

## Lecture Tutorial: Tracking High-Energy Protons from Coronal Mass Ejections

**Description:** This guided inquiry tutorial gives students the opportunity to apply their knowledge of relativistic kinematics and energy. Students analyze coronagraph images taken by the NASA’s SOHO (Solar and Heliospheric Observatory) during a significant coronal mass ejection event that sent high-energy protons toward Earth. Students discover, by working “backwards” from the detection events at SOHO, that the CME shock waves that accelerated the protons did so at a point near the Sun (within 10 Solar diameters away). This resource is designed to supplement [Lecture-Tutorials for Introductory Astronomy](#) for lecture-style classrooms as well as for use in recitation or tutorial classrooms.

### Prerequisite ideas:

- The emission of a signal (*e.g.*, a light flash) and the reception of that signal must be treated as two different events, with different times as well as different locations.
- The relationship between relativistic kinetic energy, rest mass energy, and total energy for a particle.

### Some instructor notes:

- Although the explanatory text in the tutorial handout should be fairly straightforward, the overall procedure through which the students are guided in the course of the tutorial is as follows:
  - Section I (Interpreting coronagraph images): Students recognize that a coronagraph image records events that happened near the Sun approximately eight (8) minutes before the time indicated on the coronagraph itself.
  - Section II (Tracking the acceleration event of high-energy solar protons): Starting with the assumption that the acceleration solar protons attain a kinetic energy of 200 MeV, students deduce the speed with which these protons travel toward SOHO. As they do so, students are guided to recognize that they must treat the protons as relativistic. After computing the approximate final speed in part B, students conclude the tutorial in part C by “working backwards” from the event of their detection at SOHO to the event of their sudden acceleration by the shock wave (near the Sun).
- The instructor “checkpoint” on p. 2 of the tutorial is critical for checking that students can properly relate the clock reading on a coronagraph image to the timing of an event (occurring near the Sun) that is recorded on that image. (See note above about Section I of the tutorial.)
- In part II.B of the tutorial (p. 3), you should check students’ answers for the speed of the 200 MeV protons. A non-relativistic approach would result in a speed of  $0.653c$ ; using appropriate relativistic ideas, the (actual) speed is  $0.566c$ .
- After finishing the tutorial—if time allows—encourage students to reflect on their work throughout the tutorial and invite them to articulate any assumptions that they may have made along the way. For instance, they should recognize that they treated the “Sun’s clock” as being in the same rest frame as the SOHO clock, despite the fact that Earth (and SOHO) are orbiting the Sun. Another assumption that students likely will make—and should recognize that they will have made—is to treat the radial velocity of the CME shock wave as constant.



In this activity, you will analyze a set of coronagraph images captured by the NASA's SOHO (Solar and Heliospheric Observatory), which is a camera that takes images of the Sun. The coronagraph can record coronal mass ejections (CMEs) that can come toward Earth, damaging satellites above Earth and causing aurorae in the upper atmosphere. The leading edge of a CME can contain such strong electric fields that they propel solar protons with sudden and violent accelerations. These protons can reach relativistic speeds and can be the first particles from a CME to reach Earth.

## I. Interpreting coronagraph images

An instructor will provide you and your partners a series of images taken in October 2003 from SOHO. The images, labeled “A” through “E,” record the evolution of a CME, indicated by the bright region that rapidly expands from frame to frame. The shock wave that accelerates solar protons is located at the leading edge of the CME.

- A. The opaque disk at the center of each frame—which blocks direct light from Sun—contains a white circle that indicates the size of the Sun itself.

With your partners, verify that the opaque disk at the center of each image would correspond to a spherical region (centered around the Sun) that would be approximately *5 solar diameters* across.

