate observations during every orbit of both satellites. As the continuous imaging can only be achieved with two satellites if they are on highly elliptical orbits (see Tu et al., 2005), the perigee imager would have to have a wide field of view. A design for an imager with a wide field of view (based on micro-channel plate properties) which could be flown on a low earth orbiting spacecraft has recently been developed (Hamilton et al., 2005), utilizing a proposal for an all sky X-ray camera (Fraser et al., 2002).

*Simultaneous in situ particle and field and conjugate auroral observations:* Serendipitous topside ionospheric satellite overflights of aurora observed by ground and/or satellite borne imagers, as well as targeted campaigns (Germany et al., 1997; Stenbaek-Nielsen et al., 1998; Frey et al., 2001) have provided some excellent data sets for studying the precipitation and fields that are the direct cause of auroral features. As in the case of interhemispheric conjugacy, there has not been a systematic program designed to build up a large data set of *in situ* and magnetically conjugate high time and space resolution observations. This could be achieved systematically with a specialized imager, operated on a Fast Auroral SnapshoT (FAST) type satellite, and dedicated to observing the auroral distribution at the magnetic footpoint of the satellite. The imager would have to provide multispectral observations of small dynamic phenomena with high spatial and temporal resolution over 10 s of seconds. For practical reasons, at least two spacecraft would be required in order to separate time and space dimensions of the *in situ* measurements. This is difficult and resource intensive. Fast spinning spacecraft, ideal for *in situ* measurements, will not accommodate the observational time for imaging unless a fast despun component is developed. Three-axis stabilized spacecraft, ideal for remote sensing, will not meet the *in situ* field requirements unless several duplicate plasma instruments are used.

*Machine vision:* Automatic processing of auroral images is in its infancy. At present, global auroral images can be

analyzed with automated tools to identify boundaries, integrated brightness and other straightforward geophysical parameters. More complicated analysis, such as determining the stage of substorm and the kind of auroral features in various parts of the image are done manually. Recent work has demonstrated that machine vision techniques are capable of automatic classification of auroral type in All-Sky Images (Syrjäso and Donovan, 2004), but success to date has been limited to classifying an entire image as “arc”, or “patch”, or other clear auroral form. Classifying more complicated images in which there are multiple types of aurora has yet to be accomplished. This would be a necessary step towards classifying the global distribution of *type* in global auroral images. The ultimate goal is to quantify auroral type, such as discrete, diffuse, omega bands, etc., in a way that can be automated.

It is not at all unreasonable that all of the above technical objectives could be met within the next decade. Over and above meeting these one by one, there will be synergy between missions that are carried out at the same time. There are in general several geospace missions and the world-wide array of ground instrumentation operating simultaneously. This was the essence of ISTP, and will be an objective in ILWS. With synergy between missions and ground-based observations it is possible to carry out new science with instruments that have been flown before, but not previously in a given combination. Synergy is not a new tool in space physics, but it can and will be improved upon.

#### 4. Science objectives

Of late, Universal Processes have entered the lexicon of our science. Indeed, space plasma physics inquiries have both fundamental significance to science and a unique vantage to probe the universal processes embedded in the Sun–Earth System. Nonlinearity is a universal process that permeates, to wit, the Universe. Aurora is nearly as universal, observed in all magnetized planets in the solar system that have an atmosphere. Global imaging is that crucial link which connects the fundamental science we want to understand (nonlinearity) and Nature’s gift to us to achieve this understanding – the multiscale dynamics of aurora; no other naturally occurring phenomenon is so within our experimental reach, yet so strenuously challenges our theoretical thinking. When we say geospace science has entered into the quantitative era, in the context of auroral physics, we mean a change of our mentality and approach.

To date, much of auroral imaging is an auxiliary to the substorm study, particularly that of the expansive phase. While there is great scientific value in this emphasis, there are additional pay-offs, if we allow ourselves to ask the question: “what else?” In other words, the evolution of aurora, and other global signatures of magnetospheric dynamics, contain a rich store of information on nonlinear physics which has not been fully exploited. In order to make progress, we need to make sustained (in time) and

multiscale (in space) measurements of aurora, rest assured that the auroral process has an intrinsic, if very complicated, order and pattern that points to new knowledge to be gained. The ideal would be “hyperspectral”, time-continuous, high time resolution, high space resolution, global imaging. While we are presently far from that ideal, it is within our grasp in the next decade to carry out fundamentally new observations that would achieve the technical firsts discussed in the previous section. So rather than hyperspectral, we should start with better spectral information. Rather than high spatial resolution on a global scale, we can start with global imagers operating in consort with continent-scale ASI arrays and local very high resolution observations, and so on. In other words, we should embark on a program that achieves the observational objectives laid out in the previous section.

Perhaps the most fundamental science would be achieved by simultaneous imaging across all relevant scales. The fact that complex systems give rise to repeatable structures in space and time is becoming increasingly clear. Understanding how energy cascades across scales, and the mechanisms that give rise to these structures is a goal that certainly transcends space physics, or even physics.

