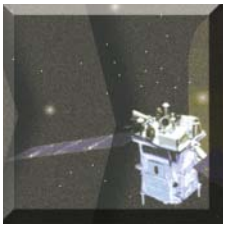

TIMED Science: First Light

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The goal of the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) mission is to characterize the physical, dynamic, energetic, and thermal structure of Earth's mesosphere, lower thermosphere, and ionosphere (MLTI) between 60 and 180 km and to understand quantitatively the processes that govern its temporal and spatial variability. Because the MLTI is at the interface between interplanetary and lower-atmospheric processes, it plays a uniquely important role in the solar-terrestrial system. This article presents the "first light" results from TIMED's suite of four instruments. TIMED has allowed the Sun-Earth Connection research community to observe for the first time the cause-and-effect chains linking the Sun, heliosphere, and magnetosphere to the Earth's upper atmosphere. This is highlighted in preliminary results from TIMED observed during a period of intense solar and geomagnetic activity in April 2002.

INTRODUCTION

Before the launch of NASA's TIMED mission,[1] our knowledge of the temperature and density structures of Earth's mesosphere, lower thermosphere, and ionosphere (MLTI) region was based on rocket-borne and ground-based measurements at a limited number of sites or satellite-borne remote sensing measurements that covered only portions of the MLTI. These measurements generally have poor vertical resolution and local time coverage. Over the past 11 years, the Upper Atmosphere Research Satellite (UARS) has provided MLTI wind measurements. The excellent data set collected by UARS has given the MLTI research community a first glimpse at the MLTI dynamic structure. We have learned that its mean background winds have a clear seasonal structure and its daily global pattern is highly variable both spatially and temporally, dominated by the presence of tides and large-/small-scale waves. However, prior to TIMED, the full MLTI momentum balance had not been well characterized. Previously, global thermospheric density and composition information was based on *in situ* satellite drag and mass spectrometer data as well as ground-based incoherent radar data.[2] Information on the mesosphere came from limited rocket measurements using mass spectrometers and falling spheres.

The MLTI temperature and density distribution is measured by TIMED using the Global Ultra-Violet Imager (GUVI) instrument in the thermosphere[3] and the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument in the stratosphere, mesosphere, and lower thermosphere.[4]

The TIMED Doppler Interferometer (TIDI) provides simultaneous wind measurements critical to establishing the momentum balance.[5] These are new scientific products that can be used to verify the atmospheric dynamic state generated by models and to provide additional insights into the sources and sinks of momentum in the MLTI.

While simultaneous measurements of basic state variables are required to study the momentum balance of the atmosphere, additional measurements of the energy inputs and outputs are required to investigate the energy balance. TIMED is the first mission that simultaneously measures all critical parameters needed to quantitatively understand the processes that control changes in the MLTI. The Solar Extreme ultraviolet Experiment (SEE) instrument[6] measures the incoming solar radiation below 200 nm, the most important energy input for the MLTI. GUVI provides high spatial resolution measurements of the auroral particle energy inputs from the magnetosphere. Composition measurements by GUVI and SABER allow the study of how solar and magnetospheric energy is absorbed and converted to heat. Wind measurements provided by TIDI and atmospheric transport parameters deduced from tracer distributions allow us to examine how the energy is redistributed through the transport of long-lived and energetically important minor species and how the atmospheric circulation induces heating and cooling. SABER provides the critical measurements of various energetically important radiative emissions, the key energy output mechanism from the MLTI. In addition, densities of energetically important species needed to accurately calculate solar energy deposition rates can be deduced from SABER data. Before the launch of TIMED, many of these critical measurements were not available simultaneously for detailed energy balance studies.

In this article we provide a glimpse of TIMED's "first light" results: the first images of the light measured by the instruments used to produce the scientific products. In addition, we briefly highlight TIMED's unique role in the solar-terrestrial chain through its observations of atmospheric effects resulting from a series of solar and geomagnetic storms in April 2002.

