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An Interdisciplinary Undergraduate Space Physics Course

Understanding The Process of Science Through One Field's Colorful History

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Students need to be aware that science is a human creation. Although the methods and ethics of science mean that, in the long run, the truth will win out, one cannot underestimate the power of personalities when considering how science is created.

Science education in this country is in its greatest period of ferment since the post-Sputnik frenzy a generation ago. In that earlier time, however, educators' emphasis was on producing more scientists and engineers. Today we recognize that all Americans need a good science background.

The ability to observe, measure, think quantitatively, and reach logical conclusions based on available evidence is a set of skills that everyone entering the workforce needs to acquire if our country is to be competitive in a global economy. Moreover, as public policy increasingly crystallizes around scientific issues, it is critical that citizens be educated in science so that they may provide informed debate and consent on these issues.

These issues are major driving factors in the systemic reform of precollege science education, which is seen the essential tool for not only developing science content knowledge, but also "scientific habits of mind" (Benchmarks for Science Literacy, 1994) Undergraduate and graduate science education have in general lagged in implementing this philosophy. However, many of the ideas solidly in the mainstream of precollege science education reform (such as a constructivist, interdisciplinary approach) are now being advocated for college science teaching (*e.g.*, McIntosh, 1994, Redish, 1994). I believe that such ideas hold considerable promise, that nontraditional courses informed by advances in precollege education should be developed, and that information about such courses be disseminated to a wider audience.

In order to develop this idea more fully, I proposed to teach a historically based course about space physics as an honors course at the University of Maryland—College Park (UMCP). The honors program at UMCP was established to foster broad-based undergraduate courses that utilize innovative teaching techniques to provide exem-

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plary education to a select group of students. Classes are small (no more than 20 students) and draw from a diverse student population. Although space physics generally is presented in advanced courses emphasizing on plasma physics, I designed an introductory course that would have four basic goals:

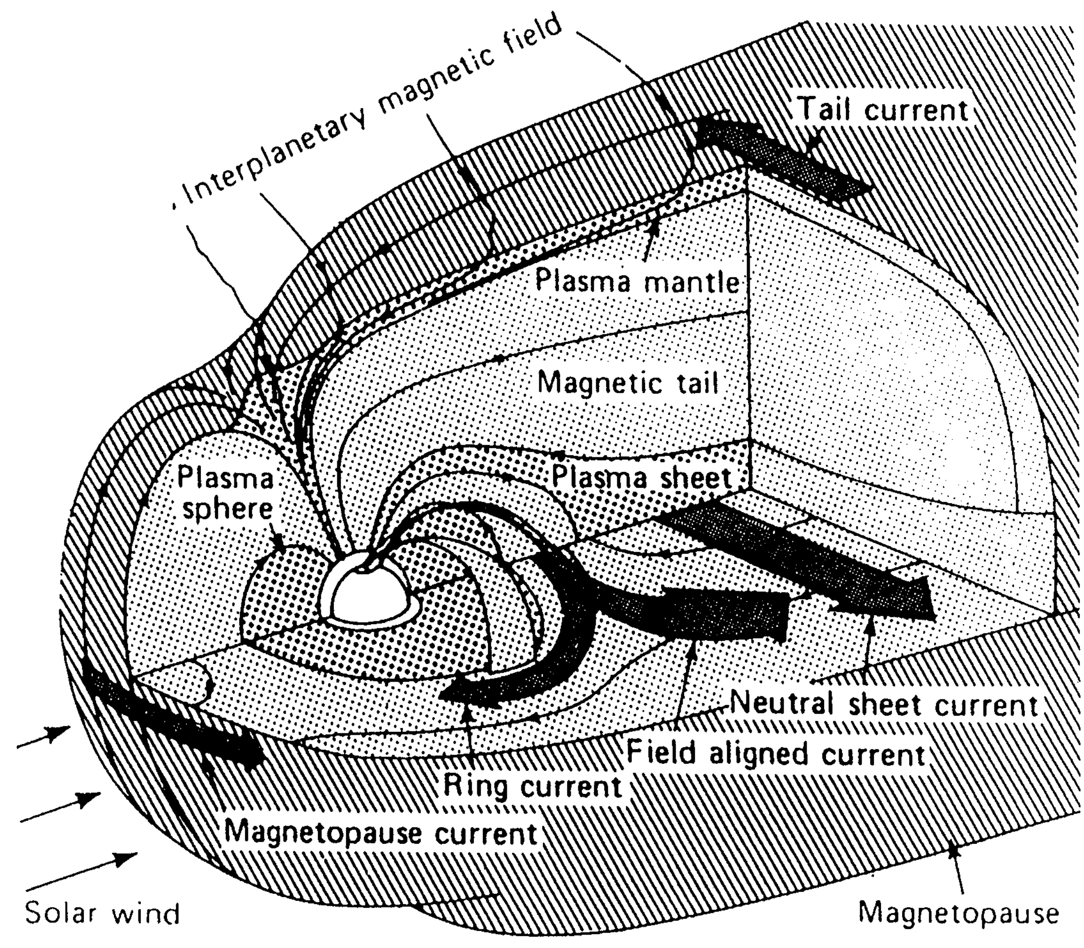
- ▲ To acquaint students with geomagnetic and auroral phenomena and their relationship to the space environment;
- ▲ To examine issues related to the history of science using the evolution of one field as an example;
- ▲ To develop familiarity with basic skills such as describing and interpreting observations, analyzing scientific papers, and communicating the results of their own research; and
- ▲ To provide some understanding of basic physics, especially those aspects that play a role in the near-earth space environment.