Spectral resolution of the LBH short and long wavelength bands will allow for time evolving maps of the energy deposition and characteristic energy. There are two main sources of the electron aurora, the first being the magnetospheric plasma sheet. The electric fields generated by the large-scale convection of magnetospheric plasma create currents that close through field aligned currents. These currents cannot be supported by the conductivity of the plasma at the ionosphere/magnetosphere boundary and electric potentials develop that accelerate the particles and can divert portions of the plasmashet population into the loss cone producing the so called inverted-V electron energy distribution that is often observed in satellite transits of the auroral oval. The second source is due to the interaction of the cold electrons in the outer ionosphere, within several Re of the earth, with Alfvén waves propagating along Earth’s magnetic field. This interaction leads to downward acceleration and precipitation of very high fluxes of low energy beam-like electrons. The Alfvén waves are indicative of reconfigurations of magnetic lines of force in the magnetotail that occur during all types of reconnection events including substorms.

Plasmashet electrons accelerated into the loss cone by inverted-V potential patterns are almost all above 1 keV of energy, while the mean energy in Alfvén wave driven aurorae is often no more than 1 keV. Multi-spectral space-based auroral imaging offers the capability of determining the mean energy of precipitating electrons. Imagers that can discriminate simultaneously between these two energy ranges and types of aurorae can do much to identify the magnetospheric source of the precipitation. Though several imaging missions to date have had some capability for these types of analyses, none have been launched that have all of the requirements: 10 km or better spatial resolution,

simultaneous imaging of spectrally separable emission, such as the N2 LBH emissions at long and short wavelengths (a nomenclature adopted by POLAR-UVI), and global imaging field of view. A properly instrumented platform could remotely identify the source regions of aurora and effectively track reconfigurations events of the magnetic field that occur during reconnection events as they occurs in the magnetotail or on the dayside magnetopause.

From the spectrally resolved FUV emissions, we can obtain a good approximation of the ion and electron energy deposition, and hence the effects of precipitation on ionospheric conductivity. By using forward modeling, we can estimate the ionization rates from the ion and electron particle precipitation, and estimate the 3D ionospheric density and composition. Because of the complexity of the feedback between the composition and the energy deposition, this is a difficult process, and requires modeling of the coupled thermosphere and ionosphere. Even with the difficulties involved, imaging with appropriate spectral resolution is the best hope for determining the large-scale particle input into the atmosphere.

The SuperDARN radars measure the doppler shift of electromagnetic waves scattering from ionospheric irregularities. This is the best technique for inferring the global distribution of ionospheric electric field, although it is at times limited by absorption or lack of irregularities. Ground-based magnetometer measurements can be used to estimate the distribution of ionospheric current. Combining the current with the conductance pattern determined in part from global auroral observations as described in the previous paragraph, an electric field can be estimated, thus providing an important complement to SuperDARN convection observations.

By determining the state of the ionospheric electric field and particle precipitation, one can start modeling the thermospheric and ionospheric dynamics with much more accuracy. The electric field and particle precipitation are of primary importance when considering the temperature structure, composition, winds, and energy balance in the thermosphere. In addition, the magnetosphere is in part controlled by the ionosphere, so specifying the conditions in this region would allow a more accurate representation of the global magnetosphere.

Sofko et al. (1995) showed that the upward field-aligned current (FAC) in the ionosphere can be written as:

$$J_{\parallel} = \sum_P \vec{B} \cdot (\nabla \times \vec{V}) - \vec{E} \cdot \nabla \sum_P - (\hat{b} \times \vec{E}) \cdot \nabla \sum_H$$

where  $\sum_P$  and  $\sum_H$  are the height integrated Pederson and Hall conductivities, respectively. Based on the above equation, it is obvious that, if the conductivities and the conductivity gradients can be determined, then the complete solution to the FAC distribution can be computed. The complementarity of the SuperDARN radars and optical instruments is obvious – provided there are adequate irregularities for obtaining good radar echoes, and that global images with adequate spectral resolution in the FUV spec-

tral band are available, the combined radar and global auroral images will provide us with the ability to specify the global distribution of upward FAC.

FUV electron auroral observations, in combination with global proton auroral images from an auroral imaging spectrograph such as the one carried on the IMAGE satellite (see above), allow us to determine the ionospheric projection of the earthward edge of the ion and electron plasma sheets. Particularly at the inner edge of the plasma sheet, there is an interesting and not fully understood relationship between convection, flux tube energy content, precipitation, and the cross-tail, ring and Region II field-aligned currents. This is particularly interesting during extreme geomagnetic events such as storms, which have durations of several days or more. During these events, auroral activity moves equatorwards to even mid-latitudes, and the CPS moves inwards across the outer radiation belts, providing a seed population for the ring current, while at the same time plasmaspheric material is drawn outwards into the trough and inner CPS. With continuous global auroral imaging we will be able to image such long-duration geomagnetic events for the first time. We will be able to explore how the CPS acts as a seed population for the inner magnetosphere, and in particular the ring current, quantify the impact of solar forcing and magnetic storms to the neutral atmosphere, and address the storm–substorm relationship.

