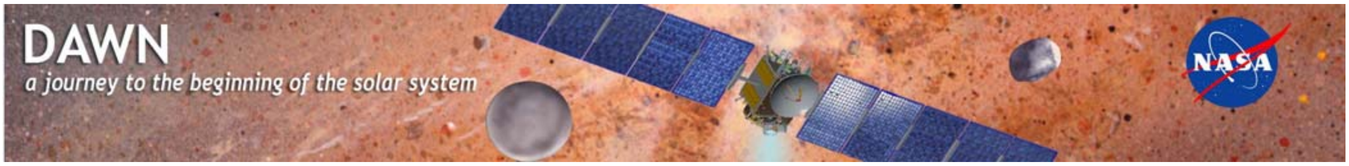


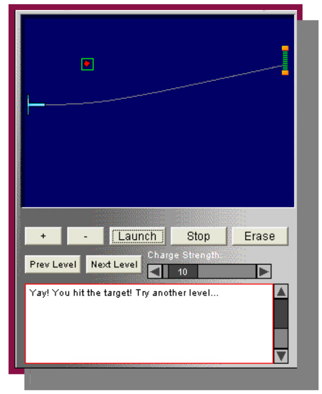
Ion Propulsion

We Need a Push!

TEACHER GUIDE – EXPLORATION

BACKGROUND

The Dawn Discovery Mission will be the first purely scientific mission to be powered by an advanced technology called ion propulsion, technology inherited from Deep Space 1 (http://www.nasa.gov/centers/glenn/about/history/ipsworks.html).



Once it leaves the Delta II rocket that launches it into space, the Dawn spacecraft will use ion propulsion to attain the additional thrust needed to reach Vesta, to go into a low altitude orbit at Vesta, then to cruise to Ceres and to achieve a low orbital path around the dwarf planet. Although it will take the Dawn spacecraft longer to go from Earth to Vesta and Ceres with ion propulsion than it would with chemical propulsion, the long trip can only be made by utilizing the efficiency of ion propulsion fuel.

The Exploration section of this Ion Propulsion Module focuses on the basic science necessary for understanding the design and operation of an ion propulsion engine.

The "working" principle behind an ion engine is much the same as what you experience when you pull hot socks from a clothes dryer on a cold winter day. The socks push away from each other because they are electrostatically charged. As they tumble against the metal parts of the clothes dryer, they rub off some electrons and become positively charged, so they repel each other.

In the Dawn spacecraft, charged particles are formed inside the magnet-ringed chamber of the ion propulsion engine. They form a plasma that moves through the chamber and provides the thrust for the spacecraft. To be effective the charged particles must be aligned and move in the right direction, undergo acceleration, and avoid premature discharge.

In this Exploration section, we will review the concepts of the formation and discharge of charged particles, the attractive and repulsive forces between charged particles, and learn more about the properties of ions in the plasma phase.

The **TEACHER GUIDE SUPPLEMENT** **CONTAINS:**

Specific NSES Science Education Standards for this guide;
Anticipated Test Results for the Student Activity, "Positive and Negative Charges"

MATERIALS

Student Texts
- "Charges"
- "Pushing with Plasma"

Student Activity, "Positive and Negative Charges"
Student Activity Report Sheet, "Positive and Negative Charges"
- One 15-cm plastic or paper metric ruler for each student or each pair of students

- If this activity is to be completed at a computer, Internet access to the following URL will be needed: http://dawn.jpl.nasa.gov/mission/ion_engine_interactive/index.html
- Alternative methods for implementing the "Positive and Negative Charges" Student Activity include the following:
  - Use a single computer and project the tutorial image on a screen, white butcher paper, or a white board. Have a student measure the deflection using a metric ruler.
  - Use a single computer connected to a large monitor. Cover the screen with a sheet of acetate so that you or students can use a marker to measure the deflection distances on the acetate.
  - Make hardcopy printouts of the tutorial screens so students can complete their report sheets individually or in pairs.

ESTIMATED TIME:
Part 1: 45 Minutes
Part 2: 20 Minutes (or as homework)
Part 3: 20 Minutes (or as homework)

PROCEDURE

Part 1: Student Activity, "Positive and Negative Charges"

1. Make the necessary arrangements for students to use computers with Internet access, either individually or in pairs, to complete this activity. If you are using an alternative method for students to complete this activity, have the necessary equipment set up for projection of the screen or make copies of the screens for student use.
2. Make copies of the "Positive and Negative Charges" Student Activity and the Report Sheet for each student or pair of students.
3. Distribute copies of Part 1 of the activity. (If students are using monitors without glass protection, give students directions for using metric rulers carefully so that they do not damage monitor screens.) Then give students adequate time to complete the tutorial section on <u>Positive and Negative Charges</u> and answer the questions on the activity sheet. **Make sure that students complete all their measurements for Part 1 on the same computer and monitor.**
4. When they have completed Part 1 of the activity, divide students into groups of four to share their answers to the questions and, as a group, to devise statements that describe how:
   a. the kind of charge on the particle affected the deflection of the test charge;
   b. the magnitude of the charge on the particle affected the deflection of the test charge; and,
   c. the distance between the charge on the particle and the test charge affected the deflection of the test charge.
5. Have each group share their statements during a follow-up classroom feedback session. You may wish to save these statements for future reference and comparison.

