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Distributing space weather monitoring instruments and educational materials worldwide for IHY 2007: The AWESOME and SID project

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Abstract

The International Heliophysical Year (IHY) aims to advance our understanding of the fundamental processes that govern the Sun, Earth, and heliosphere. The IHY Education and Outreach Program is dedicated to inspiring the next generation of space and Earth scientists as well as spreading the knowledge, beauty, and relevance of our solar system to the people of the world. In our Space Weather Monitor project we deploy a global network of sensors to high schools and universities to provide quantitative diagnostics of solar-induced ionospheric disturbances, thunderstorm intensity, and magnetospheric activity. We bring real scientific instruments and data in a cost-effective way to students throughout the world. Instruments meet the objectives of being sensitive enough to produce research-quality data, yet inexpensive enough for placement in high schools and universities. The instruments and data have been shown to be appropriate to, and usable by, high school age and early university students. Data contributed to the Stanford data center is openly shared and partnerships between groups in different nations develop naturally. Students and teachers have direct access to scientific expertise.

The result is a world-wide collaboration of scientists, teachers, and students to investigate the variability of the ionosphere. The research-quality AWESOME (Atmospheric Weather Electromagnetic System of Observation, Modeling, and Education) instruments have been selected as a participating program by the United Nations Basic Space Science Initiative (UNBSSI). The IHY Committee for International Education and Public Outreach has designated the simpler SID (Sudden Ionospheric Disturbance) monitors to be provided to teacher/student teams in each of the 192 countries of the world.

Keywords: Science education; Ionosphere; Space weather; Remote sensing; IHY; Solar flares

1. Introduction

How best could we address the goals of the IHY? Could we find a way to bring real scientific instruments and data in a cost-effective way to researchers and students? Through hands-on science, could students relate to the goals of IHY by advancing our understanding of the fundamental processes that govern the Sun, Earth, and heliosphere? Would it inspire the next generation of scientists and help spread the knowledge of our solar system and the exciting process of scientific exploration?

To find out, we undertook a 4 year test program to develop and provide space weather monitoring instruments to high schools and universities throughout the US and at selected sites around the world.

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Fig. 1. AWESOME research-quality ionospheric monitor designed for universities.

Fig. 2. SID ionospheric monitor, designed for high school use.

Our two-part program provides a network of space weather monitor sensors to a worldwide team who can perform quantitative investigations of ionospheric disturbances. The network consists of two classes of receivers: (a) a research-grade, electromagnetic receiver sensitive to Very Low Frequencies (VLF, 3–30 kHz) and Extremely Low Frequencies (ELF, 300–3000 Hz), able to detect a broad range of ionospheric phenomena (Fig. 1), and (b) low cost monitors sensitive to solar flare-induced VLF sudden ionospheric disturbances and appropriate for student use (Fig. 2). Thus the program features both research and educational components. This paper explains both, emphasizing the educational aspects.

2. Monitoring the ionosphere

2.1. Science objectives

Our chief scientific goal is quantitative comparison of local ionospheric disturbances, magnetospheric activity, and thunderstorm intensity across much of the globe through the method of ELF/VLF monitoring. ELF/VLF monitoring involves the study of three types of signals. The first are VLF transmissions in the 20–30 kHz range, operated by various navies for long-range communications with their submarines. Second, short-duration radiation from lightning strikes, known as radio atmospherics, or sferics, are guided in a similar manner between the Earth and ionosphere, enabling detection and localization of lightning strikes from thousands of kilometers away (Wood and Inan, 2004). Finally, so-called whistler signals propagating in the magnetosphere, often generated by lightning strikes, can couple into the atmosphere (Helliwell et al., 1973) and be detected by VLF receivers on the ground, often in association with ionospheric disturbances. AWESOME monitors can detect these lightning-induced disturbances. VLF methods are uniquely suited for studies of these phenomena, since many physical processes create measurable effects of more than one of these three types, each of which provides a different perspective on a given event. Although such VLF monitoring methods are widely employed, a number of scientific questions and techniques can only be answered with the existence of a world-wide network of instruments.

