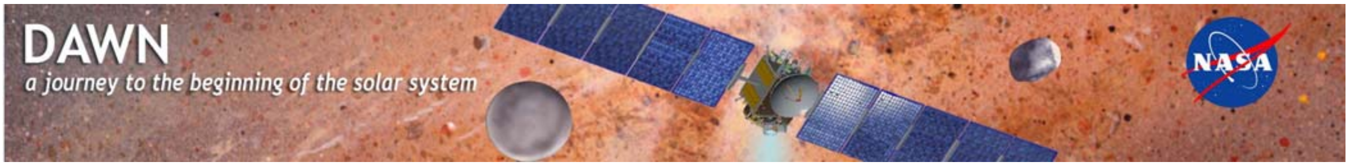


Ion Propulsion

Pushing With Plasma

STUDENT READING

SCENE 1: A high school physics class

PHYSICS TEACHER: Class, I have recently learned about an exciting new NASA project called Dawn, which will send a small spacecraft to the asteroid Vesta and dwarf planet Ceres for the ultimate purpose of learning more about the origin of the solar system. And guess what—the spacecraft fuel for the long journey will be a few kilograms of xenon.

Dawn Spacecraft Inspection
NASA/JPL

STUDENT #1: Wait a minute! In our chemistry class we've been studying fuels and almost all of them are complicated hydrocarbons like kerosene or other highly energetic molecules like hydrazine. These are the kinds of molecules that are capable of undergoing exothermic reactions to produce energy for propulsion. Xenon is neither a complicated molecule nor a hydrocarbon.

STUDENT #2: Yeah, and our chemistry teacher said that xenon is a rare gas that sometimes is called an inert gas. It doesn't react readily with anything. How can it be used as a fuel? Who does NASA think they are kidding?

PHYSICS TEACHER: Hold on. Have you noticed that our text mentions a fourth state of matter called plasma, but does not deal with it in any detail? Many physics and chemistry books list plasma as one of the four states of matter and proceed to discuss only three of them—the solid, liquid, and gaseous states. I think we need to spend some time learning something about this fourth state of matter. So, your assignment before the next class is to read this handout on plasmas. Then you will be able to understand how xenon can serve as a fuel in the Dawn mission, and we will discuss the ion propulsion engine.

<u>Plasma Handout</u>

I. Plasma—The Fourth State of Matter

Plasma tends to be ignored in most physics and chemistry texts because Earth actually is an island of extraordinary matter (gas, liquid, solid) floating in a vast sea composed of the fourth state of matter—plasma. Although plasma is the overwhelmingly dominant form of matter in the universe, earthlings typically do not deal with it. We see the effects of plasmas only in things like the soft glow of a fluorescent light, the luminosity of the Northern Lights, or the flash of a lightening bolt.

Northern Lights

So, what is a plasma (not to be confused with blood plasma)? It is neither a solid, a liquid, nor a gas; however, in some ways it resembles a gas. Unlike gases, which are composed of electrically neutral particles, plasma is composed of electrically charged, freely moving high-energy particles such as ions and electrons. For example, we would create a plasma if we somehow were able to carry out the following "reaction": H_2 (gas) $\rightarrow 2H^+$(gas) + 2 electrons (gas). The collection of hydrogen ions and free electrons produced constitute plasma. It is the freely moving aspect of the ions and electrons that makes a plasma resemble a gas more than a solid or liquid. Below we will borrow some aspects of gas behavior to describe certain characteristics of plasma, but keep in mind that this is a vast oversimplification. Physicists use entirely different systems of mathematical equations when describing the *detailed* behavior of gases and plasmas.

Perhaps the most striking differences between plasma and a gas arise from the ability of plasma to carry electrical current and to generate magnetic fields. Because of these properties plasma can be accelerated and steered by electric and magnetic fields. As you will see in this module, these features make plasma the key element in pushing a spacecraft to the far reaches of the asteroid belt. Scientists view plasma as useful and intriguing, but at the same time it is difficult to study and understand. It has been said that the properties of plasma make it "rampant with instabilities, chaosity, and non-lineararities" [http://public.lanl.gov/alp/plasma/ubiquitous.html].

Let us simplify these matters in order to gain a basic understanding of how plasma will be useful in making a trip to the asteroid belt. For many years, scientists have used a simple model of gas behavior that describes gases with remarkable ease and impressive accuracy, especially at low pressure and high temperature. This model is called the kinetic/molecular theory (KMT), which may already be familiar to you if you have studied "ideal gases."

In the KMT, gases are regarded as <u>widely separated</u>, tiny spherical balls that are <u>constantly in motion</u>. The motion is a straight line until the gas particles collide with something or are acted on by an external force. It also is the case that the velocity of the individual gas particles may differ greatly. That is, at any given moment some particles may be nearly at a standstill, while other particles are zipping along at a very fast rate. An average velocity can be defined in one of several ways, but for our purposes it is important only to recognize that average velocity is directly related to the temperature of the gas—the higher the temperature the higher the average velocity and *vice versa*. Further, recall that the kinetic energy of a moving object such as a gas particle also is directly related to the velocity of the particle (kinetic energy = ½ mass x velocity^2). Therefore, the temperature of the system determines the kinetic energy of the gas particles.

A second important aspect of the kinetic molecular theory has to do with collisions between particles. When two ideal gas particles collide, the collision is considered to be <u>perfectly elastic</u>, meaning that the *collective* kinetic energy possessed by the two colliding particles is the same after the collision as it was before the collision. In other words, in an elastic collision none of the kinetic energy of the system is converted to any other form of energy.