> Note: If students work on computers with different sized monitors, expect the actual measurements to vary with the size of the monitor. However, when each group determines the change in deflection, the calculated **<u>change ratios</u>** should be comparable to the Anticipated Results found in the Teacher Guide Supplement.

6. Distribute copies of Part 2 of the activity and give students adequate time to complete the tutorial section entitled Charge Simulator and to answer the questions in #14 on the activity sheet.
7. When they have completed Part 2 of the activity, divide students into groups of four to share
   a. their results and
   b. their answers to questions in #14 and come to consensus as a group on the answers.
8. During the feedback session have groups report:
   a. If they completed the activity on different computers, have them compare their results with those of other groups. Were they exactly the same? Were the trends the same? [Their results probably will not be exactly the same. The size and pixel size setting of the computer screen will have an effect on the size of the simulation rectangle and the placement of the charged particle may be slightly different depending upon students' perspective. However, the change in deflection should be similar and the trends should be the same, taking into consideration that there are inherent errors in measurement that are always a part of quantitative scientific experimentation.]
   b. How did their results compare with their descriptive statements in Procedure 4 above? [Discuss any difference between them.]
   c. Which factor had the greatest effect on the path of the test charge—the size of the charge on the particle or the placement of the charged particle? [If students make careful measurements, they should find that doubling the charge should have doubled the deflection of the test charge; while doubling the distance should have decreased the deflection to only 1/4 of what it was originally. See the "Anticipated Test Results" in the Teacher Guide Supplement. Their results should be fairly consistent with Coulomb's Law, which they will discover as they read the student text, "Charges"]
   d. What predictions did they make regarding the effect of positively-charged particles on test charge deflections? [If you are not going to assign Part 3 of the activity, this would be the time to discuss their predictions and question the rationale for them.]
9. Optional: If you wish students to test their predictions from 8 c., distribute copies of Part 3 of the activity

Doing the Calculations

If your students need help in finding a method of analysis to determine the change in deflection, use the "Anticipated Test Results" in the Teacher Guide Supplement, to guide them.

a) To find the change in deflection when doubling the charge at a distance of 1.5 cm from end of gun and 1 cm above the undeflected path, 1.7 cm / 0.9 cm = 1.9
1.5 cm from end of gun and 2 cm above the undeflected path, 0.7 cm/0.3 cm = 2.3
The average change in deflection, (1.9 + 2.3)/2 = 2.1, shows that doubling the charge doubles the change in deflection. This agrees well with the value calculated from the Coulomb's Law formula.

b) To find the change in deflection when doubling the distance 1.5 cm from the end of gun and a charge of 5, 0.3/0.9 = .3
1.5 cm from the end of gun and a charge of 10, 0.7/1.7= .33
The change in deflection, (.3+.33)/2= .31, indicates that when the distance is doubled, the deflection is only 1/3 as great. One can also state this in terms of halving the distance increases the deflection by a factor of 3. The theoretical result from Coulomb's Law shows that doubling the distance between the charges, reduces the deflection to ¼ its original value. Therefore, these experimental values are very close to the calculated values.

and give students adequate time to complete the procedure. During a classroom feedback session ask students questions similar to:

a. Did their results match their predictions? If not, ask how the results were different from their predictions.
b. Which factor had the greatest effect on the path of the test charge? Is this the same factor that had the greatest effect when you used a negatively-charged particle? [Again, the results should have been the same except that the deflection was in the opposite direction.]