2.2. The problem

ELF/VLF remote sensing enables study of an extraordinarily broad set of phenomena, each of which impacts the ionosphere in a unique way, including solar flares, cosmic gamma ray bursts, lightning strikes and lightning-related effects, earthquakes, electron precipitation, aurora, and more. Due to the extremely sensitive nature of the lower ionosphere, even small changes can be readily detected with the proper instrumentation. Waves at ELF/VLF frequencies are efficiently guided between the Earth and lower ionosphere, and thus can be detected at global distances. We monitor world-wide transmissions in the 20–30 kHz range, a band containing many signals sent by various navies for long-range communications with submarines. Solar- and lightning-induced transient lower ionospheric disturbances can be monitored by measuring changes in the amplitude and phase of waves from these transmitters.

Although ionospheric monitors already existed, our team was required to develop new technology to meet project objectives:

- Instruments must be sensitive enough to produce research-quality data, yet inexpensive enough for placement in high schools and universities around the world.
- The instruments, data, and supporting educational materials must be effective, appropriate to, and usable by, high school age and early university students.
- Students must be able to share data and communicate with each other.
- There must be a way for teachers and students to quickly access scientific expertise.
- The project must have minimal needs requirements (e.g. require no expensive additional equipment) and be extendable to developing nations and wide distribution.

- The project must educate, enthuse, and excite students, hopefully encouraging them to continue in studies for science, technology, engineering, and math (STEM) careers.

2.3. Our new monitors: SID and AWESOME

The Sudden Ionospheric Disturbance (SID) monitors were inspired by a suggestion from Paul Mortfield that the Stanford Solar Center deploy an instrument already in use by the AAVSO, the American Association of Variable Star Observers (AAVSO website). The AAVSO monitors measure a single selected radio frequency to detect the effects of solar events on VLF radio wave propagation within the Earth's ionosphere. However, the AAVSO instrument required extensive construction, testing, tuning, and equipment (Scherrer and Scherrer, 2005) which were not feasible for high school classes. With funding from the NSF Center for Integrated Space – Weather Modeling (CISM), in conjunction with Ray Mitchell and William Clark, local teachers selected for their electronics expertise, we undertook a 2-year redesign of the SID monitors. The result was a preassembled new instrument appropriate for high schools, at the low cost of about US$250.

Stanford's Holographic Array for Ionospheric Lightning (HAIL) project was already studying the physical nature of quiescent and transient changes in the lower ionosphere. HAIL instrumentation consisted of fully digital VLF receivers deployed at nine high schools. While successful, the instruments cost about US$30,000, beyond what could be supported in a large distribution. Again with funding from CISM, Morris Cohen and Justin Tan undertook a 2-year redesign of the original HAIL instrument. The outcome was the Atmospheric Weather Electromagnetic System for Observation, Modeling, and Education (AWESOME) monitor, designed to do what SID does (narrowband amplitude), but also to measure narrowband phase, provide higher sensitivity, and save the full ELF/VLF electromagnetic waveform (broadband data, 100 kHz). The new AWESOME took advantage of advances in GPS technology, circuit board fabrication, and computing resources – resulting in the minimal cost of about US$3,000 each.

Both monitors come preassembled, but students "buy in" by designing and building their own antenna, which costs little and takes a few hours to assemble. Participants also provide a simple PC to record the data and, if possible, an internet connection to share their data with the rest of the team. We chose to provide ready-built technology because it is more easily incorporated into classrooms and it encourages students to focus on the science rather than getting bogged down in the time-consuming complication of equipment assembly, calibration, and testing. Stanford collects the data and provides access to researchers and scientific and technical assistance to participants.

3. Ionospheric phenomena

A solar flare is a sudden, rapid, and intense variation in brightness occurring when magnetic energy that has built up in the solar atmosphere is suddenly released. Radiation is emitted across the entire electromagnetic spectrum. The energy released during a flare is typically on the order of $10^{27}$to 10^{32} ergs/s. Sudden Ionospheric Disturbances (SIDs) occur in association with solar flares and have a very strong and relatively long-lasting effect on the ionosphere (Thomson and Cliverd, 2001). Strong solar flares have been known to knock out satellite and network communications. Earth's dayside ionosphere responds quickly and dramatically ($\sim$2.5 min 1/e rise time) to the X-ray and EUV input by an abrupt increase in total electron content.