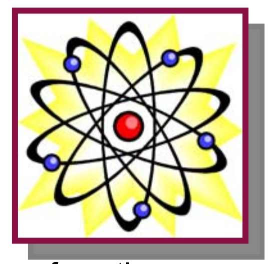
An inelastic collision, as you probably would guess by now, is one in which the kinetic energy of the system of colliding particles after the collision is not the same as it was before the collision. How can this be? One answer might be that some of the kinetic energy is used to create a new particle system of higher potential energy. Another answer is that some of the kinetic energy might be used to excite one of the colliding atoms to a higher electronic energy state.

These features of ideal gas behavior, while not entirely appropriate for describing plasma, nevertheless help create a picture of plasma structure. If we now superimpose the fact that plasma contains charged particles such as ions and electrons that generate electric and magnetic fields, we have a reasonably good picture of what constitutes plasma. As we shall see, ion propulsion engines ultimately require plasma for their successful operation.

SCENE 2: Physics class the next day

TEACHER: Now that you understand a lot about plasma, we can turn to the most important feature of plasma from the point of view of the Dawn mission: plasma interacts with externally applied electric and magnetic fields. Interaction with electric fields arises because of the charge carried by plasma particles and interaction with magnetic fields results from the fact that *moving* charged particles generate a magnetic field of their own. And everyone knows that magnetic fields interact with each other. Because of these special properties of plasma it is possible to manipulate them in various ways. For example, it is possible to direct a plasma stream in a particular direction by applying electric or magnetic fields. This idea is central to the operation of an ion propulsion engine.

II. Creation of Plasma



Our question is "How does one create ions and electrons to make plasma and what are the characteristics of such systems?" For our purposes, we will focus on the creation of positive ions, or cations, for reasons that will become obvious later in this activity.

First, let us review some fundamentals once again. Ionization, with the formation of positive ions, requires the removal of one or more of the electrons bound to an atom in a shell or orbital. We will only be interested in the removal of a single electron from the outermost reaches of the atom, creating a monopositive cation. The removal of such an electron requires the input of energy into the system, and the total energy increment needed to remove the electron completely from the atom is called the ionization energy or ionization potential. The noble gases, such as xenon, generally have high ionization potentials. Note that while this text focuses on monoatomic gases like Xe, much of what is said could be generalized to include gases consisting of molecules like carbon dioxide.

In the gaseous phase, the energy increment needed to effect ionization can be delivered to the atom in a variety of ways. Two ionizing events, among several others, that one might visualize immediately are as follows:

(a) the atom might undergo an inelastic collision with another particle of sufficiently high kinetic energy to bump an electron from the atom. The other particle might be an electron, another atom, or even another ion. The collision process might be driven by purely thermal means (i.e., high temperatures with consequent high kinetic energies), by particle acceleration through an external electric field, with a radioactive decay product such as an alpha particle, or perhaps by other means. Note that if the bombarding particle is an electron, the system, after collision, will consist of a cation and two electrons (the original electron and the one knocked off the target atom). The collision would be inelastic because the potential energy of the target atom would not be the same as that of the ion formed from it.

(b) the atom might be struck by a photon of sufficiently high energy to provide the increment of energy necessary for ionization. If the photon source is external to the sample gas the process is called photoionization.

When a sample of gas is subjected to an ionization technique of some type designed to create plasma, one does not expect all of the gaseous atoms to be ionized at any given time. This is the case for several possible reasons. For example, it may be physically impossible to keep the entire sample in the "ionization region" of the apparatus. It is also found that various recombination processes can occur wherein an electron reattaches itself to an ion, thus regenerating a neutral atom. The point is that in most cases plasma consists of ions and electrons with an inevitable neutral atom population mixed in.

III. Some Properties of Plasma

Imagine now that by one means or another we have created plasma. What would be its nature? What processes might occur at the atomic level? These and other questions need to be addressed and from the outset we should recognize that the details are quite complicated. Here we will try to generalize and only outline some of the more important conclusions. Once again, imagine plasma as a chaotic mixture of particles moving about at great average velocity while being contained within the walls of a vessel. Keep in mind that plasma is quasi-neutral, meaning that from a larger perspective it has a net charge of zero, but in zooming in to a smaller region, that spot may be positive or negative in charge.

Clearly, there will be many possible types of collisional phenomena that we can imagine as taking place in the plasma. A complete catalog of these phenomena is not needed but we shall try to list some of the processes that might occur simply to underline the complexity of the issue. Keep in mind that some of the collisional processes might be elastic in nature and some might be inelastic. Or they might fall into some other category that we will leave unspecified.

We can envision the following types of collisions in plasma:

1. electrons with atoms
2. electrons with ions
3. electrons with electrons
4. ions with ions
5. atoms with atoms
6. ions with atoms

Some of these possibilities are less likely than others. For example, the probability of electron-electron collision is expected to be very low since the two particles carry the same charge and would be expected to repel each other as they draw near to one another. Nevertheless, if one recognizes that within each of the above broad categories one can have several different collisional outcomes (inelastic *vs.* elastic, for example), it is quite obvious that plasma is dynamic and complex.

Finally, note that no mention has been made of the result of collision of plasma components with container walls. This adds another dimension to the complexity of the problem because ions may pick up electrons from the container wall or they may interact chemically with the wall. Or, electrons in the plasma may be attracted to the wall and removed from the scene.