TIMED INSTRUMENTS

SEE First Light

The SEE instrument consists of a spectrometer and a suite of photometers that measure incoming full-disk solar vacuum ultraviolet (VUV) irradiance from 0.1 to 200 nm. The VUV range includes the soft X-rays (XUV) from 0.1 to 30 nm, the extreme ultraviolet (EUV) from 30 to 120 nm, and the far ultraviolet (FUV) from 120 to 200 nm. SEE is composed of two solar sensors: the XUV Photometer System that measures the XUV from 0.1 to 34 nm and H Lyman-α emission at 121.6 nm, and the EUV Grating Spectrograph that measures the EUV and FUV from 26 to 200 nm. An example solar spectrum measured by SEE is shown in Fig. 1. The individual emission lines are from the solar chromosphere and corona, while the continuum seen at wavelengths above 140 nm is from the upper photosphere.

Solar radiation at XUV, EUV, FUV, and mid-ultraviolet (MUV) wavelengths is the main MLTI energy source. Part of the FUV and MUV solar radiation responsible for O_2 and O_3 photodissociation and heating in the stratosphere, mesosphere, and lower thermosphere has been measured for the last 10 years by the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) and Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) instruments onboard UARS. Energetic XUV and EUV solar radiation have never been measured simultaneously to characterize their solar cycle variabilities. These highly variable sources are responsible for atmospheric excitation, dissociation, and ionization in the MLTI. In fact, other than occasional rocket measurements, the Atmosphere Explorer (AE) mission in the late 1970s and early 1980s was the last satellite mission to provide systematic solar EUV measurements. Before the launch of the Student Nitric Oxide Experiment (SNOE) and TIMED, the only solar XUV/EUV spectrum available was that of Hinteregger et al.,[7] which was derived from AE measurements. SEE is the first instrument to provide continuous measurements of solar flux from soft X-ray to FUV wavelengths over a long duration. These measurements are needed for the proper specification of solar energy inputs.

GUVI First Light

GUVI is a spatial-scanning FUV spectrograph that measures composition and temperature in the lower thermosphere as well as auroral energy inputs.

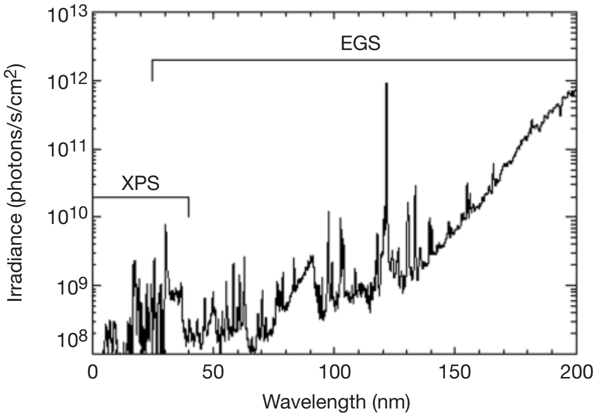

Figure 1. Solar soft X-ray (XUV), far ultraviolet (FUV), and extreme ultraviolet (EUV) spectrum measured by the SEE instrument on 18 January 2002 (XPS = XUV Photometer System, EGS = EUV Grating Spectrograph). Plot courtesy of T. N. Woods and the SEE team.

It observes the primary FUV spectral features that arise from major constituents of the upper atmosphere, namely, H, O, and N_2, through their emission spectra and O_2 through its absorption spectrum. Specifically, GUVI measures the major emission features of H Lyman-α at 121.6 nm, O emission lines at 130.4 and 135.6 nm, and N_2 Lyman-Birge-Hopfield (LBH) bands at 165 and 185 nm. All five of these spectral features, or "colors," are observed simultaneously and downlinked by GUVI. Each orbit of GUVI measurements is composed of a swath measurement, roughly 3000 km in width, that scans the Earth's disk beginning 60° from nadir across the disk and through the limb on the anti-sunward side of the spacecraft.

