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Astronomy Education Review

2009, AER, 8, 010102-1, 10.3847/AER2009013

Advanced Undergraduate and Early Graduate Physics Students' Misconception About Solar Wind Flow: Evidence of Students' Difficulties in Distinguishing Paradigms

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Received: 04/7/08, Revised: 01/20/09, Published: 03/12/09

Abstract

Anecdotal evidence has suggested that advanced undergraduate students confuse the spiral structure of the interplanetary magnetic field with the flow of the solar wind. Though it is a small study, this paper documents this misconception and begins to investigate the underlying issues behind it. We present evidence that the traditional presentation of this concept can lead to this misconception and that it persists into graduate school. Two consistent models of plasmas that apply under different circumstances are presented during the course. Evidence suggests that students attempt to apply the models to inappropriate circumstances, which leads to a misconception. There is also evidence that a fundamental mechanics misconception contributes to students' difficulties. Finally, we argue that many of the broad conclusions of the research done at the introductory undergraduate level are applicable to upper division and graduate students. In particular, we conclude that direct instruction at this level through lecture-demonstration can leave students with misconceptions and even unintentionally reinforce those misconceptions.

1. INTRODUCTION

The Center for Integrated Space Weather Modeling (CISM) is a National Science Foundation funded Science and Technology Center (STC) with the mission to develop an integrated physics based computer model to predict the state of the space environment and its impacts on humans and technological systems (Hughes and Hudson 2004). To support this mission, the CISM Strategic Plan [http://www.bu.edu/cism/Publications/EducationPlan.pdf] includes an education program, part of which involves developing curricular materials for advanced undergraduates and beginning graduate students (Simpson 2004; Lopez and Gross 2008; Lopez 2008). In order to inform this curriculum development the authors of the present article undertook a program to understand the state of advanced students' conceptual knowledge of space physics.

The purpose of this paper is to report on one result of this research that illuminates issues about advanced students' learning. This paper describes the several separate pieces of evidence, which individually are not very strong, but that together all point to some specific issues regarding advanced student learning. The first issue is that even advanced students of physics and astronomy can often hold misconceptions that are well documented at the introductory undergraduate level. This issue has already been revealed by physics education research (McDermott 2001). A second interpretation of our results is that when students are presented with different but consistent representations of a phenomenon, e.g., single particle motion vs. the fluid theory for describing a plasma, they may have trouble reconciling the two. Moreover, there is evidence to suggest that direct instruction can unintentionally reinforce the misconception. In this paper, we will focus on one particular misconception, where students often confuse the velocity direction of the solar wind, which is mainly radial, with the direction of the magnetic field embedded in the solar wind, which takes on a spiral pattern primarily due to the rotation of the sun.

The result reported here was part of a broader study undertaken to inform curriculum development for the CISM summer school. The study involved two types of data. First, students were presented with a diagnostic test both at the beginning and end of an upper-division course in space physics. Additionally, students in the course were asked to volunteer for individual interviews. The interviews lasted between 30 minutes and 1 hour and covered material that was on the test. These interviews illuminated some of the students thinking on the test items.

From the diagnostic tests and the interviews a number of issues appeared. One of these involved the flow of the solar wind. The solar wind is known to flow mainly outward from the sun carrying the magnetic field embedded in the plasma structure. As the solar wind flows out and the sun rotates, the magnetic field forms a classic Archimedean Spiral structure first describe by Parker nearly 50 years ago (e.g., Kivelson and Russell 1995). The present work shows that students have trouble distinguishing between the flow of the solar wind and the spiral structure. In fact, it may be that presenting the spiral structure of the magnetic field introduces the misconception even when the instructor warns the students against the pitfall; though, this misconception has been reported in other studies of more general audience. Morrow *et al.* reported a similar misconception from a museum going audience who viewed an exhibit on space weather (Morrow *et al.* 2005). Similarly, Doxas reported this misconception in an undergraduate science class for pre-service elementary school teachers (I. Doxas, private communication, 2006). We should be cautious when connecting these results to the work reported here because the audiences are very different. However, it should also be noted that for all the audiences, exposure to the structure of the solar wind prior to the works reported would be limited to nonexistent. Thus it may be that the advanced science students are keying off of the same visual cues that the general audience is using and coming to the same conclusions. However, this is speculation and one would need more research on the subject before one could come to robust conclusions.