A Contextual Overview

Space is not empty. It is filled with ionized gases, called plasmas, and electromagnetic fields. Most of the visible universe is in the plasma state, although on Earth we are more familiar with the other three states of matter—solids, liquids and gases. In our environment, plasmas are encountered only in natural electrical discharges such as lightning, in man-made objects such as the plasmaspheres so prevalent at novelty gift shops, or in devices at research centers in which experiments in controlled nuclear fusion are conducted. The most spectacular encounter with natural plasmas is found in the polar upper atmosphere, where aurorae are commonly visible; the aurora acts as the "television screen" for plasma processes occurring in space ultimately powered by the sun.

The sun produces a continuous outflow of plasma, known as the solar wind, that fills interplanetary space. When this plasma strikes Earth's magnetic field, a comet-shaped cavity called the magnetosphere is formed in the solar wind. The magnetosphere boundary is located where the internal (mostly magnetic) and external (mostly plasma) pressures balance. On the dayside, the Earth's magnetic field is compressed and blunted into a bullet-head shape by the force of the solar wind flow. On the nightside, the Earth's magnetic field is drawn out into a long magnetotail extending several hundred

Figure 1. A cutaway view of the magnetosphere, the comet-shaped region of space controlled by the Earth's magnetic field. Also indicated in the figure are several of the major regions and currents that comprise the magnetosphere. The Van Allen radiation belts, which are not labeled in this figure, generally lie within the plasmasphere.



earth radii antisunward. By comparison, the moon orbits at 60 earth radii. Figure 1 depicts a schematic model of the earth's magnetosphere, which itself contains many internal structures.

Large-scale plasma physics generally employs the language of magnetohydrodynamics—hydrodynamics in which the fluid is electrically conducting. This is why we speak of balancing magnetic and plasma pressure at the magnetosphere's boundary. The balance is created through enormous electrical currents that deform and confine the Earth's magnetic field to the comet-like shape called the magnetosphere. These currents total between one and five million amperes. Some of the currents flow down along the Earth's magnetic field into the polar regions. If the currents are strong enough, processes that are still not completely understood create acceleration regions that energize upward-moving ions and downward-moving electrons. The accelerated electrons strike the upper atmosphere and cause a glow like that in a neon tube, which is called the aurora.

The electrical energy that drives the currents comes from the flow of the solar wind past the Earth's magnetic field, which creates a cosmic dynamo. The total current that is driven depends on how much solar-wind energy is coupled to the magnetosphere, which in turn is dependent on how much interconnection there is between the interplanetary magnetic field and the magnetospheric field. When that energy input is especially large, the result is a disturbance in the Earth's magnetic field called a geomagnetic storm.

The first person to report such geomagnetic disturbances was a well-known London instrument maker and Royal Society Fellow, George Graham (Graham, 1724). Shortly thereafter, it was noted that such disturbances were attended by auroral displays of unusual activity and brilliance (Celsius, 1740). By the late 19th century, thanks to the work of scientists like Alexander Humbolt, Carl Friedrich Gauss, Edward Sabine and Richard Carrington, it was known that "magnetic storms" were a global phenomenon (if a poorly understood one) and that they were in some way connected to the sun and solar activity (see Chapman and Bartels, 1940, Chapter 26).