Each orbit of GUVI observations can be further separated into three different categories according to the excitation sources of the observed emissions: dayglow, aurora, and nightglow. In addition, each GUVI scan contains a limb portion, which provides a limb emission rate profile as a function of tangent height, and a disk portion, which provides two-dimensional images of vertically integrated emission brightness. From the 135.6-nm and LBH emissions in the daytime limb measurements, GUVI is able to infer the temperature and densities of major thermospheric species, i.e., O, N_2, and O_2. From the disk image, GUVI is able to deduce the characteristic energy and flux of the precipitating electrons in the aurora region, column O/N_2 density ratio in the daylit region, and total electron content in the dark.

Figure 2 shows a composite image of three of the five observed colors for the nighttime disk portions of the orbits of 17 January 2002. The 130.4-nm emissions are seen as blue intensities, 135.6-nm emissions as green, and LBH emissions as red. The color scale of 130.4 nm is 10 times larger than the other two (e.g., 1 unit of 130.4 nm, 10 units of 135.6 nm, and LBH produce white).

In the aurora, the main source of 130.4-nm emissions is electron collisional excitation of O. In Fig. 2 this is seen as the intense blue-white features near the poles. Any relative enhancement of 135.6-nm and LBH emissions will appear less blue. In general, auroral precipitation of more energetic electrons will penetrate deeper into the atmosphere, thus increasing the N_2 LBH emission relative to O emission and appearing more red in the figure. Although 130.4 nm is the brightest auroral line, it is not ideal for auroral morphology studies because it is strongly scattered in the atmosphere. The next brightest electron auroral emission is 135.6 nm, which is scattered to a much more limited degree. GUVI has the resolution to detect and separate the 135.6-nm emission from the 130.4-nm line. Combining the 135.6-nm emission with the N_2 LBH emission brightness measured in the aurora, one can infer the characteristic energy and flux of the precipitating electrons in the auroral region.

Not shown in Fig. 2 is the hydrogen 121.6-nm line that arises from a combination of geocoronal and proton/hydrogen atom auroral emissions. As a result, Lyman-α can be used to estimate the proton flux in the auroral region.

In addition to the auroral oval, persistent features of the Earth's FUV irradiance are the equatorial airglow arcs that are observable at night. In Fig. 2, they are seen in the 135.6- and 130.4-nm emissions that appear as two greenish-blue bands along the magnetic equator. These two arcs reflect the state of the ionosphere at low magnetic latitudes and are a direct result of the electron transport due to the interaction of neutral winds and surrounding electric and magnetic fields. These two atomic oxygen emissions arise predominantly from the recombination of atomic oxygen ions with electrons at these latitudes. Therefore, during the nighttime pass of the orbit, GUVI can provide two-dimensional images of total electron content on the disk as well as electron density profiles on the limb in the equatorial arcs.

Although not shown in Fig. 2, changes in the color balance on the disk during the daytime portion of the orbit also reflect changes in the composition of the upper atmosphere. As the LBH and 135.6-nm emissions are excited by the photoelectron impact excitation of N_2 and O, respectively, the ratio of the intensities of the two emissions provides information on the column abundance of O relative to N_2 (O/N_2), a key indicator of the thermospheric state. GUVI is the first instrument sensitive enough to examine, in detail, composition changes in the upper atmosphere.

