National Aeronautics and Space Administration

Introductory Experiments with Plasma:

A NASA Educator's Guide

Introductory Experiments with Plasma

Dr. Sten Odenwald (Astrophysicist)

Ms. Christina Milotte (Curriculum Developer)

Dr. Hilarie Davis (Curriculum Developer)

Version 1.0 March 2025

NASA-Heliophysics Education Activation Team

NP-2023-5-068-GSFC

Acknowledgments

This resource was developed by the NASA Heliophysics Education Activation Team as part of its program of creating and disseminating resources for teachers and Learners that describe the major concepts in Heliophysics – the study of how the sun interacts with Earth and the solar system through its gravity, radiation and space weather influences.

We would like to thank Ms. Rachel Geiter and her sixth-grade testers for their help in field testing these activities and providing hands-on feedback for improving them.

Cover art: Photograph of an aurora borealis. (Credit Wikipedia/ Joshua Strang)

Introduction

This Guide is an introduction to plasma, the fourth state of matter, with many hands-on experiments designed to explore the various aspects of this substance. The strategy of this book is to first introduce Learners to the basic properties of plasmas by having them apply criteria defining plasmas to common objects that they see around them. This is an Introductory exploration of their world that does not require any new observations. Most of the experiments can be conducted with easily obtainable materials.

Introductory information for teachers is also provided to indicate how the content aligns with a variety of science, math and engineering standards. Although this Guide can be used by life-long learners, it is designed to be a reference for teachers looking for interesting experiments in plasma science, or students looking for science fair project ideas. Each experiment provides a list of materials and a step-by-step guide to setting up and conducting the experiment. There are also guiding questions and occasional math problems to help quantify the output of these experiments.

The Introductory experiments E1 and E2 are designed so learners can passively explore their environment and use the criteria for recognizing a plasma to identify plasmas in their environment. No equipment or safety instructions are necessary. The exercises test the Learner's knowledge about the definition of a plasma state and their observational skills in applying this definition to the things they see in their environment using a gallery of photographs.

Unless otherwise noted, all figures and illustrations are courtesy of the First Author.

Table of Contents

I. Notes for Educators

Each experiment provides the educator with an overview of the activity, student learning objectives, and a step-by-step process for conducting the activity. All of the activities model *Science and Engineering Practices* described in the NGSS guidelines, including analyzing and interpreting data. Other assessments can be added by the educator as part of the student's portfolio, including science journaling and engaging in research.

These activities can be conducted during class or can be done at home. No parent supervision is needed. Both activities can be conducted in a single class period (~45 minutes).

Introductory Concepts

Earth's Place in the Universe (NGSS: 1-ESS1-1) - Use observations of the sun, moon and stars to describe patterns that can be predicted.

Matter and Its interactions (NGSS: 2-PS1-1) – Plan and conduct an investigation to describe and classify different kinds of materials by their observable properties.

Weather and Climate (NGSS: ESS2.D) - Establish that the Sun is hot and glows (emits its own light). Make the observation that lightning is also hot and glows. Both contain a form of matter called plasma.

Structure and Properties of Matter (NGSS: PS1.A)- Four different kinds of matter exist: solid, liquid, gas, ***and plasma***. The state of matter depends on temperature and energy. For example, a solid ice cube turns into liquid water when heated; liquid water turns into gas when heated. When gas in the air is heated a lot, it turns into ***plasma***. Matter can be described and classified by its observable properties. Stars, lightning, and aurora produce their own light and are made from plasmas.

Energy: Relationship Between Energy and Forces (NGSS: PS3.C)**-** When objects collide, the contact forces transfer energy so as to change the objects' motions. Particles in ***plasma*** move very fast because they have a lot of energy. Sometimes, when fast particles collide, they can merge (or fuse together) to form new particles. A lot of energy is produced when particles fuse together. This process is called ***fusion***. At other times the collisions cause the particles to split apart. This is called ionization, and it produces plasmas.