The balance of this paper will present evidence for this misconception and some possible interpretations of student thinking based on student interviews. In addition, results from a final exam at the graduate level are presented showing that the misconception persists into graduate school.

2. BACKGROUND ON THE SOLAR WIND

Space physics mainly consists of the study of very-low-density plasmas and their interaction with astronomical objects such as the Sun and planets, and the various magnetic fields associated with those objects. The Sun generates the solar wind, magnetized neutral plasma mainly composed of hydrogen nuclei and electrons which, after undergoing acceleration in the coronal region within a few solar radii of the sun, flows out in a radial direction at nearly a constant speed. The typical speed of a parcel of solar wind is usually between 250 and 700 km/s depending on the particular conditions and origin on the Sun, though higher speeds have been recorded during extreme solar conditions. The solar wind density decreases as the inverse square of the distance from the sun. At the Earth's orbit the density is between 1 and 10 particles per cubic centimeter, again varying with solar wind conditions. The Sun rotates approximately once every 27 days, though it rotates faster at the equator than at the poles. As a region on the sun that generates a fast solar wind stream rotates, it will generate a spiral pattern of fast solar wind much like a lawn sprinkler generates a spiral pattern of water even though each of the individual water droplets is traveling in a straight line. Additionally, since the sun consists of a convecting plasma, it is a dynamo that generates a strong magnetic field, much like the Earth generates its magnetic field. Due to the particular conditions of the solar wind, this magnetic field is "frozen in" to the conducting fluid of the solar wind and is carried in the radial direction away from the Sun. Thus a field line with a foot point on the Sun also forms a spiral pattern as the foot point on the Sun rotates, and the solar wind drags the line out in radial direction. All of this was initially described by Eugene Parker in the late 1950s and is often referred to in the standard textbooks as the Parker Spiral. A typical image that describes the development of the Parker Spiral can be found at the Goddard Space Flight Center Website (NASA 2002). Similar images are used in the textbooks for the courses studied in this work (Baumjohann and Treumann 2006, p. 164; Tascione 1994, p. 33).

3. COURSE AND STUDENTS INVOLVED IN THIS STUDY

The field of space physics is small and specialized, involving well under 1000 researchers working throughout the country. Only a few physics or astronomy departments have specialists in space physics and so only a small number of courses in space physics are offered each year at the undergraduate level. One of the authors is at a department that does offer space physics courses and so took advantage of the opportunity to work with several course instructors to gather data from the students taking this course. This department offers two courses at the undergraduate level and one at the introductory graduate level devoted to space physics. Still, there are less then 20 students in any one of these classes, so any sample size will be inherently small. Thus strict adherence to the standard development of diagnostic tests could not be undertaken (e.g., Ding *et al.* 2006). The course under study is offered in the astronomy department of a major private research university and is intended for upper division majors in the department. The prerequisites for this course include introductory calculus based physics and an advanced mathematical methods course taught in the physics department. The goal of this course is for students to learn the physics of plasmas using the space environment as a context. For example, in order to understand the motion of energetic particles in Earth's magnetic field students must understand how particles move in a variety of field configurations including a uniform magnetic field, a combination a magnetic field and an electric field, and a magnetic field with curvature and a gradient. An alternative representation of plasmas is that of a conducting fluid which is also presented in the course. In this representation the motion of the individual particles is not represented; instead the bulk motion is analyzed using magneto-hydrodynamic theory. Yet a third representation presented in the course is a statistical mechanics representation of the plasma. Evidence from this study suggests that the students may have mixed the results of the various paradigms. This will be discussed further in the next section.