Part 2: Charges

1. Distribute the “Charges” student text. Introduce it, saying something similar to: “When you experimented with positive and negative charges, you found that the magnitude of the charges and the distance between the charges both had an effect on the amount that the test charge was deflected. However, **there was a difference in the deflection effect when you doubled the distance between the charges as compared with doubling the charge of one of the particles.** As you read this student text on “Charges” look for the reason why this might be so.
2. You may either give student class time to read the student text or assign it as homework.
3. During a classroom feedback session ask students questions selected from the following, depending upon the background of your students.
   a. How do we use the terms “positively charged” and “negatively charged” differently from the way Ben Franklin used them? [Franklin said matter was "positively" charged when it contained too much of an invisible fluid; when it was deficient in the fluid he said it was "negatively" charged. Today we consider electric charge to be a fundamental property of two subatomic particles—electrons and protons.]
   b. How can a proton be said to have a +1 charge and an electron a -1 charge at the same time that we say that an electron carries a charge of 1.602×10^{-19} Coulomb? [When we speak of +1 and -1 charges, we are indicating only that a proton and an electron have equal, but opposite charges. Note that there are no units on these charges. A coulomb is the standard SI unit of charge and we have measured the charge of an electron to be 1.602×10^{-19} Coulomb.]
   c. Why do we describe static electricity in terms of electrons being transferred, rather than in terms of protons being transferred? [Because only electrons are found in the outer regions of atoms, whereas protons are nuclear particles.]
   d. If electrons are transferred *to* an object by friction, what is the static charge on the object? [negative] What is the charge on the object *from* which the electrons were removed? [positive]
   e. If the surfaces of the following pairs of objects were rubbed together, in which directions would the electrons be transferred?

Gives up electrons more easily

Very dry human hands
Leather
Rabbit fur
Glass
Human hair
Nylon
Wool
Silk
Aluminum
Paper
Cotton
Steel
Wood
Amber
Hard rubber
Nickel, Copper
Brass, Silver
Gold, Platinum
Polyester
Styrofoam
Plastic wrap
Scotch tape
Silicon
Teflon

Gives up electrons less easily

i. Silk and leather [silk]
ii. Nylon and polyester [polyester]
iii. Aluminum and silicon [silicon]
iv. Teflon and glass [Teflon]

f. If an electron encounters a proton and goes into orbit around it, what particle is formed? What is its charge? [A proton and an electron form a neutral (no net charge) hydrogen atom.] How does Coulomb's Law, which can be represented by the mathematical equation, $F = k\, q_1 q_2/r^2$, help explain the results you obtained when you explored the tutorial on Positive and Negative Charges? [As you doubled the charge on the particle that you manipulated, you doubled the size of F because the charges are in the numerator of the equation. When you doubled the distance between the charges, you decreased F to 1/4 of what is had been because the square of the distance is found in the denominator of the equation. In other words, F is directly proportional to the magnitude of the charges but inversely proportional to the square of the distance between the charges.]

g. Coulombic and gravitational forces are described by equations having exactly the same form. Yet the two types differ in a very important respect. How are they different? [Coulombic forces can be either positive or negative, but there is no negative gravitational force.]

In the mathematical equation for Coulomb's Law, $F = k\, q_1 q_2/r^2$
F = the electrical force between two charged objects;
k = Coulomb's Law constant;
q_1 and q_2 = the quantity of the charge of each object; and,
r is the distance separating the two charged objects

Part 3: Pushing with Plasma

1. As you distribute copies of the "Pushing with Plasma" student text, remind students that an ion propulsion engine will power the Dawn spacecraft. They should be looking for applications of the "Pushing with Plasma" information in ion propulsion technology.
2. You may either give student class time to read the student text or assign it as homework.
3. During a classroom feedback session ask students questions similar to:
   a. According to the Kinetic/Molecular Theory, what are some properties of ideal gases? [Gas particles are widely separated, tiny spherical particles that are constantly in motion. They move in a straight line until they collide with something or are acted on by an external force. When two ideal gas particles collide, the collision is perfectly elastic.]
   b. What are some differences between gases and plasma? [Plasma is a state of matter. In gases, the particles are neutral; in plasma, the particles are ions, charged particles. Plasma can carry electrical current and it can be accelerated and steered by electric fields.]
   c. Read the thermometer and then say, "The temperature of the gas particles in this room today is ___. What does this mean in terms of the kinetic energy and velocity of the gas particles in the room?" [Make sure that students can apply the current temperature of the room to the following terms:
      i. the velocity of a single gas particle and the kinetic energy of that particle (kinetic energy = ½ mass x velocity^2);

ii. the average kinetic energy of a sample of gas and the velocity of the individual gas particles, which may differ greatly; and,
iii. the temperature of a gas sample, which reflects (or determines) the average velocity of the gas particles in the sample and the velocity of individual gas particles in the sample.]