Lightning can also indirectly generate ionospheric disturbances, when some of the released energy escapes the atmosphere and enters the magnetosphere in the form of whistler waves. Whistler waves can exchange energy with Van Allen radiation belt particles trapped in the magnetosphere through gyroresonance (Inan and Helliwell, 1978). This not only causes the whistler waves to grow in power, but also redirects the particles so that they precipitate onto the ionosphere where they produce measurable changes in the electron density profile (Helliwell et al., 1973). These so-called Lightning-induced Electron Precipitation (LEP) events may play a dominant role in the loss processes of the radiation belts.

Cosmic Gamma-ray Bursts (GRB) also have a very large effect on the ionospheric profile (Inan et al., 1999). They can produce enormous effects (20 dB or more) lasting many minutes on the signals propagating through the ionosphere.

The recent discovery of Terrestrial Gamma-ray Flashes (TGFs) by the CGRO spacecraft (Fishman et al., 1994) and subsequent detection by the RHESSI spacecraft (Smith et al., 2005), open broad questions about the nature of the physical processes associated with lightning strikes that produce the extremely high electric fields and highly relativistic electrons responsible for gamma-ray emission. Energy levels from these TGFs exceed 20 MeV (Smith et al., 2005), rivaling the energy levels of powerful cosmic sources such as black holes and collapsing stars, except they originate in our own atmosphere. Though most TGFs are closely linked with individual lightning strokes (Inan et al., 1996; Cohen et al., 2006), the nature of the physical processes that generate TGFs remains unknown.

Finally, limited but elusive evidence exists that ionospheric disturbances may occur in association with, or prior to, strong earthquakes (Freund, 2005). ELF emissions have been detected at short range from the epicenter (Fraser-Smith et al., 1990), and longer range VLF monitoring may detect shifts in the diurnal variations of VLF transmitter signals (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998; Chakrabarti et al., 2005). Earthquakes are spread globally and occur unpredictably. It is difficult to distinguish small earthquake-related effects from other types of disturbances without reliable corroborating evidence from an extensive network of receivers.

4. A space weather monitor network

4.1. The program

Imagine a student watching a severe ionospheric disturbance unfold in real time on their classroom SID detector, and then getting a text message (if the ionosphere isn't too disturbed) from another time zone across the world wondering whether she'd seen the event in the same way. What would the differences reveal about the way the Earth responded to the flare? With a network of stations, a picture that has never been seen before would form, showing in detail how the ionosphere responds to different kinds of extraterrestrial inputs.

With our newly designed instruments, and NASA funding, we set up such an experimental network by producing and distributing 100 SID and 10 AWESOME monitors to high schools and universities in the US and in a dozen other countries. Over a period of $1\frac{1}{2}$ years we communicated extensively with monitor hosts, answered questions from students and teachers, provided a centralized collection of data with web-based analysis tools, and in many other ways enabled and supported a network of student research sites.

Appropriate training of teachers is the key to successful student performance in science (Rising Above the Gathering Storm, 2006). The development of the National Science Education Standards (National Research Council, 1996) and Benchmarks for Science Literacy (AAAS, 1993) highlighted the need for educator professional development and, in the USA, has led to the creation of programs for the preparation of teachers to teach science materials (McDermott, 2006). In partnership with Chabot Space & Science Center (Chabot website) we have developed supportive SID teacher training, classroom activities, research suggestions, and background materials to accompany placement of monitors. These materials are provided in the form of educator guides and a teacher workshop. For IHY distribution, the workshop will be converted to CD/DVD/online training format and materials will be translated by Stanford Alumni volunteers into the six official languages of the United Nations (Arabic, Chinese, English, French, Russian, and Spanish). A version of the materials and monitor package for the blind is under consideration.

Our program includes a centralized data repository hosted at Sanford; a mechanism for establishing mentor partnerships between research scientists, radio enthusiasts, teachers, and students; and the ability to facilitate data exchange and form collaborations among teachers, students, and classrooms worldwide.