Kristian Birkeland, a Norwegian physicist who studied under Henri Poincaré, took up the study of geomagnetic perturbations and the aurora at the turn of the century. Birkeland was a fascinating character who raised money from a variety of sources to finance polar expeditions and establish magnetic observatories (Egeland, 1984). Using data from these and other magnetic observatories around the world, he came to the conclusion that the electric currents during geomagnetic disturbances were "... driven by a supply of electricity from without." Birkeland envisioned solar electrons coming in streams from the sun, flowing down along the Earth's magnetic field, driving spatially-localized horizontal currents a couple of hundred kilometers above the Earth's surface, then flowing back out (see Figure 2).

Birkeland's ideas encountered some skepticism, and there were some problems with his scenario. Critics pointed out that beams of electrons would disperse due to self-repulsion of like charges, and that if the Sun emitted negative charges it would itself become positively charged. These objections did not sway Birkeland, who was convinced that auroral magnetic disturbances were driven by current systems that connected to space through a magnetic field-aligned component. In the last few years of his life his health and the quality of his work suffered, perhaps as a result of mercury poisoning (Dessler, 1984). Birkeland died in 1917 in Tokyo trying to make his way back to Norway from Egypt the long way via the Far East because of the war.

The next great figure in geomagnetism was Sidney Chapman, who entered the field in 1918. Chapman played a pivotal role in several areas, among them studies of geomagnetic storms and a theory of the ionosphere. He was a prolific writer and very personable, as well as being a brilliant scientist; in due course he came to dominate the field. Chapman's and Birkeland's approaches to physics were very different, and Chapman did not accept much of anything that Birkeland did (possible reasons for this are discussed by Dessler, 1984). He felt that Birkeland had misinterpreted his observations and he put no credence in Birkeland's concept of field-aligned currents. Because of Chapman's influence, the scientific consensus was that the currents associated with Birkeland's disturbances were completely contained in the ionosphere (Figure 3).

This was the state of affairs when Hannes Alfven entered the field. Alfven's approach to physics was much like Birkeland's—intuitive and heavily influenced by laboratory experiments. He felt that many of Birkeland's ideas, such as the existence of field-aligned currents, were correct, though he agreed with Chapman that clouds of ionized gas, or plasma, emitted from the sun would have to have equal numbers of positive and negative charges, unlike Birkeland's electron streams. Throughout his most of his career he had to battle against Chapman, the outstanding senior scientist of the time. As a result Alfven was forced to publish primarily in obscure Swedish journals. In 1950 he published Cosmical Electrodynamics, which was his attempt to reach (and convince) a wider audience. However, most of Alfven's ideas were not quickly accepted by the community, and even those that in time were accepted were often not attributed to him (Dessler, 1970). Nevertheless, recognition of his contributions finally came in 1970 when he was awarded the Nobel Prize in physics.

When manmade satellites began to orbit the Earth, a wealth of new phenomena were discovered. The first great discovery was the radiation belts, named after their discoverer, James Van Allen. The discovery of the solar wind, theoretically predicted by Gene

Parker in 1958, and of different regions of the magnetosphere, soon followed. The "geography" of space began to be mapped.

One of the more curious discoveries was the magnetic perturbations observed by polar orbiting spacecraft. Originally interpreted as standing hydromagnetic waves, it turned out that they were the signature of Birkeland's field-aligned currents (see Dessler, 1984). Within just a few years field-aligned currents, also called Birkeland currents, were accepted as real by the entire scientific community. Not only is existence of Birkeland currents now acknowledged as a matter of course, but they are now seen as critical transmitters of information and energy from one point of the magnetosphere to another, providing a direct electrical connection between Earth's ionosphere and the space environment.

Although space physics might seem to many to be a rather esoteric field with little broader import, this kind of sudden shift in scientific consensus is an excellent case study for the evolution of science as a whole. As Kuhn (1970) discussed, science occasionally undergoes "paradigm shifts," in which the existing order of things is overturned or severely modified to account for new observations that cannot be contained within the existing pattern, thus creating a new paradigm. This process is by no means a smooth one, and early doubters of the old paradigm risk being marginalized within the existing community, as was Alfven.