Each cohort was taught by a different instructor and used a different textbook (cohort 1: Tascione 1994; cohort 2: Baumjohann and Treumann 1997), but the goals and general outline of the course were the same. During the course, one or two lectures were explicitly devoted to the structure of the solar wind and so explicitly relevant to the question above. In these lectures, the instructor derived the solar wind structure from first principles physics concepts. Each course was delivered using the traditional lecture format and emphasis was placed on problem solving. A minor difference between the two cohorts was that the instructor for cohort 1 held weekly scheduled problem solving sessions outside of class time while the instructor for cohort 2 simply held regular office hours. The problem solving sessions for cohort 1 were not mandatory but were strongly encouraged. During one such session, which was observed by one of the authors, approximately two thirds of the students were present and the instructor circulated around helping individual students with homework problems. One author observed both instructors during class. Both are capable instructors who devoted an appropriate and similar amount of effort to the course. They consider their role as instructors to be an important part of their position as faculty members.

The pretest was delivered at the end of the first course meeting and the posttest was delivered at the end of the last class meeting. While the majority of the students were astronomy majors, approximately 20% (4 of 19) of cohort 1 and slightly over 50% (10 of 19) of cohort 2 were engineering majors. Approximately half of the second cohort were not present for the posttest. It was planned for the last day of class and many students did not attend. In any given year there are fewer then 20 students in a section so results will be reported as raw numbers as well as percentages so as not to mask the effect of small sample size.

4. PRE- AND POSTTEST RESULTS FROM AN ADVANCED UNDERGRADUATE CLASS

To develop a diagnostic test, the authors drew upon their own experience and informal conversations with experts in the field to draft the questions. These were further refined in consultation with three instructors who teach the undergraduate and introductory level graduate courses in space physics. This test consisted of 14 questions on both basic physics and space physics concepts. The test length was short due to limitations in the time allotted to deliver it. Thus it was by no means meant to be a comprehensive diagnostic test in space physics. The test items were judged to be the most likely to give insight into how students approached some of the more problematic concepts. Individual students aggregate scores are not considered in this study, as we are more concerned with individual items rather than the whole.

Experts in the area of solar wind research have significant anecdotal evidence (N. Crooker, private communication) that students confuse the spiral structure of the solar wind with the flow direction of the solar wind. To verify this claim and explore it more systematically the following question was constructed and administered as part of the concept test.

At 1 AU (Earth's orbital distance), the solar wind flows:
(a) out from the sun in a spiral pattern following the field lines.
(b) out from the sun in a spiral pattern because it continues to rotate with the sun.
(c) in a circular orbit around the sun.
(d) radially out from the sun.
(e) none of the above.

The raw results from the above question for the pre and post-test for both cohorts are presented in Table 1

Table 1. Pre- and posttest results for solar wind question

	Cohort 1		Cohort 2	
Answers	**Pretest[a]**	**Posttest**	**Pretest**	**Posttest**
a	7 (37%)	4 (25%)	6 (33%)	3 (33%)
b	0	3 (19%)	1 (6%)	1 (11%)
c	0	0	0	0
d	12 (63%)	9 (56%)	11 (61%)	5 (56%)
e	0	0	0	0
Confidence	2.74	3.31	1.39	3.22

[a]On the pretest, b was not an option.

For all questions on the diagnostic, students were asked to rate their confidence on a 0 to 4 scale, where "0" represents a complete guess and "4" represents complete certainty. On the pretest for the first cohort, a slightly different question was presented where distracter "a" was only "out from the sun in a spiral pattern" and distracter "b" was something completely different. From the student responses in the pretest for cohort 1 it is clear that the original distracter "b" had no affect while distracter "a" was significant. To further understand this response, distracter "b" was replaced and "a" was modified. The results will be discussed below.

These results suggest that between 35% and 45% of students from both cohorts on both the pretest and posttest believe that the solar wind flows in a spiral pattern (responses "a" and "b"). In addition, exposure to a course in space physics does not affect the aggregate outcome although there is a significant increase in students' confidence from the pretest to the posttest. For the course that these students participated in the primary goal was for students to understand physics concepts, particularly plasma physics, in the context of the space environment. Thus issues specific to the solar wind are only addressed in this context for perhaps one or two lectures.