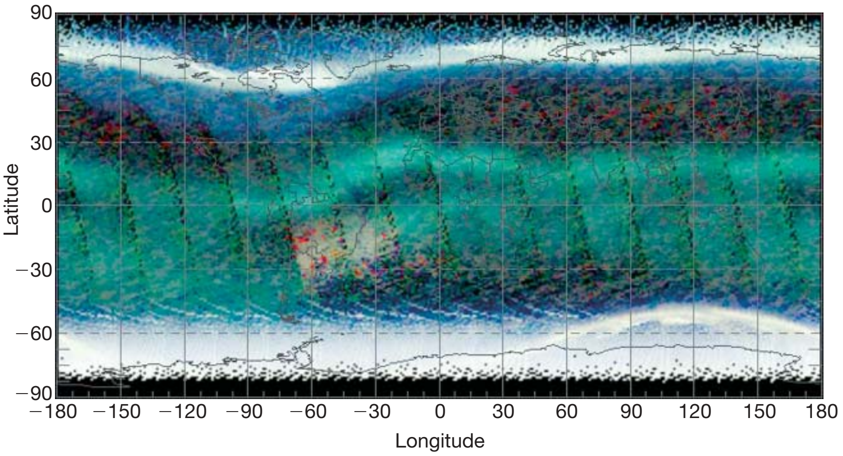

Figure 2. Composite GUVI image of three different "colors" measured during 17 January 2002. Image courtesy of B. C. Wolven and the GUVI team.

In addition, the observed GUVI FUV spectral brightness can also be used to infer the solar energy input. Both precipitating particles and solar EUV radiation are important sources of energy into the thermosphere, and their high variability can significantly impact the temporal and spatial variation in the structure of the thermosphere and ionosphere.

SABER First Light

The SABER instrument is an infrared radiometer that provides measurements of basic state variables (i.e., pressure, density, and temperature), key atmospheric heating and cooling rates, and concentrations of radiatively important species. These measurements, combined with those provided by the other TIMED instruments, allow atmospheric scientists to quantitatively examine, for the first time, the relative importance of various momentum and energy sources and sinks in the MLTI region. Most importantly, the key atmospheric infrared cooling emissions can only be observed from space, and the success of SABER provides this critical set of measurements for the TIMED investigation.

SABER is acquiring measurements in a range of the atmosphere where the radiation and chemistry are very different from those in lower atmospheric regions since molecules are sparser and less active, extending into an area of challenging radiative balance. By understanding the physics behind these emissions and using mathematical inversion, SABER is able to retrieve the thermal and density structure of the mesosphere and lower thermosphere and infer concentrations of radiatively important species.

Figure 3 shows some typical daytime and nighttime measurements of these limb radiances, observed on 18 January 2002, from the near- to mid-infrared over the range of 1.27 to 17.00 μm. From the CO_2 4.3-μm emission (green, Fig. 3a) and the CO_2 narrow- and wideband emissions (Fig. 3b), SABER is able to infer the temperature, density, and CO_2 concentration in the stratosphere, mesosphere, and lower thermosphere. From the O_3 emission at 9.6 μm (dark blue, Fig. 3a), the ozone concentration from 15 to 100 km is derived. In addition, water vapor concentration can be inferred from the H_2O emission line at 6.9 μm (pink, Fig. 3a), an important chemical and dynamical species in the atmosphere. The profiles in Fig. 3 were taken in one vertical scan at roughly one geographic location in latitude and longitude. SABER measures approximately 90 limb profiles per orbit for roughly 15 orbits a day, sampling the globe every 20° in longitude near the equator.

Based on measurements of the composition of molecular species, such as O_3 and CO_2, atmospheric heating due to the absorption of solar and terrestrial radiation can be calculated. SABER also provides the first systematic measurements of key atmospheric radiative cooling emissions along with basic state variables during both day and night. Among them, the CO_2 15.2-μm narrowband emission (Fig. 3b) is the main energy output in the mesosphere and the NO 5.3-μm emission (light blue, Fig. 3a) is one of the most important cooling agents in the lower thermosphere. These two SABER measurements, along with the O 63-μm fine structure cooling rate (calculated using GUVI O measurements) and heat conduction rates (calculated using GUVI temperature measurements), provide the major cooling rates needed to investigate the MLTI energy balance.

