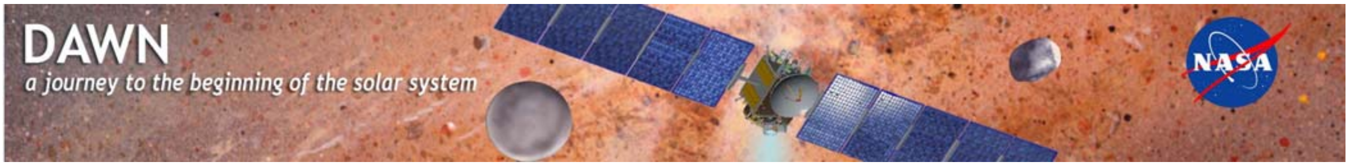


Ion Propulsion

Getting Charged Up!

TEACHER GUIDE – SYNTHESIS

BACKGROUND
In the Interaction/Synthesis section of the Ion Propulsion Module, students will follow a single xenon atom as it travels through an ion propulsion engine, pulling together the scientific concepts that play a part in moving the Dawn spacecraft.

One of the most difficult jobs for you, the instructor, is to help students understand the concept of *relative charge*, which is introduced in the student text, "A Trip through an Ion Propulsion Engine." The information in this graphic is basic to students using an informed, experimental method rather than just a "trial and error" mode when they "Design an Ion Engine" in the assessment simulation.

The **TEACHER GUIDE SUPPLEMENT CONTAINS:**

Specific standards for this guide

MATERIALS

A class set of color copies of: "A Trip through an Ion Propulsion Engine."
A computer, projector, and screen to project the PowerPoint: "One Xenon Atom Through an Ion Engine"

ESTIMATED TIME:
Part 1: 45 Minutes
Part 2: 15 Minutes

PROCEDURE

Using "One Xenon Atom"
The reading is designed to be used along with the PowerPoint presentation. If you use the reading along with the PowerPoint, students may have questions during the presentation. If so, you may either answer those questions at the time or keep a list of the questions on paper or on the chalkboard and address them after they have completed the presentation.

Part 1: Use the following script as you present the One Xenon Atom PowerPoint presentation:

Slide 1: The most significant word in this title is "*Simplified.*" If you have read the student texts entitled "Pushing with Plasma" and "Charges," you know that what is happening in the mixture of gaseous particles in an ion engine chamber is very complex.

However, in this presentation, we will focus on what a *single* xenon atom (or ion) "sees" and "does" as it goes through the reactions and processes that provide the ion jet propulsion engine's thrust.

Slide 2: A xenon atom undergoes four basic processes as it moves through an ion propulsion engine.

{click} A xenon atom is injected into the engine chamber and is ionized by a
{click} collision with an energetic electron.

{click} An electrically charged grid gradually accelerates the ion
{click} so that it lines up with a small hole in the grid
{click} The ion passes through the hole in the first grid and is greatly accelerated
{click} as it approaches a hole in the second electrically-charged grid.
{click} Once the ion passes through the second grid, it is neutralized to form a xenon atom that is left in space.

We will examine these processes more fully during the presentation.

Slide 3: Xenon is a desirable propellant gas for ion propulsion for three reasons.
{click}
First, it is an inert gas, so corrosion reactions with the metal chamber are minimal.
{click}
Second, Xenon's first ionization energy, the energy required to remove one electron from a neutral Xenon atom, is 12.1 kJ/mol or 0.125 eV/atom*. This a low first ionization energy for a inert gas, although it is relatively high when compared with other elements.
{click}
Third, with an atomic mass of 131.3 g/mol, the charge-to-mass ratio of the Xenon ion is 7.14 x 10^5 coul/kg, which can provide exhaust speeds of approximately 106 km/h.

*An electron volt (eV) is the energy a particle of one electronic charge acquires from falling through a potential difference of one volt, which is equal to 1.6 x 10^{-19} joule.

Slide 4: The color scheme in these graphics is the same as that used in the tutorials for the Student Activity "Positive and Negative Charges" simulation. Negatively charged electrons are red, positively charged ions are blue, and neutral atoms are green.

You can think of the **relative charges** on the grids, the chamber, the electrons, and the xenon ions, as being similar to that of signed numbers on a number line.

In the tutorials, you assigned charge strengths to the particles that you placed in the chamber. When you changed the strength on a negative particle from 5 to 10, the <u>size</u> of the particle increased. This also means that you moved to the left on the charge number line. In other words,
{click} a particle with a –5 charge is <u>more negative</u> than the positively-charged test bullet, but it is also <u>less negative</u> than
{click} the particle with –10 charge.

When you change the strength of a positively-charged particle from 5 to 10, you move to the right on the number line. So the particle
{click} with +5 charge is less positive than
{click} the particle with +10 charge, but more positive than any particle that is to the left of it on the number line. As we trace the path of a xenon ion through an ion engine, we must think in terms of <u>relative</u> positive and negative charges.