Aside from the simple fact that the northern and southern auroral ovals are ever-present features of the terrestrial environment, and that discrete auroral forms are sometimes conjugate and sometimes not, surprisingly little is known in relation to auroral conjugacy. We certainly expect the proton aurora and diffuse electron aurora to be essentially magnetically conjugate phenomena, although a systematic demonstration that this is in fact true would certainly be helpful. It would be more interesting, however, to explore how differences in the discrete aurora might reflect significant and temporally varying field-aligned electric potentials. Along the same lines, there is some evidence that substorms are more prevalent around equinox than around solstice, a possible indication that the substorm onset can be affected by the difference between the conductivity in the two hemispheres. A systematic program to build up a data base of conjugate auroral observations would obviously be of tremendous scientific value. It would also be a powerful complement to high time and space resolution auroral observations at the magnetic footprint of a FAST-type satellite. The *in situ* auroral conjugate observations would allow us to explore the auroral electrodynamics on a fundamentally new level. They would facilitate exploration of how spatial structure of electromagnetic fields in the topside ionosphere is related to structure in the aurora, and the mechanism(s) by which auroral electrons are accelerated.

The auroral observations described in this paper would provide an excellent basis for testing global magnetospheric models, and in particular their ability to quantitatively



reproduce longer duration geomagnetic events such as storms, given adequate specification of the solar wind conditions. This in turn would allow us to critique our understanding of the physics of geospace, at least the physics that is represented in the models. It is commonly held that methods for automatic classification of images (i.e., machine vision) are being developed to facilitate automatic processing of large image data bases. In fact, the primary motivation is to *quantify auroral type* in a way that can be compared with model outputs or used as an input to models. This would allow another important quality of the aurora – namely its type which is in general different in different regions – to be used quantitatively rather than qualitatively. It is only a matter of time before such algorithms are capable of providing this information on a routine basis.

Finally, global auroral imaging is a powerful complement to all other geospace missions that may be mounted during ILWS. The ESA Swarm mission is just one example. Swarm will consist of three satellites in low altitude orbits, carrying out high precision electric and magnetic field observations. The primary mission objective is to explore the internal field of the Earth, which requires the higher quality observations of the external electric and magnetic fields than have been obtained to date (*their noise is our signal!*). Swarm electric and magnetic field observations will provide us with detailed field-aligned current, transverse ionospheric current, and Poynting flux measurements obtained to date, and builds on the successful heritage of the Ørsted and CHAMP satellite missions (see e.g., Neubert and Christiansen, 2003; Moretto et al., 2002). Global auroral observations, in conjunction with Swarm electric and magnetic field measurements, would advance our understanding of the relationship between the global FAC distribution and the aurora (testing, for example, FACs derived from SuperDARN inferred convection and auroral observation inferred conductivity as discussed above), and the role of Poynting flux in the overall deposition of energy in the ionosphere and thermosphere (see eg., Wygant et al., 2000). The LWS Ionosphere Thermosphere Storm Probes (ITSP) is another mission that will greatly benefit from continuous global imaging. The imaging requirements put forth in this paper will enable the determination of the dynamics and scale of the O/N<sub>2</sub> ratio for high and mid latitudes. These large scale observations over long periods of time are needed for the ITSP mission to extend the in situ measurements to global models of ionospheric–thermospheric variability.

## 5. Summary

There are important classes of global auroral observations that have not been done or have been done only to a limited extent. These are simultaneous imaging across all relevant scales, spectral resolution of sufficient quality to allow for global maps of characteristic energy and energy flux of precipitating electrons, continuous global auroral

imaging for time periods spanning long-duration geomagnetic events, interhemispheric conjugate observations, auroral observations magnetically conjugate to *in situ* measurements, and automatic classification of auroral images. As well, we can reasonably expect that, if the effort is made, each of these technical objectives can be achieved within the next decade. That is, within the ILWS era.

ILWS seeks to understand geospace as a complex coupled system. This ambitious goal demands synoptic observations such as global auroral imaging. Given that global auroral imaging would play an essential role in meeting the overarching objectives of ILWS, and given that there is at present no funded mission during the ILWS time frame that incorporates a global auroral imager, it is urgent that the international imaging community act now, rather than later, to make imaging a part of ILWS, rather than the unfortunately missing essential piece.

Colloquially speaking, if we are going to do something, then we should do something new. It would be exciting to attempt to address most, if not all of the technical objectives outlined in Section 3. Certainly KuaFu-B (see Tu et al., 2005) would address continuous imaging and the separation of LBH long and short, if that mission goes forward. Any global auroral imaging mission, in conjunction with ground-based arrays of ASIs such as MIRACLE, and a well-placed narrow field of view imager (see Fig. 3), will allow us to achieve simultaneous imaging across all scales. Continuous imaging is an excellent first-step towards comprehensive interhemispheric auroral imaging. These are readily achievable goals.

While we have only briefly touched on the science that these new observations would facilitate, we hope it is clear that an imaging program that meets some or all of the objectives set out in Section 3 would lead to fundamentally new science on many levels. As it is already doing in the wake of the great successes of the Polar and IMAGE programs, auroral imaging would provide far more than simply context.

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