TIDI First Light

The TIDI instrument, a Fabry-Perot interferometer, measures horizontal vector winds in the mesosphere and lower thermosphere and the high-resolution spectral brightness of various airglow emission lines originating

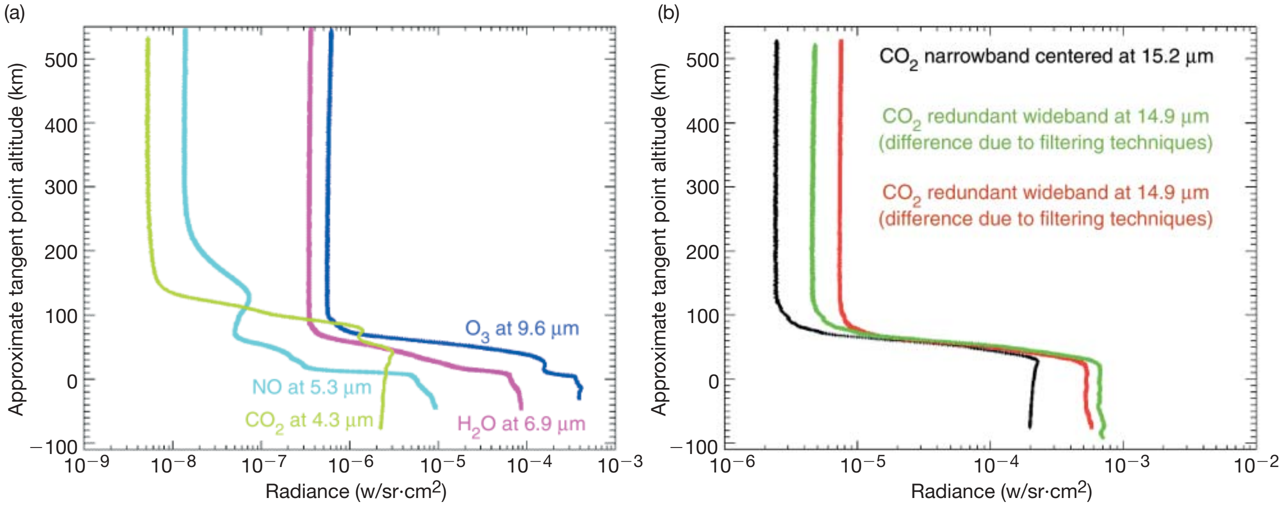

Figure 3. SABER altitude profile of limb radiances for selected channels on 18 January 2002 during (a) daytime at 39° latitude and 214° longitude, and (b) nighttime at 5° latitude and 117° longitude. The two CO_2 redundant wideband curves in (b) are different owing to the filtering techniques used. Plots courtesy of J. M. Russell III and the SABER team.

in the atmosphere. The TIDI telescopes perform limb scans simultaneously in four orthogonal directions: two at 45° forward but on either side of the spacecraft's velocity vector and two at 45° rearward of the spacecraft. Figure 4 (top panel) shows the composite images of the line spectral brightness measured by TIDI's four telescopes as a function of wavelength (*y* axis) and time or tangent height (*x* axis) at a fixed latitude and longitude. These four views provide the measurements necessary to construct the horizontally resolved vector winds as a function of altitude within the MLTI region along two parallel tracks, one on either side of the spacecraft.

TIDI measures wind by measuring the Doppler shift of the atmospheric emission features as shown in the top panel of Fig. 4. The bottom panel presents the measured and modeled line spectra from one of its telescopes. The *x* axis is the instrument spectral channel number corresponding to discrete wavenumbers and the *y* axis is the measured spectral brightness. The solid black curve shown here is the measured spectrum and the dashed black curve is the model predicted spectrum. Within one TIDI spectral brightness measurement, two adjacent O_2 emission lines can be measured simultaneously and the same lines, but different interference order, can also fall inside the TIDI detector. The individual contributions from these sources to the total spectral brightness that TIDI measures are shown in the figure as the colored curves. From the small shifts in the frequencies of the spectra or the small change in the symmetry (or asymmetry) of the line, TIDI is able to derive the winds in the mesosphere and lower thermosphere.