Structure and Properties of Matter (NGSS: PS1.A) - Matter of any type can be subdivided into particles that are too small to see, but even then, the matter still exists and can be detected by other means. ***Plasma*** is a type of matter made of particles that can interact both by colliding, but also at a distance. These particles, called ions and electrons, have electric charge.

II. The Plasma State

- **How was plasma discovered?**
- **What is a plasma?**
- **What are some examples of plasmas and how they form?**

A Bit of History

How was the plasma state first discovered, and who came up with such an odd word? Plasmas were probably discovered accidentally by the ancient Greeks who experimented with creating sparks by rubbing amber with fur. They did not have a word for what the composition of these sparks was. Going back further than that, humans have marveled at lightning bolts since long before recorded history.

The idea that a plasma was a mixture of electrons, ions, and neutral matter didn't really come into its own until the late 1800's. Between 1860 and 1875, scientists experimented with electrical currents flowing through tubes containing various gases. They noticed a glow forming as the current passed through the gas. In 1928, Irving Langmuir came up with the word "plasma" to describe these gasses. He thought this medium lets electrons move through space the same way that blood plasma lets red and white blood cells move through arteries and veins.

Basic Description of the Plasma State:

Matter is composed of atoms. Each atom has a positively charged nucleus surrounded by negatively charged electrons. When the number of positive and negative charges are equal, the atom has no charge at all. It is called a neutral atom. This is the normal state of matter that you see around you in the form of solids, liquids, and gases.

- Solids are composed of atoms that are held together tightly to form crystals.
- Liquids are collections of atoms at higher temperatures that still feel each other's electric forces but can't completely break away.
- Gases are a collection of atoms that have enough energy to spend most of their time far away from each other.

If you were to draw a diagram of where the atoms are in each of these states it would look like this:

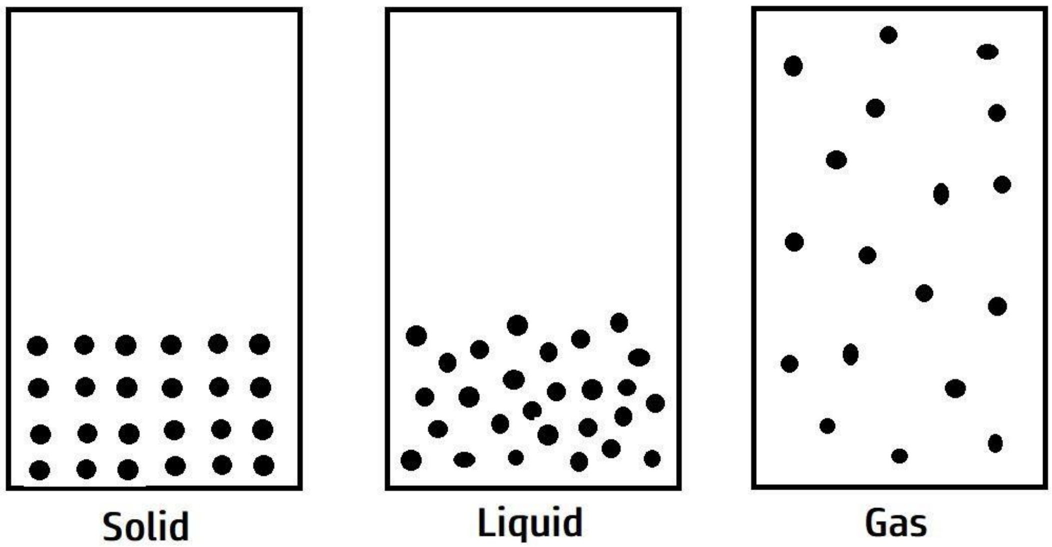


Figure 1. Illustration of how atoms are distributed in the three basic states of matter.