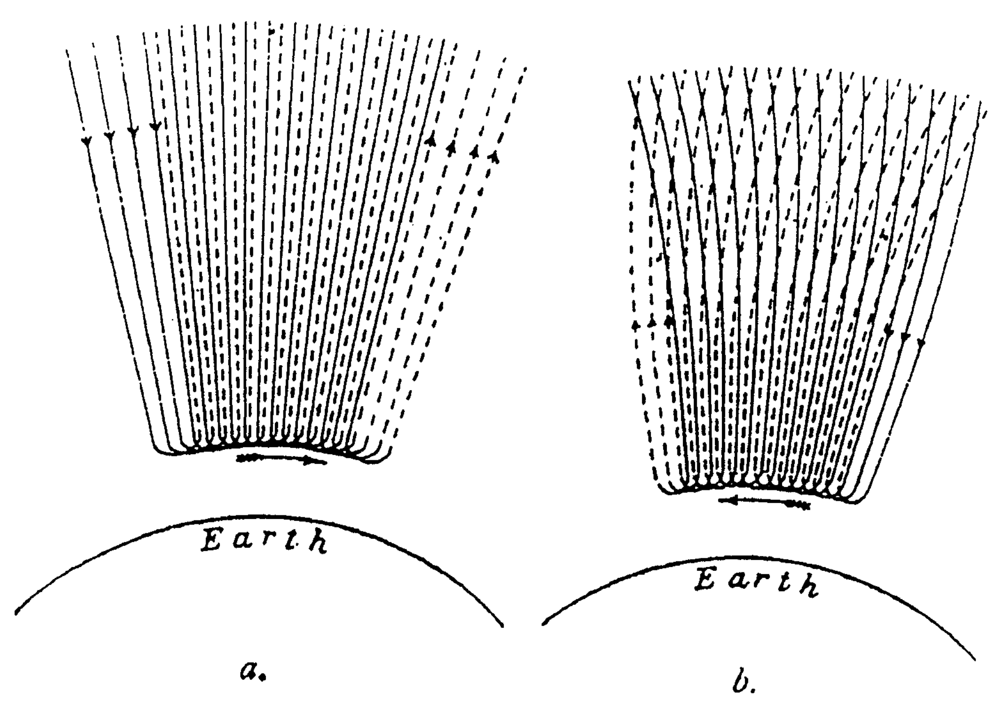
This kind of story is one worth telling, since students need to be aware that science is a human creation. Although the methods and ethics of science mean that, in the long run, the truth will win out, one cannot underestimate the power of personalities when considering how science is created. Unfortunately, science is too often presented as a precise progression, and scientists are portrayed as infallible priests of that mysterious discipline. Such perceptions are unhealthy in a democratic society because they lead to unrealistic expectations on one hand, and mistrust engendered by the unfathomable on the other. In the real world, it may not be enough to know something about science when making the decisions that all citizens must make. It may also be important to have some understanding of how science is created.

Course Design

An essential element of good science education revolves around skills that are often referred to as "scientific process skills." These include the ability to observe, analyze those observations, come to logical and defendable conclusions based on the evidence, and to communicate one's findings clearly to others. These skills are fairly independent of any particular field of science, though common to all science. As pointed out above, I strongly believe that another important (and often overlooked) aspect of science education revolves around the process of science as a human endeavor.

The honors course "The Space Environment and the Solar-Terrestrial Connection" attempts to address both issues by approaching a scientific subject historically, retracing the steps of the scientists who made the discover-

Figure 2. Birkeland's original figure showing his proposed path of solar electrons along the polar magnetic field, and the resulting current system.



ies. Six students registered for the course, which was taught as part of the 1994 Spring Semester at University of Maryland. They represented a surprisingly diverse group of students given the small total number, ranging from a junior English major who had never studied calculus, to a freshman physics major who had a strong foundation in basic physics and mathematics.