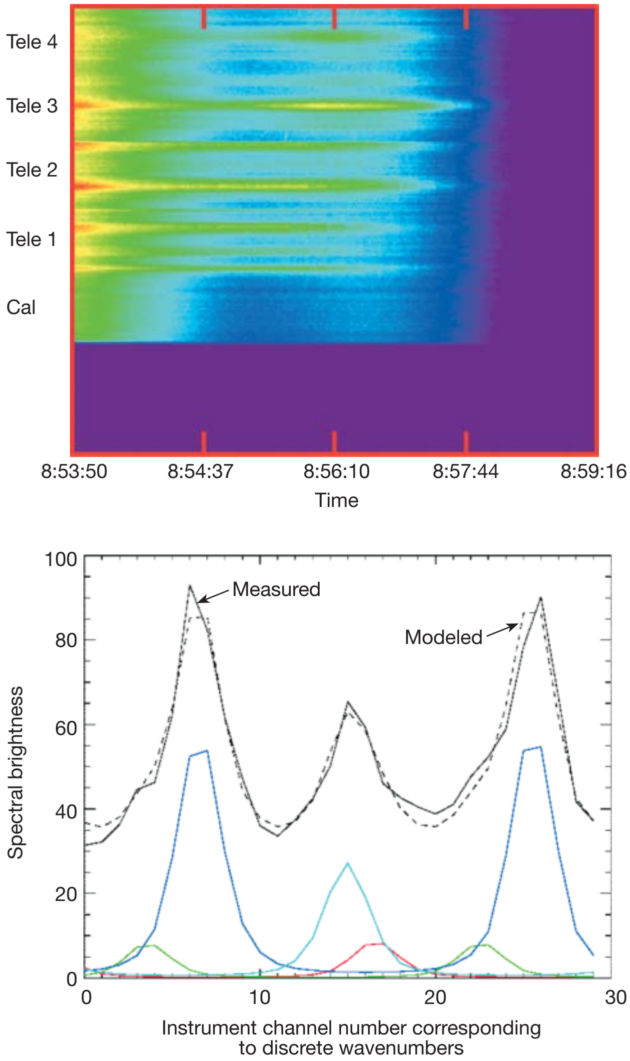

Figure 4. Top: O_2 atmospheric line during the first emissions survey on 3 January 2002: detector image is from TIDI's four telescopes and calibration field during a long upward scan at ≈15° latitude, ≈95° longitude. Bottom: comparison of measured and modeled spectra; colored curves below are the modeled components. Figure courtesy of T. L. Killeen and the TIDI team.

PRELIMINARY SCIENCE RETURN: APRIL STORMS CASE STUDY

TIMED has already provided important new information on the chain of physical processes connecting the Sun and Earth. This connection was highlighted in April 2002 when TIMED, through its normal operations, observed the atmosphere's response to a series of strong solar storms.

Although several NASA spacecraft measured this strong activity coming from the Sun, TIMED provided the critical link between what happened on the Sun and the Earth's response. The solar active region 9906 produced a series of geo-effective events during 17–24 April 2002: two halo coronal mass ejections (CMEs) as its field of view traversed the solar disk and an X-class flare and solar particle event accompanied by a CME (not aimed directly at Earth) as its field of view approached the Sun's limb. All of the CMEs lifted off the Sun with high velocity and were observed to arrive at Earth in a relatively short time, driving shocked solar wind plasma accompanied by significant populations of soft (tens of kilovolts to a few mega-electonvolts) solar particles. In addition, the SEE instrument saw increases in X-ray irradiance by a factor of 8, while longer wavelengths were enhanced much less.

The April storms were a unique event in that the close succession of CMEs had a cumulative effect on the magnetosphere and the MLTI. At first, an interplanetary CME triggered a magnetic storm on 17 April, but activity in the region had not fully subsided before a second round of CMEs hit on 19 April, producing a second magnetic storm. Throughout the 7-day storm event, the polar cap was bathed in different species and energy ranges of solar particles. Soft protons (and electrons in the first storm) entered the polar cap with each CME, and hard solar protons expelled by the X-class flare filled the polar cap for more than 48 h at a time when magnetic activity was low. On 23 April, the magnetosphere was clipped by a third round of CMEs that produced only weak magnetic activity levels.