That is not to say though that the course has no effect on the students with regards to this question. When individual responses are analyzed, slightly less than half the students change their answers from pretest to posttest. In Table 2, the change in student responses from the pretest to the posttest is shown for those students that took both. For each cohort three columns are shown. In the first column is the number of students that answered this question correctly on both the pre- and the posttest. The second column shows the number of students that answered correctly on the pretest but answered incorrectly on the posttest. The third column for each cohort gives the number of students who answered incorrectly on the pretest but correctly on the posttest. The balance of students answered incorrectly on both the pretest and the posttest (not shown).

Table 2. Changes in student responses before pre- and postcourse

Cohort 1 ($n=15$)			Cohort 2 ($n=9$)		
Correct and correct	**Correct to wrong**	**Wrong to correct**	**Correct and correct**	**Correct to wrong**	**Wrong to correct**
5 (33%)	4 (27%)	3 (20%)	4 (44%)	3 (33%)	1 (11%)

The modifiers on distracters "a" and "b" give some indication of students thinking on this problem. The modifier in "a" suggests that respondents view the plasma as a collection of individual charged particles. In the particle model of the solar wind, the particles follow the field lines. Here the focus of the course may come into play. Since the primary focus of the course is to teach physics concepts using the space environment as an example, emphasis is given on understanding the interaction between various magnetic field configurations and charged particles. This raises some cognitive dissonance with the students when considering the motion of plasmas which are made up of those particles. More on this in the interview section.

The modifier in "b" suggests that respondents still maintain the misconception from mechanics that objects moving in a circle will continue to move in a circle even if no force is acting on them. This is a well-known misconception on the part of undergraduate students, and it forms the basis of three items in the Force Concept Inventory (Hestenes *et al.* 1992), a diagnostic test widely used by physics education researchers (e.g., Hake 1998). There is an alternative interpretation though. Participants may argue that field lines are in a spiral pattern because the sun is rotating. Thus this could also be a manifestation of the confusion between particles that follow field lines and plasma flow. Unfortunately, student interviews did not touch on this topic.

5. INTERVIEW RESULTS

Students in each cohort were asked to volunteer to participate in individual interviews. Interviews lasted between 30 minutes and 1 hour. A modest incentive was offered for participating, and a total of eight interviews were done during the semester that the student took the course. It would have been ideal to interview these students after the course was completed, but since the course is offered in the spring semester, most of the students would leave the area for the summer. Seniors taking the course would graduate and for those students that did return, there would be at least 3 months between the course and the interview. We see below that the interviews give insight into the conflicts the students face during the course and why they might have changed answers between the pre- and posttest.

A variety of topics were covered including the nature of particle motion in magnetic fields, the nature of the solar wind, and the structure of the Earth's magnetosphere. All students were asked about the flow of the solar wind. An example of a response that was considered correct is here:

I: Okay. So what direction does it [the solar wind] flow?
P: Away from the sun.
I: Okay. Is it radial, or…?
P: Yeah, radial.
I: Is it purely radial? Does it have any structure to it or any…?
P: I'm not sure, but I would think it probably has some kind of structure because I'm thinking that it changes magnitude. Well, no. Probably no structure.

"I" here indicates the interviewer and "P" is the participant. This interview was conducted early in the semester prior to any discussion of the solar wind structure. The last response of the participant indicates that the student is unaware of the spiral structure. It is notable that this participant changed their response from a correct response on the pretest to an incorrect response on the posttest.

More insight can be gained from the following response to the same questions from another participant interview that was also conducted early in the semester.