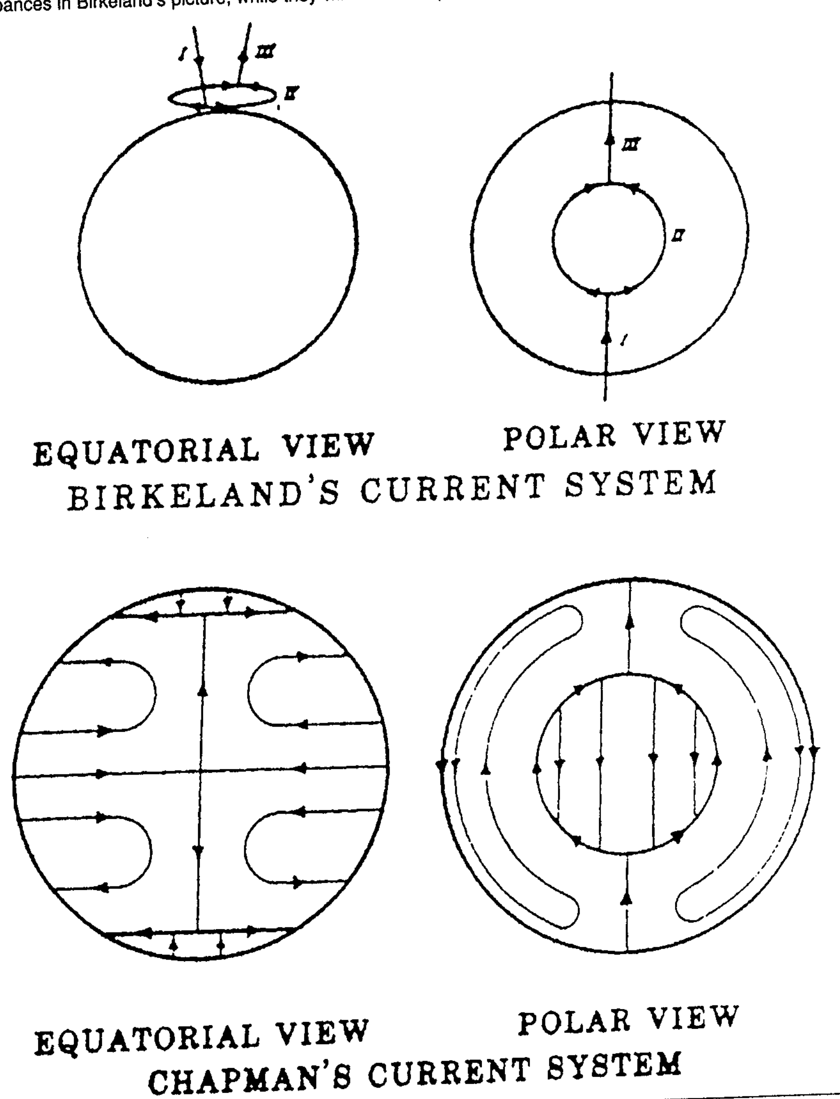
The pedagogical approach is inquiry-based and constructivist. In their first assignment, the students were asked to write a short essay about what they know about space, how they know it, and what more they would like to learn. Students also were asked to write a similar essay about electromagnetism. In addition, the first class was used as a general discussion to examine the students' understanding of concepts like "force" and "gravity." These essays, and the results of that first class, were used to develop a primer on basic physics and electromagnetism that occupied the first few weeks of the class. It turned out that the concepts of "force" and "gravity" were reasonably well understood; these concepts served as templates for developing understanding about electric and magnetic fields, their sources, and the forces associated with them.

In teaching this subject matter I tried to be Socratic as possible, and my method was much enhanced by the small number of students. By posing the right question it was often possible to elicit the response needed to move the discussion forward. Still, I had to rely some of the time on traditional didactic presentation. In addition, we conducted investigations both in and out of class using simple materials (magnets, pins, strings, batteries, bulbs, wires). The purpose of these experiments was to use simple observations of electromagnetic forces to determine the essential attributes of those forces (such as that the magnetic force on an electric current flowing in a wire is perpendicular to the direction of the current and to the line between the magnet and the current).

Once the students had some concept of electric currents creating magnetic fields, they were introduced to magnetometer records, or magnetograms, presented by Stewart (1861). That paper is the first publication of geomagnetic field data using the then-new photorecordation techniques. The students were divided into research groups of two, and each pair was asked to select one magnetogram of the seven days' worth presented in Stewart (1861). All groups chose September 1, 1859, which was the most magnetically disturbed day of the group. Their task was to examine the observations, then write a joint description of those observations. I then assigned them to write an essay about Stewart (1861) and his conclusions, and an essay comparing how they described the observations with what Balfour Stewart wrote.