As the temperature increases from left to right in the figure, the atoms arrange themselves into the forms we know as solid, liquid, and gas. This is all okay if the atoms don't collide too violently. If they do break apart, you get a new form of matter called a plasma.

A plasma is a form of matter that has been heated so much that the individual atoms collide violently. Normally, you just get a very hot gas when you heat matter. If you start with a block of ice and heat it, you eventually get steam (water vapor) as the gaseous form of water. But when the temperature is high enough, the collisions cause atoms to break apart. You get a new kind of gas that has three parts:

1. Some normal atoms,
2. Some atoms that have lost one or more of their electrons (called ions),
3. And the electrons themselves buzzing around in between.

This new collection of atoms, ions, and electrons is called the plasma state, or just a plasma, which is shown in the Figure 2 cartoon.

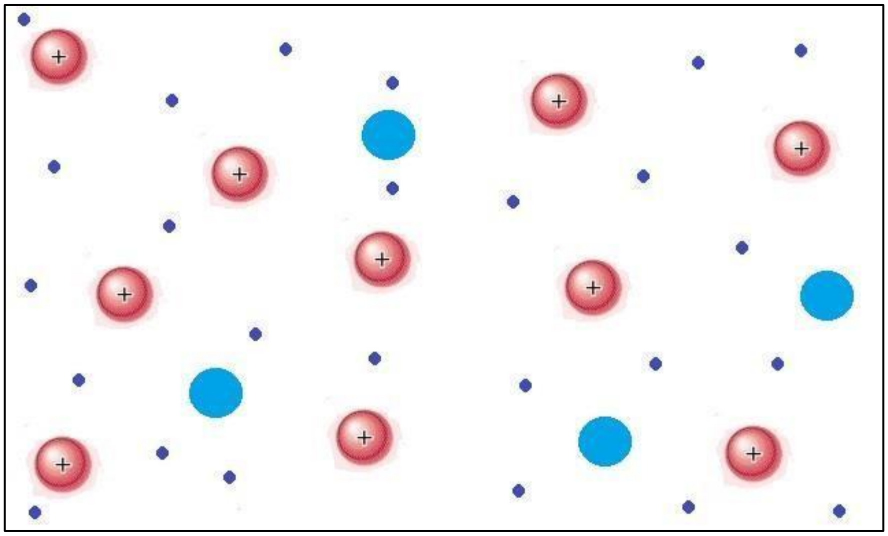


Figure 2. Illustration of a plasma. The dots are the free electrons. The red circles are the positively charged ions that contributed the free electrons. The blue circles are the non-ionized neutral atoms that remain in low temperature plasmas. They will be absent in fully ionized hot plasmas.

Although the name seems exotic and a bit mysterious, plasmas can be found everywhere, including in your kitchen, in your car, and in a lightning storm. The entire Sun is just one big ball of plasma! Once you know what to look for, you can find plasma in many unusual places in your everyday life. The one place you will NOT find this kind of plasma is inside your bloodstream. The plasma in your blood is a completely different thing. It just happens to have the same name.

Common Types of Plasmas

Plasmas form whenever gases are heated to several thousand degrees or more. Sometimes this can happen in a very small region of space no bigger than a rice grain. At other times, an entire galaxy of stars can become embedded in a plasma. How they are formed depends on just how quickly a gas can be heated and how rapidly the electrons can be removed by recombining with the ions. Here are a few common examples of plasmas.

Sparks in electric stoves and grills

Anything that makes a spark is making a plasma. A spark is created whenever a gap forms in an electrical circuit. This gap usually prevents an electrical current from flowing in the circuit because the air within the gap is such a good insulator. But if you increase the voltage in the battery, the accumulated electric charges on one side of the gap becomes so large that a plasma starts forming. As the voltage across the gap increases by adding more batteries to the circuit, the plasma keeps growing in size until it makes contact with the other side of the gap. The result is an avalanche of the electrons in the plasma that rush across the gap to complete the electrical circuit.