4.2. Educational techniques and enabling student research

Best teaching practices and current research on how students learn informed our decisions for designing the program and preparing supplementary materials. Since as early as the Sputnik era there has been a national consensus on the need for teaching science as inquiry (How People Learn, 2000; Jarrett, 1997; Lopez, 1995; Matson and Sharon Parsons, 2006; McDermott, 1991, 2006). Inquiry is a form of self-directed learning where students take more responsibility for determining what they need to learn, identifying resources and how best to learn from them, using resources and reporting their learning, and assessing their progress in learning (Centre for Teaching and Learning, 2007)

In addition, learning is enhanced when teachers pay attention and respond to the knowledge, beliefs, and misconceptions that learners bring to a learning task (Hake, 1998; How People Learn, 2000; A Private Universe). This type of "learner-centered" environment also includes teaching practices that are culturally responsive and encourages attempts to discover what students think in relation to the problems at hand, enables them to discuss their misconceptions sensitively, and gives them situations to think about which will enable them to readjust their ideas (How People Learn, 2000).

Knowledge-centered environments take seriously the need to help students become knowledgeable by learning in ways that lead to understanding and subsequent transfer. In addition to being learner-centered and knowledge-centered, effectively designed learning materials must also be assessment centered. That is, they should provide opportunities for feedback and revision of concepts and initial misconceptions. (How People Learn, 2000). Likewise, the SID program itself as well as its educational materials are benefiting from professional evaluation of activities and use of monitors in the classroom (Caper Team).

As most scientists know, and many studies confirm, the best way to learn science is to do science (American Association for the Advancement of Science, 1993; Boyer Commission, 1998; Lopez, 1995; How People Learn, 2000). And the positive effect of undergraduate research on the recruitment and retention rate of students, especially minority students, in the science fields is well-documented (for example see NSF RISE program; NSF REU). By focusing on a hands-on, in depth inquiry based learning environment, we have attempted to counter the "mile wide, inch deep" (TIMSS, 1995) type of science program so many students are exposed to.

SID data are easy to read and understand, thus being highly appropriate for creative use in student research. Data recorded by our SID instruments resemble seismograph data (Figs. 3 and 4). In addition to solar flare phenomena, the graphs host a wealth of details about the Earth's ionosphere and how it changes during the day/night cycle, from season to season, and how it responds to lightning storms and other ionospheric events. Student researchers can compare their data with that from NOAA's GOES satellite to help identify solar flares. Students using a monitor prototype have already identified flares that the

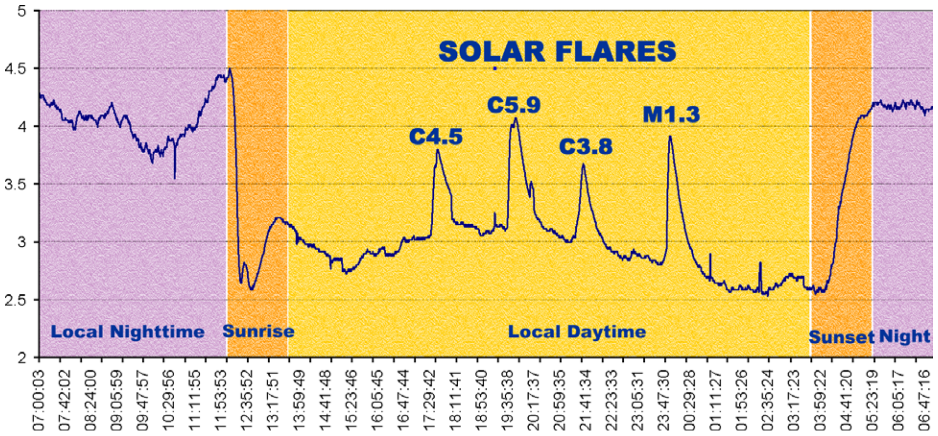

Fig. 3. SID Data. Note the characteristic sunrise/sunset patterns. Solar flares show up as spikes. The amplitude and phase of these signals vary according to diurnal, seasonal, and transient changes in the ionosphere.

GOES catalog “missed” perhaps due to human error. Students can trace events back to specific active regions on the Sun and can view corresponding images from NASA solar observatories such as SOHO/MDI, SOHO/EIT, TRACE, STEREO, and eventually SDO.