Slide 5: As the xenon plasma moves through the Ion Engine, the charges on parts of the engine that it encounters are in the **reverse order** of the signed number line, that is, in order of increasing negative charge:

{click} the engine walls are less negative
{click} than the xenon ion plasma, which is less negative
{click} than the first electrode grid, which is less negative
{click} than the second electrode grid.

It is important to remember that some processes in the Ion Engine depend upon the ***difference in magnitude*** of the charges on particles, the chamber and grids.

Based on this information can you see how a positively-charged Xenon ion can be attracted to a LESS positively charged electrode grid?

Slide 6: When a solar-powered ion engine is running, energetic electrons are emitted from a hollow-tube cathode. These electrons enter the ionization chamber where the positive engine wall attracts them,
{click} giving them additional energy to ionize the Xenon atoms.

In the simplified graphic on the right,
{click} this symbol (ê-) represents an electron with sufficient energy to ionize a Xenon atom. As it travels toward the engine walls, it undergoes a collision with
{click} a Xenon atom Xe, to form
{click} a Xenon ion Xe+ and
{click} another electron, e-˘.
{click} This electron e-* is the electron that was involved in the collision, but it is now at a lower kinetic energy than it had prior to the collision. This collision is inelastic, so some kinetic energy is also converted into another form of energy. The electrons present after the collision are attracted to the engine walls.

The "Pushing with Plasma" student text describes the many types of collisions that charged particles can undergo while in a mixture of atoms, ions, and electrons. However, if the Xenon ion is to contribute to the thrust of the ion engine, it *must* remain a charged particle and instead of moving randomly in the chamber, it must also be aligned to move in the same direction as other Xenon ions toward the rear of the engine.

Slide 7:
{click} The function of the two electrically-charged grids at the rear the Dawn ion engine is to move Xenon ions in the same plane and to accelerate them.
In our enlarged graphic,
{click} the first electrode grid encountered by a Xenon ion is labeled V+ which indicates that it is positively-charged ***relative to the second electrode grid***
{click} at the rear of the engine, labeled V**-**. Remember however, it is ***more negative*** than the walls of engine and the
{click} Xenon ions.

{click} Although the distance between the grids appears to be quite large, the second electrode, V**-** , is located only about 1000 micrometers (m) (the width of 10 human hairs) away from the first electrode.

Since the first grid is slightly negative compared to the Xenon ions, the ions are drawn toward it. The grid moves the ions in the correct plane and increases the chance of the ions going through the grid by increasing the effective surface area of the hole.

{click} Once near the first grid, the ion ”feels” the great potential difference between the first and second grid and is accelerated to very high speeds. A “lensing affect” by the electric field on the first grid also helps improve the chances of the ion going through the holes in the grid.

The blue arrow in this graphic indicates that our xenon ion is now a part of a very directionalized stream of ions going through the first grid. This ion stream is sometimes referred to as a thrust beam or plasma stream.

{click} Negative electrons that were not attracted to the engine walls can be attracted to the grid and are discharged when they strike it as indicated by the
{click} white flash.

{click} Occasionally a xenon ion strikes the grid, where it is
{click} neutralized and
{click} reforms a xenon atom. If it is to contribute to the engine’s thrust it must then be re-ionized by collision with an electron.

Slide 8:
{click} The Xenon ion stream is accelerated between the first and second grid.

{click}   The second grid is more negative than the first electrode by 1,280 volts, so the grid exerts a strong electrostatic pull on the positively-charged Xenon ion stream, accelerating the ions at a rate of 8.7×10^{11} m/s/s

{click} to a speed of 35,000 m/s as they move between the two grids. This change in momentum is translated to the spacecraft if the ions pass through a hole in the last grid.

{click} According to Newton's 3rd law, a reaction force accelerates the grid, which is attached to the spacecraft, forward
{click} with 1/50th of a pound (92 milliNewtons) of thrust. This is the amount of force roughly equal to the weight of a piece of printer paper as it rests on your hand.

{click} If an ion doesn’t go through the grid,

{click} its collision with the grid causes it to accelerate in the opposite direction. This applies a force that completely negates the force applied to the spacecraft because of the first acceleration.

Slide 9: Remember that electron that was removed from the Xenon atom during the ionization process? Well, that electron (and others resulting from the ionization of Xenon atoms) has moved from the chamber walls to a cathode toward the rear of the engine. Shortly after moving through the second grid, but before the beam leaves the engine, the Xenon ion recombines with an electron released from the cathode, thus reforming a neutral Xenon atom.

This is important since the second grid is very negatively charged. If the positively-charged ion is not neutralized, it will stop and reverse its direction. This is even worse than having an ion stopped as it hits the grid since the change in momentum is much greater. This slows the spacecraft instead of speeding it up.

Slide 10: How do these very tiny Xenon ions provide enough thrust to move the spacecraft? Thrust is the reaction force described by Newton's Third Law when a system accelerates mass in one direction to propel a vehicle in the opposite direction.