P: Yeah, so I suppose […]. It would certainly would be radial but there may be problems if it is charge traveling along field lines and things, uhm it would want to travel along those field lines…so…
P: Because it would…uhm, the charged particles would tend to move ….uhm well [mumble mumble mumble] They would tend to want to stick along that field line. […]
So it starts doing like this little weird spiral deal…so it wouldn't want to uhm…to go radial away like that. But I know that the solar wind goes…uhm, comes towards us…so it must have some sort of mechanism driving it radially away. So I do think that the solar wind is net uncharged. And that makes sense to me. So, then I don't think the solar winds a plasma, but I do tend to associate those two…maybe its just space physics in general, that say plasma and solar wind…Uhm, but I do think the solar wind is [undecipherable]. That would still make sense because it wouldn't still be net uncharged because there's a million little things here. If you take a little zone and there…statistically no net charge but there is a net current so. Hum…interesting.

Here the interview participant gives more of a hint about their thinking on this subject. A cognitive dissonance is developing between the "impression" that the solar wind is flowing radially, and the physics that governs individual motion of the particles in the plasma. This participant also changed their answer from a correct answer on the pretest to an incorrect one on the posttest.

6. RESULTS FROM A GRADUATE LEVEL COURSE

This misconception persists through to graduate school. On the final exam for a first year graduate course in space physics offered during the fall of 2005 students were asked to diagram the flow of the solar wind and the structure of the solar magnetic field. A response that received full credit is shown in Figure 1.

Figure 2 is a typical incorrect answer. In this figure the student has indicated that the solar wind flow follows the magnetic field structure. Of the 15 students taking the exam, 8 answered this question incorrectly, with the majority of the incorrect answers being of this type.

As a second part to this question, students were asked to calculate the distance at which the spiral has gone through 360 deg. This is a simple calculation with the explicit assumption that the solar wind flows radially. Of the 8 students who incorrectly answered the first part, half (4) completed the calculation successfully. Thus, even at the graduate level, we see students who can do the calculations for physics "problems" but do not have the conceptual understanding that the problems are assumed to be testing. This is consistent with the findings from physics education research (McDermott 2001).

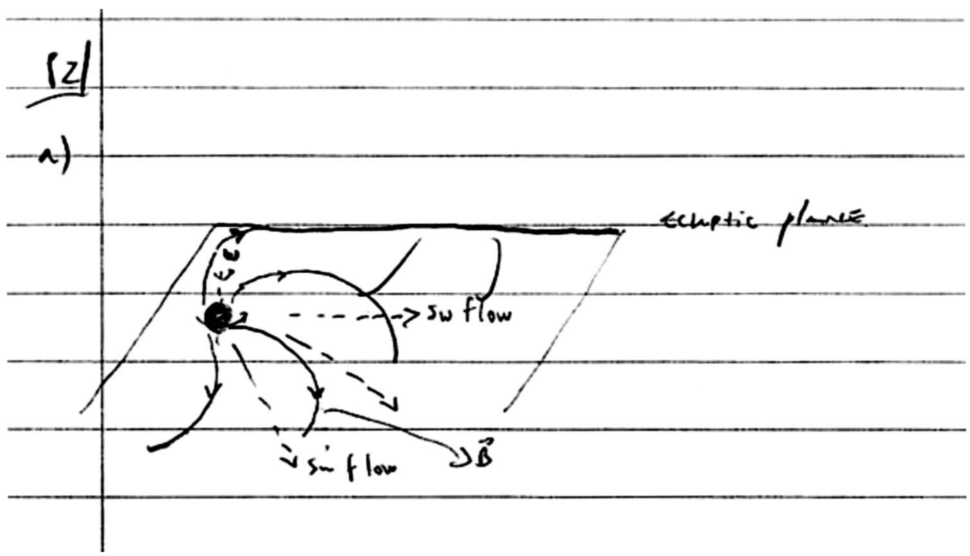

Figure 1. Full credit response to solar wind question on graduate level final exam