To meet the goal of exciting the next generation of scientists, we provided a collection of potential research projects and ideas modeled on inquiry-based formats and designed to inspire and engage, as well as a start-up research lab activity, thoroughly documented and designed

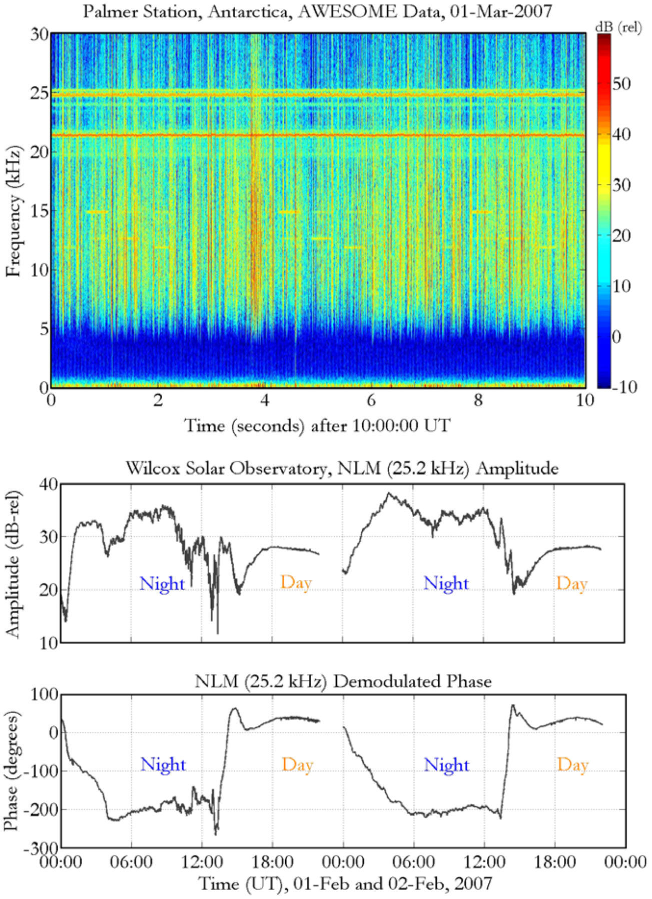

Fig. 4. Data from the AWESOME monitor is typically viewed in one of two forms shown here: the spectrograms (above) show broadband data while the VLF transmitter plots (below) show narrowband data. In the spectrograph, received at Palmer Station, Antarctica, the frequent vertical lines known as radio atmospherics, or sferics, originate from lightning strikes anywhere on Earth. These sferics often launch “whistler” signals, which can escape the atmosphere entirely, propagate in the magnetosphere and land on the other end. These can be seen as the curved shape features near the bottom in the 1–5 kHz range. The horizontal lines represent the signals from VLF radio transmitters.

to develop techniques for, and expertise in, understanding and analyzing SID data. Research suggestions emphasize collaboration and include comparing and understanding sunrise and sunset ionospheric phenomena at different latitudes, longitudes, and seasons; monitoring solar flares and tracing their history on the Sun; monitoring and understanding ionization effects such as day/night cycles, and the effects of events like solar eclipses, lightning storms, meteors, and gamma ray events; antenna design and its affect on performance; prediction of solar events and their affects on the ionosphere; identification of unknown signatures in SID data; and ionospheric changes as earthquake predictors.

About 50 students have undertaken successful research projects on all subjects save the prediction of solar events (for which an activity is being designed) and earthquake monitoring, which necessarily relies on the sporadic nature of earthquakes. Though these suggested activities were targeted for high school level, there is a rich set of physics that can be creatively investigated at levels through introductory college.

4.3. Case study – alignment with science standards

To assure effectiveness, we closely aligned our project with the US National Science Education Standards (National Research Council, 1996). The Standards emphasize science as inquiry. Unifying concepts and processes parallel those in the Standards, and include focus on the fundamental aspects of solar activity and their effects on the Earth, on obtaining data, taking measurements, on observing and understanding change and constancy, and learning to interpret and explain results from data.