- B. Turn your attention now to images “B” through “D,” which show the progression of the CME. With your partners, analyze these images by carrying out the following steps:
  1. Mark on these images the farthest extent of the CME. We will assume that these locations that you marked indicate the leading edge of the CME shock wave.
  2. On each image B – D, measure the (approximate) distance from the center of the Sun to the leading edge of the shock wave. (It is fine to use a number of solar diameters, *e.g.*, “6.5 $d_{\odot}$ ”).
  3. On images B, C, and D the SOHO clock reads times of 11:42, 12:18, and 12:42, respectively. On each image write down the (approximate) reading that a clock located near the Sun would read. (That is, if the “Sun’s clock” could actually appear on each SOHO image, how—if at all—would the reading on this clock differ from the reading on the SOHO clock?)

*Hint:* SOHO is about 1 million km away from Earth and 1 AU is about 150 million km, so the distance between the Sun and SOHO is about 149 million kilometers.



- C. To help you check your work in part B above, particularly in step B.3, consider the following dialogue among three students who are discussing their ideas about the “Sun’s clock.”

Arturo: “Well, we obviously cannot put a clock on the Sun *and* expect it to stay intact! But *if* we could place a clock very near the Sun, then we could treat that clock as being at rest with respect to SOHO, right?”

Bruno: “Right, both clocks we could approximate both clocks as being in the same rest frame. So, *if* we could actually see the ‘Sun’s clock’ in these images, wouldn’t it show the *same* time on it as what the SOHO time stamp says?”

Cristiana: “I agree with you too, Arturo, but wouldn’t light from the ‘Sun’s clock’ have to travel from the Sun to SOHO to be recorded on these SOHO images?”

With your partners, identify the various ideas raised by these three students. Do you agree more with *Bruno’s* or *Christiana’s* ideas about the readings on the “Sun’s clock?” Discuss your reasoning with your partners.

Are your results in part B—in which you identified locations and times of the CME shock wave—consistent with your group’s discussion about the student dialogue (above)? If not, resolve any inconsistencies.



Please **STOP** here for an instructor to visit your group and check your work thus far in analyzing the coronagraph images.

## II. Tracking the acceleration event of high-energy solar protons

The kinetic energy acquired by the solar protons from the CME shock wave can reach hundreds of MeVs.

- A. The last image of the set (“E”) from the October 2003 event shows the SOHO being flooded with high energy protons. With your partners, convince yourselves that image “D” (not “E”) records the *earliest arrival* of solar protons at SOHO (and hence, the arrival of the highest energy protons).



**For the remainder of this tutorial:** We will estimate where (that is, how many solar diameters from the Sun) the highest energy protons were accelerated by the CME shock wave. For this particular event, we will assume that the highest energy protons were accelerated to about 200 MeV by the shock wave.

- B. With your partners, determine the speed (relative to the Sun and Earth) of the 200-MeV protons.

In your work, show that if you were to erroneously use a *nonrelativistic* approach, your result would disagree by more than 10% with the relativistic result.

Nonrelativistic result: \_\_\_\_\_

Relativistic result: \_\_\_\_\_

- C. We can assume to a good approximation that the shock wave from the CME suddenly accelerated these protons when those protons were *very near* (that is, measurable in solar diameters away from) the Sun.

With this in mind, and using your results above, estimate where and when these protons were suddenly accelerated by determining the following:

1. The approximate *time interval* (measured by either SOHO's clock or a "Sun clock") for the 200-MeV protons to travel from the Sun to the Earth



2. The approximate *time*, as measured by the “*Sun’s* clock,” at which the shock wave from the CME suddenly accelerated the solar protons
  
3. The farthest extent of the CME shock wave at the time you determined in question 2 above—and hence, the approximate *location* (measured in solar diameters away from the Sun) of the solar protons when they were suddenly accelerated by the CME shock wave

*Note:* For question 3 above you will probably need to interpolate between two images in the SOHO image set. You should find that the shock wave accelerated the protons at a distance within 10 solar diameters from the Sun. That means that the protons traveled the vast majority of the distance between the Sun and the Earth after having been accelerated by the shock wave!