After this series of events, evidence from NASA's Polar spacecraft and the NOAA Polar Orbiting Environmental Satellite suggested that the proton and electron radiation belts were modified, providing a long-lived source of high-energy precipitating particles for the MLTI region. In addition, a coordinated ground-based observation campaign, which included many of TIMED's ground-based partners, was conducted during these events and showed significant enhancements in ionospheric density and temperature. These observations increased our knowledge of the magnetospheric energy inputs during this time period. (A wide variety of satellites and ground-based instruments observed different aspects of the April storm event, and members of these satellite teams are currently collaborating on a joint analysis of the observations.)

There were several interesting features in the auroral oval during this sequence of storms. GUVI captured the intensification of broad regions of the auroral oval, including a double oval configuration (Fig. 5) caused by the strong driving of auroral activity. Bright proton auroras were also observed throughout the storm sequence. Dramatic perturbations in nitric oxide, mesospheric ozone, and atmospheric composition and heating were documented by SABER and GUVI. The neutral winds in the mesosphere obtained from TIDI suggested enhancements in the dynamics below 100 km. Figure 6 shows the global distribution of the NO 5.3-μm energy loss rate (J/cm^3/s) at 110 km observed by SABER before the impact of the solar disturbance (10 April) and during the height of the magnetic storm (18 April). The large emission at high latitudes is due to the production of NO from auroral processes. As the geomagnetic activity increases, NO production is enhanced at high latitudes and may move equatorward as the auroral ovals expand. Clearly, the increase in NO emissions observed by SABER on 18 April reflects the increased auroral energy deposited into the high-latitude region.

Preliminary TIMED observations of these storms have been featured in special sessions of the Spring and Fall 2002 American Geophysical Union meetings and in a dedicated Storms Workshops at APL in August 2002. Information about the workshops can be found at http://storms.jhuapl.edu/. TIMED's study of short-term events such as these April solar storms will provide a better understanding of the dynamics of this gateway region.