To initially test our hypothesis that alignment with standards and hands-on access to data could improve science understanding, early in the program we placed prototype SID monitors with students in Richard Styner's sophomore science class at San Leandro High School in California USA, a minority-serving institution. Student teams chose to correlate their captured solar events with environmental changes on Earth. They collected data on local occurrences such as hospital emergency admissions, wildfires, student behavioral referrals, and police activity, and compared these with solar activity recorded by their SID monitor. Students performed analyses and drew conclusions, generated written reports, and gave presentations on their research, which Solar Center staff attended. From the presentations and written reports, it was clear that students could successfully work with the monitors and had achieved a general understanding of the heliophysical processes that govern the Sun and Earth.

The students also learned a great deal about the challenges in collecting environmental data, hence furthering their understanding of the nature of scientific knowledge and science as a human endeavor, as encouraged by the Standards. The pairing of the instrument with scientific inquiry improved student understanding of technological design and the functions technology can play in science. Finally, as the Standards encourage, the project facilitated teachers and students working directly with scientists and real data, providing them unique opportunities to experience the nature of scientific inquiry. Although the US National Science Standards do not specifically apply to other nations, we found the concepts and guiding principles were strong and valid models for teaching students in this inner-city environment and could feasibly be extended throughout the world.

4.4. Case study – encouraging students into STEM careers

A recent report by the National Academies (2006) notes the need to "increase America's [and presumably the world's] talent pool by vastly improving K-12 science and mathematics education" in order to "sustain and strengthen the Nation's traditional commitment to long-term basic research." As noted earlier, abundant evidence shows that high school and college science teaching is improved when the students engage in doing real science on real data. We wanted to contribute to the training, involvement in, and enthusiasm for science, technology, engineering, and math (STEM) careers, and especially encourage better representation from members of underserved and underutilized groups. Our target of high school age classrooms allowed us to focus on students while they are still able to "take the next step" (e.g. complete required math and science subjects) before choosing a major or career target. The enthusiasm generated by working with their own hands-on solar activity monitor, their introduction to information technology through our data and communications facilities, and their direct experience with Scientist Mentors as role models should encourage students to go farther and consider career choices in science and technology.

As an example, Leandra Merola, a student at South Side High School in Rockville Centre, New York USA, undertook a three-month SID-based research project, "A Study of the Effects of Sunrise and Sunset on the Ionosphere as Observed by VLF Wave Behavior." Her teacher was Richard Kurtz and Stanford Solar Center put Ms. Merola in touch with mentors Nick Gross, of CISM, and Don Rice, Center for Atmospheric and Space Sciences, Utah State University. She also had access to Miriam Forman, at the State University of New York at Stony Brook. Ms. Merola defined her own project, set her own goals, installed the SID monitor, captured data for several months, and undertook analyses of how solar-induced changes to the ionosphere affected the sunrise and sunset signatures of VLF waves propagating through the ionosphere. Her project was entered in the prestigious Intel Science Talent Search competition, "America's oldest and most highly regarded pre-college science competition…often referred to as the junior Nobel Prize" (Intel website). Her work was also selected to be presented at the Regional Round of the Junior Science and Humanities

Symposium (Junior Science and Humanities Symposium, website), a highly competitive gathering where Ms. Merola placed third of 120 students invited. Ms. Merola has received a full scholarship based partially on her accomplishments with the SID monitor, and intends to pursue a career in science.

With the expansion of our network, we hope to strengthen the world's future workforce by developing the critical skills and capabilities needed by engaging students in hands-on research with real scientific data to give them direct experience in STEM fields (Fig. 5).