Mathematically expressed,
{click} the force of the ions, $F_i = m_i a_i$,
{click} equals
{click} the force in the opposite direction on the spacecraft engine, $F_e = m_e a_e$. So, $m_e a_e = m_i a_I$

Although the mass of Xenon ions is very small, they provide enough thrust to propel the
{click} 750-kg Dawn spacecraft in the opposite direction. The positively-charged Xenon ions actually pull the negatively-charged grid toward them with enough force to
{click} change the spacecraft's velocity 10^{-5} m/s. That doesn't sound like a very great acceleration, but it is enough to propel the Dawn spacecraft on its 6.3 billion kilometer, 8-year trip to Vesta and Ceres.

Part 2: The follow-up classroom discussion should focus on the following concepts:

1. How is the concept of ***relative charge*** (or ***difference in magnitude***) different from the way in which you have thought about positive and negative charges? [Up to now, most students have probably thought of "ground having 0 charge with positive and negative charges on either side of it." Their experience has them thinking only in terms of whether two charged particles attract or repel each other. They have not considered the relationship of the magnitude of two like charges being "relative;" specifically the situation where one charge is "more negative" than another negative charge. You may want to project the number line from the text and use additional comparisons to reinforce the concept. For example, you could ask, "Is -4 more or less negative than -3? Is +6 more or less positive than +2?"].
   Why is the concept of ***relative charge*** (or ***difference in magnitude***) important to the understanding of how an ion propulsion engine operates? [It is important because some processes in the ion engine depend upon the ***difference in magnitude*** of the charges on particles, the chamber, and grids. For example, a positively-charged xenon ion would not normally be thought to be attracted to a positively-charged grid, but the grid is positive with respective to the negative grid, but negative with respect to the xenon ion.]

2. Why can the positive xenon ions be "focused" so that they all move in the same direction, rather than travel randomly as gas particles do? [Because the electrically charged grids generate fields and charged particles like xenon ions can be accelerated, i.e., changed in speed and/or direction, by the field. Gas particles are neutral so they are not affected by the field.]

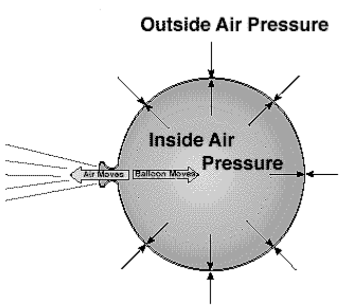
Propulsion Misconceptions

In what ways is the thrust provided by a stream of xenon ions in an ion propulsion engine similar to and/or different from a deflating balloon?

Balloon

When we release an inflated balloon, we can feel a stream of air coming from the open end and see the balloon moving in an opposite direction. *Many people have the wrong perception as to why a balloon is pushed through the air when released.* Most believe that the air escaping the nozzle is pushing on the air in the room to provide a thrust. If this were true, a balloon (or rocket for that matter) would not work in space. If we look at this situation with respect to Newton's 3rd law (action-reaction) we can quickly see the mistake and understand more fully where the thrust for the balloon comes from.

The following diagram illustrates the force on the balloon and the air in the balloon:



The force of the air molecules inside the balloon on the wall of the balloon is the only force on the balloon and this force causes acceleration when there is an opening in the balloon. A balloon in space (without air outside the balloon) would act the same as a balloon on Earth. (There is a problem with the balloon exploding in the low pressure of space.)

The misconception comes when people believe that the air rushing out of the balloon pushes on the air in the room. It is true that as the air molecule inside the balloon rushes out the nozzle, it exerts a force on the air molecules outside of the balloon. However, neither of these forces acts on the balloon in any way.

3. Why is it important to the operation of an ion propulsion system that the xenon ions can be "focused?" [It is the attraction of the xenon ions for the negative grid that provides the thrust that moves the spacecraft. To attain maximum thrust, the xenon ions must be pulling the negative grid in the same direction. Also, the xenon ions must be traveling in a direction that allows them to go through the grids rather than touching them and being discharged.]

4. During the wrap-up session, tell the students:
   You will work with a simulation model of an ion propulsion engine in the next part of the Ion Propulsion Module. As you manipulate the variables in the simulation to achieve the greatest forward thrust, you will be applying what you have learned in both the "Positive and Negative Charges" activity and the information about the operation of an ion propulsion engine in the "One Xenon Atom" graphic.

Teacher Guide Supplement

***NSES Science Education Standards* addressed in this guide:**

Physical Science (Grades 9–12)

Structure of Atoms

Matter is made of minute particles called atoms, and atoms are composed of even smaller components. These components have measurable properties, such as mass and electrical charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons.

Structure and Properties of Matter

- In gases, molecules or atoms move almost independently of each other and are mostly far apart.

Motions and Forces

- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship, $F = ma$, which is independent of the nature of the force. Whenever one object exerts force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

  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.