This approach continued when we examined the magnetograms collected by Kristian Birkeland during his polar expeditions. After we reviewed as a class the observations, and discussed some conclusions that could be drawn from them, the students read what Birkeland (1908) had to say and wrote a report about his conclusions. We then proceeded to examine some of the work of Sidney Chapman, using ex-

Figure 3. A comparison between Birkeland's current system and that advocated by Chapman (from Akasofu, 1984). Both are capable of explaining the major features of geomagnetic perturbations recorded on the ground. However, polar-orbiting spacecraft will encounter transverse magnetic disturbances in Birkeland's picture, while they will not in Chapman's.



cerpts from *Geomagnetism* (1940). Students were able to see from the data how Chapman defined a magnetic storm, and both the similarities and dissimilarities with the events presented by Birkeland. We also reviewed what Chapman had to say about Birkeland's classification of geomagnetic disturbances—a classification that Chapman rejected.

Following Chapman, we discussed excerpts from H. Alfven's *Cosmical Electrodynamics* (1950), as well as some of the reaction to Birkeland's and Alfven's ideas in the scientific literature of the forties and fifties. By that point my students could not contain themselves. "Who was right?" they asked. "Birkeland and Alfven, or Chapman?" I would have preferred not to tell them and let them discover the answer from the space-age observations we were soon to encounter. However, due to a succession of winter storms in early '94 that closed the university several times and cut our total class time, I felt forced to take a shortcut. I told them that the field-aligned currents deduced by Birkeland are real.

This precipitated a marvelous discussion about personalities, the progress of science, and the essential nature of peer-review. Students initially felt that Chapman was a bad person for rejecting Alfven's papers, and saw Alfven as some kind of tragic hero. But I explained to them that Chapman was actually a wonderful human being by all accounts, whereas Alfven could be somewhat irascible and cantankerous. In rereading Chapman's criticism of Birkeland the students realized that it was measured, not mean-spirited. Moreover, I explained to my students that it is the duty of every scientist to honestly render judgment (when asked) on their colleagues' papers, and that on occasion I have felt forced to render harsh judgements on work done by people I consider to be personal friends. It just so happens that sometimes, for a variety of reasons, science can go awry, and the peer-review process, being inherently conservative, reinforces the mistaken view until new evidence or insight can break down barriers.

We continued to follow the story into the space age. We began with an examination of radiation data from *Explorer III* taken in 1958 and presented by Van Allen (1983) in a historical account of the early days of space exploration. Those data show a curious "dropout region" where the radiation flux seemed to go to zero. Another figure, also presented by Van Allen (1983), showed that in the laboratory the response of the Geiger tube dropped to zero if the incoming radiation was too great. The students concluded that the dropout region was actually a region of very high radiation where the Geiger tubes became saturated. This was the same conclusion reached by Van Allen and his assistants, and they announced the discovery of the radiation belts that bear his name.

Science occasionally undergoes "paradigm shifts," in which the existing order of things is overturned or severely modified to account for new observations that cannot be contained within the existing pattern.

This was followed by a general discussion of magnetospheric structure. Using their understanding of ground magnetometer measurements, the students were able to examine spacecraft data and connect what happens in space to events on the ground. We examined several cases of such events that were very familiar to the students from the ground magnetometer perspective, but unfamiliar from the satellite point of view. This allowed them to see how important Birkeland currents are to our current understanding, since they are the basic agents of the connection between space and the ionosphere.

The students also had to write a paper on Kuhn (1970), which accounted for 20 percent of their grades. In general, the students showed a good understanding of the points that Kuhn makes in his book. They were able to draw heavily on their understanding of the development of space physics to illustrate certain points. Although I have no control group to which to compare, I think that the students' understanding of Kuhn's thesis was much enhanced by their experiential study of one relatively small paradigm shift—as one student put it, "I could really see what he was talking about."

I based my assessment of the students on a mixture of traditional and alternative means. In addition to the various writing assignments in the course, students were assigned some traditional problems in vector algebra and basic physics (10 percent of the grade). This could be scored in a traditional manner. Still, much of the assessment was performance-based, which was much enhanced given the small number of students in the class. A large part of the grade (40 percent) depended on how well they performed on in-class analysis of data and in the discussions that followed.