d. What is the difference between perfectly elastic and inelastic collisions? Which type of collision do you envision occurring in the ion propulsion engine of the Dawn spacecraft? [In a perfectly elastic collision, the *collective* kinetic energy possessed by the two colliding particles is the same after the collision as it was before the collision, so none of the kinetic energy of the system is converted to any other form of energy. In an inelastic collision, the kinetic energy of the system of colliding particles after the collision is not the same as it was before the collision. Since perfectly elastic collisions can occur only in an ideal gas, the collisions taking place in an ion propulsion engine are inelastic.]
e. What kinds of gas particles can undergo inelastic collisions? [Any kind of gas particle−neutral atoms and molecules−as well as charged gas particles.]
f. Would the collision of two billiard balls be an elastic or an inelastic event?Give the rationale for your answer. [Inelastic because some energy would be lost as heat due to friction between the balls and the table top. Therefore, the collective energy of the balls would not be the same as it was before the collision.]
g. Where on the periodic table do you find elements that have low ionization energies? [On the left side and through the transition elements; metals have relatively low ionization energies.]
   Where would you find elements that have high electron affinity values? [On the upper right; nonmetals tend to have high electron affinities.]
h. If all electrons have the same charge, why aren't the ionization energies of atoms of all elements the same? [Because ionization energy refers to the amount of energy that it takes to remove an electron from an atom and the charge on the electron is only one factor in the attractive force that holds an electron in an atom.]
   What are some other factors? [They include the magnitude of positive charge of the nucleus, the distance between the nucleus and the electron, the shielding factor of electrons situated between the nucleus and the outer electron, and the electron configuration of the atom.]
i. What are two ways in which ionization might occur in the gaseous phase? [1) An inelastic collision with a particle having enough kinetic energy to remove an electron; and, 2) in photoionization, where light strikes a metal.]
j. Why do ionic gases (or plasma) interact with external electric and magnetic fields, whereas other gases do not? [They interact with electric field because of their charge. *Moving* charged particles generate a magnetic field and magnetic fields interact with each other.]
k. Why does this property of plasma make it useful in ion propulsion? [It is possible to direct an ionic gas in a particular direction by applying electric and magnetic fields in the proper way.]

In the wrap-up session, conclude the discussion with a statement similar to:
In this Exploration section, you have explored the attractive and repulsive forces of charged particles. You have also learned that ion propulsion engines could not operate effectively without the positively-charged xenon ions that are part of the plasma found in the ion engine chamber. In the Development

section of the Ion Propulsion module, you will be learning more about the design and operation of the ion propulsion engine as well as the solar panels that furnish the energy for the engine.

Teacher Guide Supplement

A. *National Science Education Standards* addressed in this guide

Science as Inquiry (Grades 9–12)
Abilities Necessary to Do Inquiry

Identify questions and concepts that guide scientific investigations
Use technology and mathematics to improve investigations and communications
Formulate and revise scientific explanations and models using logic and evidence

Physical Science (Grades 9–12)
Structure of Atoms

Each atom has a positively charged nucleus surrounded by negatively charged electrons.

Motion and Forces

The electric force is a universal force that exists between any two charged objects. Opposite charges attract while like charges repel. The strength of the force is proportional to the charges, and, as with gravitation, inversely proportional to the square of the distance between them.
Electricity and magnetism are two aspects of a single electromagnetic force. Moving electric charges produce magnetic forces.

Conservation of Energy and the Increase in Disorder

Heat consists of random motion and the vibrations of atoms, molecules, and ion. The higher the temperature, the greater the atomic and molecular motion.

B. Sample Data from Student Activity, "Positive and Negative Charges"

Anticipated results for negatively-charged particle

Location of negatively-charged particle		Charge on **negative** particle	Distance from **top** of screen	Deflection from path	Change in deflection
From end of gun	Above the undeflected path				
1.5 cm	1 cm	5	18 mm	9 mm	Doubling charge 1.5 cm/1 cm =17/9 = 1.88
1.5 cm	1 cm	10	10 mm	17 mm	Doubling charge 1.5 cm/2 cm = 7/3 = 2.33
				Doubling charge Calculated average increase in deflection = 2	Doubling charge Experimental average increase in deflection = 2.1
1.5 cm	2 cm	5	24 mm	3	Doubling distance 1.5 cm/chg 5 = 3/9 = .33
1.5 cm	2 cm	10	20 mm	7	Doubling distance 1.5 cm/chg 10 = 7/17 = .41
				Doubling distance Calculated average decrease in deflection = .25	Doubling distance Experimental average increase in deflection = .37

Anticipated results for positively-charged particle

Location of positively-charged particle		Charge on **positive** particle	Distance from **bottom** of screen	Deflection from path
From end of gun	Above the undeflected path			
1.5 cm	1 cm	5	23 mm	7 mm
1.5 cm	1 cm	10	16 mm	14 mm
1.5 cm	2 cm	5	25 mm	5 mm
1.5 cm	2 cm	10	22 mm	8 mm