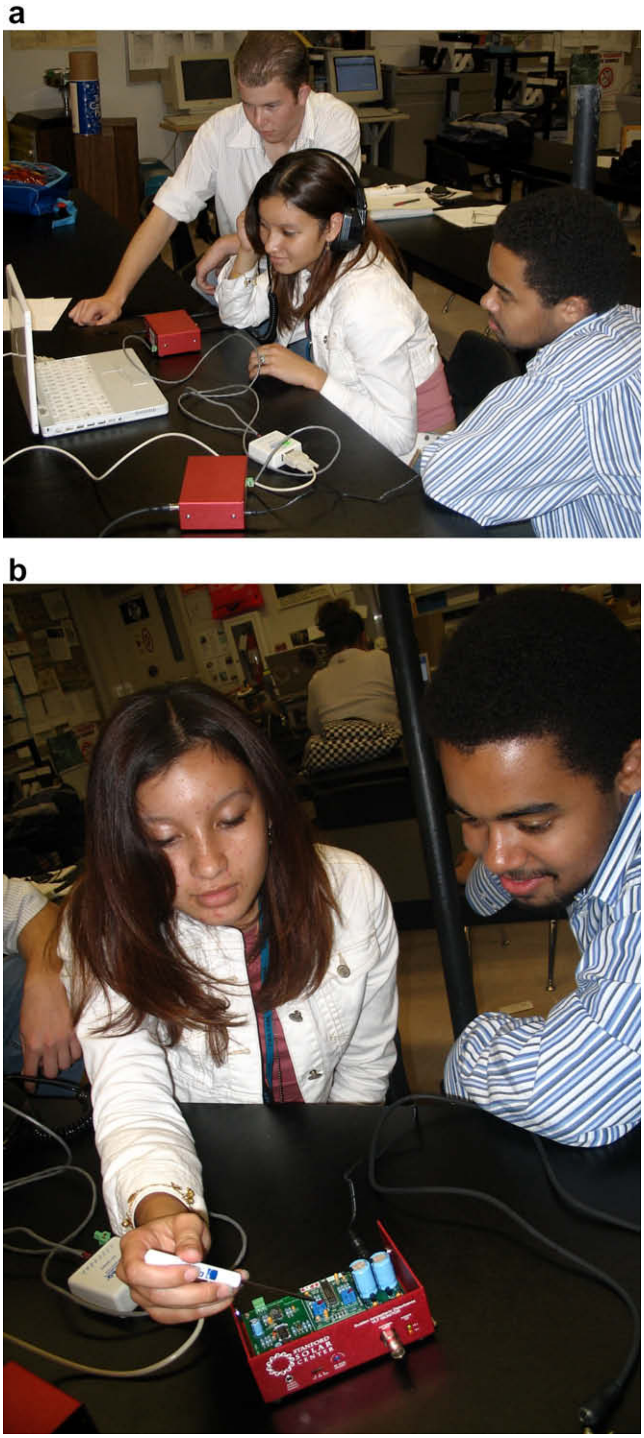

Fig. 5. Students at Deer Valley High School in Antioch, California, USA experiment with their monitors.

5. Extension to IHY

Because of the success of our test project, our AWESOME monitors have been selected by the IHY United Nations Basic Space Science Initiative (UNBSSI) as a Participating Program (United Nations, 2005). The IHY International Committee for Education and Public Outreach has designated our SID program to be of particular interest for use in their pre-college education program (Rabello-Soares, 2006). AWESOME monitors have already been placed in ten countries and SIDs in twelve countries as beta tests of the functionality of the program at international sites. Our plan is to place 25 additional AWESOME monitors with science teams in developing nations and provide SID monitors to interested educators in each of the 68 countries of the world with identified IHY National Coordinators. Supplemental funding is being sought to allow us to place SID monitors in each of the remaining ~124 countries of the world.

6. Summary

Through the Space Weather Monitor Project, we have brought real scientific instruments and data in a cost-effective way to students and researchers throughout the world. Instruments meet the objectives of being sensitive enough to produce research-quality data, yet inexpensive enough for placement in high schools and universities. The instruments, data, and supporting educational materials have been shown to be appropriate to, and usable by, high school age and early university students. Data contributed to the Stanford data center is openly shared and partnerships between groups in different nations develop naturally. Students and teachers have direct access to scientific expertise. Finally, the project has been shown to educate, enthuse, and excite students, encouraging them to continue in studies for STEM careers.

The IHY provides a unique opportunity to expand, on a truly global level, the lessons learned from our monitor placement and to support deployment of scientific instruments to a network of students, teachers, and researchers in developing nations and around the world. This is a step towards meeting the IHY goals of advancing our understanding of the fundamental processes that govern the Sun, Earth, and heliosphere and also inspiring the next generation of space and Earth scientists and spreading the knowledge, beauty, and relevance of our solar system to the people of the world.

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