The final exam incorporated models of some aspects of how a scientific community functions. A week before class ended, students were divided into two research groups, with a careful balancing of individual strengths. Each group was given a package of data plots representing a geophysical event similar to one that had been examined in class. Without discussing with the other group, each group prepared a small paper based on their data and returned it to me on the last day of class. The papers constituted 40 percent of the final exam grade (the final being 30 percent of the course grade).

On final exam day, the students were individually given a copy of the research papers from the other group. They then wrote reviews of that paper, which constituted 60 percent of the final exam grade. Asking students to review anonymously the results of other students' research proved to be an excellent summative assessment tool. In my own career, I have noted that when I read a referee's review of a paper I have submitted, I have a good idea of how well the referee understands the subject matter. Sometimes the comments show tremendous insight, whereas other times it is clear that the referee doesn't have a clue.

Since the data presented to the student groups incorporated all of the major topics we had discussed in class, the students were forced to rely on the broad range of core content and process skills in both the writing of the paper and the review. The review was an especially powerful tool in this regard, and the students' comments were surprisingly sophisticated. In one review a student pointed out "...that they associate characteristics of a general magnetic storm, such as the existence of a ring current, with a substorm. A substorm, as we now know, may or may not include a ring current." That student also commended the paper for some "... keen observations...", and concluded that as a scientific paper it "... would not have been published but it's [sic] good work for college freshmen." Another review pointed out that a particular argument was made based on the simultaneity of a particle flux increase at two different spacecraft, yet the data show "...a time delay of 3 minutes," and that on the basis of that delay the argument may be invalid. Such careful attention to detail and analytic approach will serve these students well in the future.

To conclude, I feel that this course achieved what I envisaged. My students learned some physics—enough, at any rate, to understand the course's subject matter. They gained insight into how science really works. They displayed an ability to analyze and integrate data in a meaningful fashion, and to solve problems. Finally, they learned something about the space environment. At the end of the final exam, I reinforced that learning by returning their initial essays on what they know about space. By reading those, they realized how far they had come in understanding the electrical connection between sun and earth, and the vision of a universe filled with cosmic plasmas, magnetic fields, and electric currents. ❑

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References

AAAS. 1993. Benchmarks for Science Literacy. New York: Oxford University Press.

Akasofu, S.-I. 1984. The magnetospheric currents: An introduction. In T.A. Potemra, ed. *Magnetospheric Currents.* 29-48. Washington, D.C.: American Geophysical Union.

Alfven, H. 1950. *Cosmical Electrodynamics.* The International Series of Monographs on Physics 13. London: Oxford University Press.

Birkeland, K. 1908. *The Norwegian Aurora Polaris 1902-1903.* Volume 1. Christiana, Norway: Aschelong.

Chapman, S ., and J. Bartels. 1940. *Geomagnetism.* New York: Oxford University Press.

Celsius, A. 1740. Bermerkungen uber der Magnetnadel stundliche Veranderungen in ihrer Abweichung. Svensk. Vet. Acad. Handl. 296-299.

Dessler, A. J. 1970. Swedish Iconoclast Recognized after Many Years of Rejection and Obscurity. *Science* 170: 604-606.

Dessler, A. J. 1984. The evolution of arguments regarding the existence of field-aligned currents. In T.A. Potemra, ed. *Magnetospheric Currents.* 22-28. Washington, D.C.: American Geophysical Union.

Egeland, A. 1984. Kristian Birkeland: The man and the scientist. In T.A. Potemra, ed. *Magnetospheric Currents.* 29-48. Washington, D.C.: American Geophysical Union.

Graham, G. 1724. Phil. Trans. R. Soc., London. 383: 96.

Kuhn, T. 1970. *The Structure of Scientific Revolutions.*

McIntosh, W.J. 1994. Systemic Reform and the College Science Educator, *J. Coll. Sci. Teaching* 23: 265-266.

Redish, Edward S. Implications of cognitive studies for teaching physics. *Am. J. Phys.* 62: 796-803.

Stewart, B. 1861. On the Great Magnetic Disturbance which extended from August 28 to September 7, 1859, as recorded by Photography at the Kew Observatory. Phil. Trans. R. Soc. London. 151: 428-433.

Van Allen, J. 1983. *Origins of Magnetospheric Physics.* Washington, D.C.: Smithsonian Institution Press.

Van Heuvelen, A. 1991. Learning to think like a physicist: A review of research-based instructional strategies. *Am. J. Phys.* 59: 891-897, 1991.