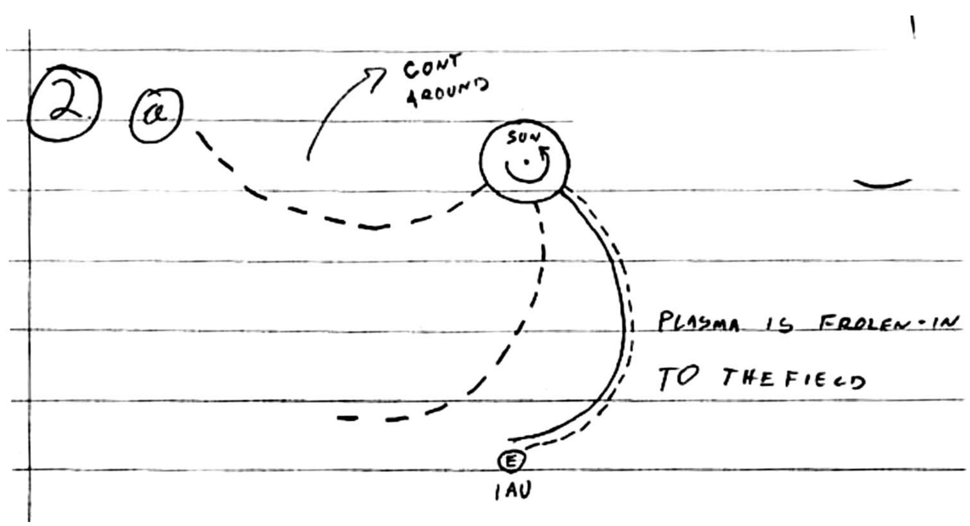

Figure 2. Zero credit response to solar wind question on graduate level final exam

7. CONCLUSIONS

Though this study is small, the results highlight two important points. Because a significant fraction of the students changed their answer from the correct answer to an incorrect answer, direct instruction (lecture in this case) may have a detrimental effect on student understanding of this concept. Another issue that this highlights is the mixing of paradigms by students when constructing new knowledge. In both of the cohorts studied in this work, students were presented with two models for plasmas: a microscopic model, where the plasma is treated as individual charged particles responding to electric and magnetic fields, and macroscopic hydrodynamics model, where the plasma is considered to be a fully ionized fluid that interacts with and affects the electric and magnetic fields. It is clear from both the test results and the interviews that some of the students were using the microscopic description ("particles spiraling around a magnetic field line") to describe the motion of the macroscopic fluid, the solar wind, flowing outward from the Sun.

As stated in the Introduction, the results presented here are part of a large study undertaken to inform curriculum development at the undergraduate and graduate level. Two different techniques have been explored in the CISM Space Weather Summer School. First, an ambitious activity was undertaken where Summer School participants mimic parcels of solar wind plasma connected by ropes that represent magnetic field lines. The ends of the rope are fixed to a rotating sun (represented by other students), while the students who are mimicking the solar wind parcels move radially outward from the sun. Pictures of this were taken from above and shown to the students afterwards. Figure 3 shows just such a picture (N. Crocker, private communication). This activity was undertaken prior to the work reported here and it relied on the reputation and enthusiasm of a particular instructor.