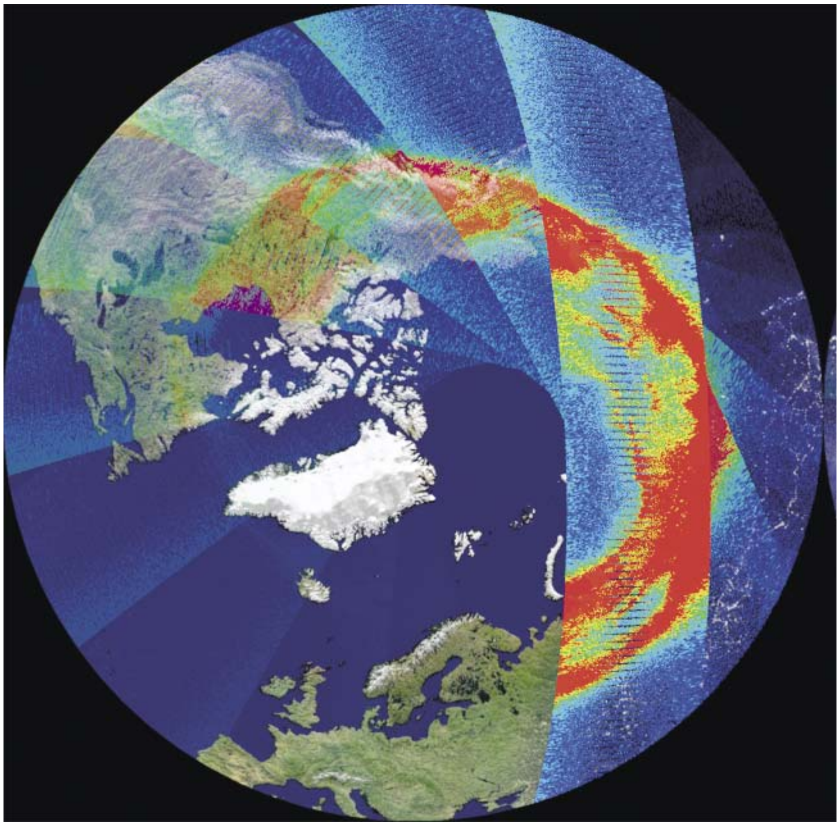

Figure 5. GUVI showed intense auroras, indicated in red, occurring over the Earth's northern region during solar storms in April 2002, and extending much farther south than usual. Several data tracks, acquired during multiple spacecraft passes, are superimposed over the image to show the location of the auroras. Image courtesy of R. J. Barnes and the GUVI team.

CONCLUSION

TIMED has been very successful since its launch in December 2001. It has provided the first simultaneous measurements of MLTI density, winds, and temperature structures, critical elements for a detailed understanding of MLTI momentum balance. It has also provided the first simultaneous measurements of MLTI energy inputs and radiative energy outputs that are needed to quantitatively understand the MLTI energy balance. Most importantly, TIMED observations allow the Sun-Earth Connection community, for the first time, to investigate the MLTI response to various types of external energy inputs.

During the past year and a half, the entire TIMED team has devoted most of its attention to improving the accuracy of the measurement products through vigorous validation efforts using coordinated ground-based and other spaceborne observations. Results have been presented at many professional conferences (e.g., AGU, COSPAR, IUGG), and a number of papers

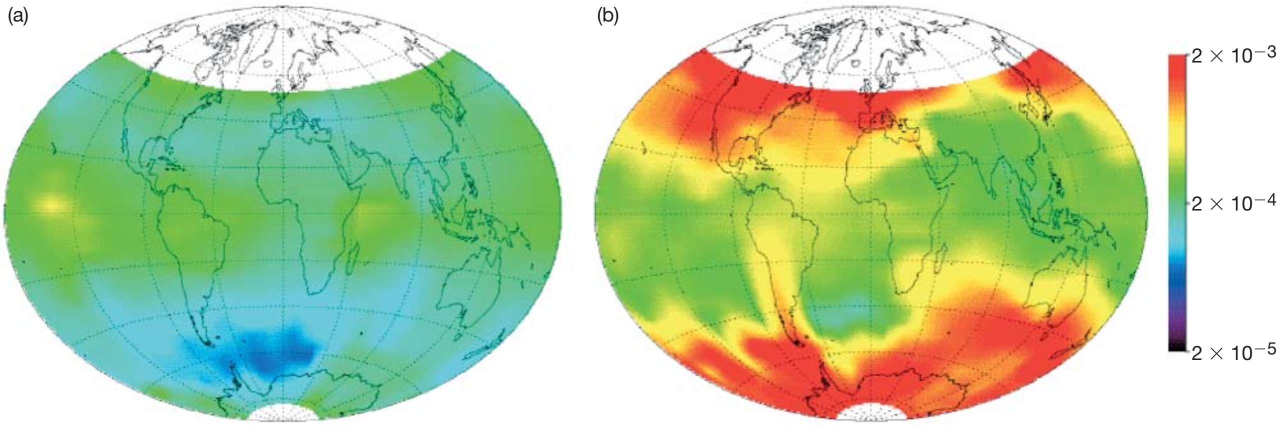

Figure 6. NO 5.3-μm irradiance at 110 km for (a) 10 April and (b) 18 April 2002, showing the influence of the magnetospheric disturbance resulting from the solar storm on 17 April 2002. Images courtesy of J. M. Russell III and the SABER team.

have been submitted for publication. A list of these presentations and papers may be found on the TIMED Web site (www.timed.jhuapl.edu).

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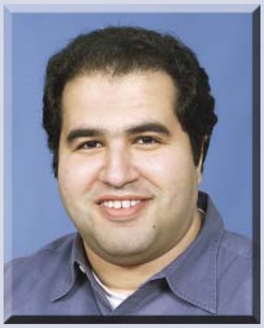

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