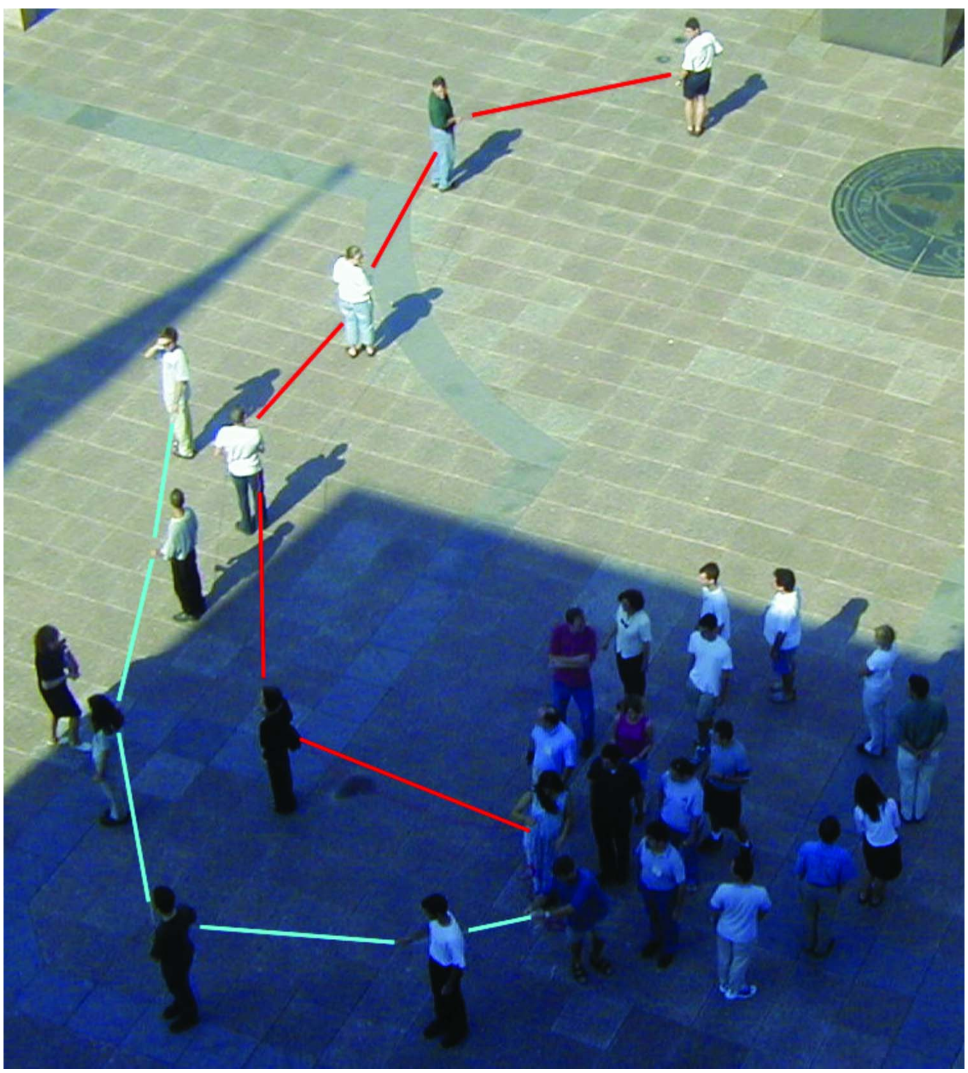

Figure 3. Picture of students simulating the solar wind with embedded magnetic field represented by ropes that students are holding. The ropes have been highlighted in the picture to make them move visible

An alternative approach takes advantage of a Summer School feature, the scheduled afternoon lab sessions (Simpson 2004; Lopez and Gross 2008; Lopez 2008). In one of the lab activities, students spend an afternoon exploring the results of a solar wind simulation (Odstrcil 2003). As part of this exploration students are asked to explore the angle between the solar wind velocity and the embedded magnetic field. This activity provides strong visual and kinesthetic evidence for the accepted answer. Group discussion during the lab and in-class polling shows that students, who begin the activity with a variety of opinions regarding questions similar to the pretest question, eventually come to consensus on the accepted answer.

More broadly, the results of discipline-based education research, such as physics and astronomy education research, conducted at the introductory undergraduate level can inform teaching at the upper divisions as well. This body of work has shown that students' misconceptions at the introductory level can persist into the upper divisions, consistent with the results presented in this paper. Furthermore, this body of work has shown that just telling students something through direct instruction is not enough; the instructor must constantly probe for understanding and be aware of common misconceptions that students have and then use techniques and activities for overcoming those misconceptions. The work presented here has provided yet another example of this and shows that the lesson is relevant even for advanced undergraduates and early graduate students. When discussing the results of the graduate final exam question, the instructor was heard to proclaim "This was not what I taught them.", to which one of the authors replied, "Yes, but it is what they learned."

Acknowledgments

The authors would like to thank W. J. Hughes, H. Spence, and M. Oppenheim for discussions about this work. This work was supported by CISM, which is funded by the STC Program of the National Science Foundation under Agreement No. ATM-0120950.

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