When you turn on your electric stove or grill, you first hear a click...click...click sound until the gas is ignited. These clicking sounds are caused by the circuit that is making sparks to ignite the gas. These sparks are only a few millimeters long, but they produce a small amount of plasma at a temperature of 2,000 to 3,000 °F.

Sparks in an electric candle igniter

Rather than using matches, you can now buy electric candle igniters. These handheld wands use an ordinary battery and then boost the battery voltage by 1000 times. The tip of the wand is the open circuit with a gap of about 2 millimeters. The voltage is enough to cause a spark across the gap, and this spark, with its plasma, is enough to start the wick of the candle to burn.

Figure 3. Spark from an electric candle igniter.

Sparks in an automobile

One common place that relies on producing electric sparks is in your automobile engine. It uses ‘spark plugs’ to detonate the gasoline vapor to run the engine. The gap in a typical sparkplug is about 0.035-inches so the minimum voltage your car needs to provide a spark is about 2,700 volts. This voltage comes from the coil of wire in the car’s ignition coil (called a step-up transformer) that increases the 12 V battery voltage by about 220 times. This gap has a very critical width. If it is too wide, your ignition coil cannot produce the increased voltage needed to cause a spark and so your car will not run at all. Modern all-electric cars do not use spark plugs so you will not find any plasma in them.

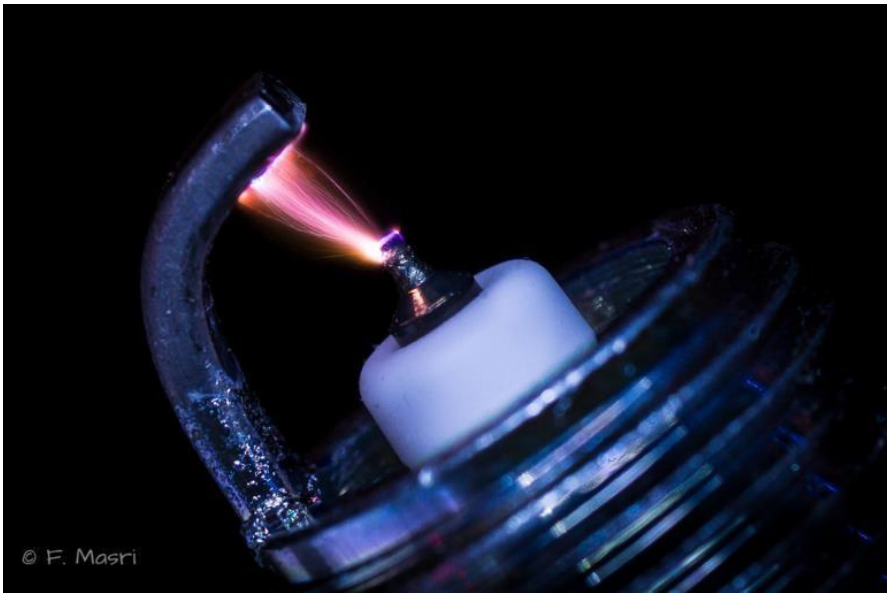


Figure 4. A spark produced by an automobile sparkplug.

Lightning

Sparks are a great source of plasma if you only want a few cubic millimeters worth, but for the really big quantities involving thousands of cubic meters, nothing beats a good old-fashioned lightning strike. The accumulation of negative charge at the base of the cloud causes negative charges in the ground to be repelled and so the ground builds up a large positive charge consisting of ions. Eventually, a lightning ‘spark’ discharge occurs to equalize the charge between the cloud and ground. This happens in a channel about 20 meters in diameter and up to 10 km long where the atmosphere will be heated to over 25,000º Celsius. This temperature is more than enough to ionize both the oxygen and nitrogen atoms in the atmosphere so that a plasma is formed. This plasma emits lots of light, which is why lightning is so spectacular.

Figure 5. Example of lightning strokes during a storm. (Credit: Wikipedia/Nelumadau)

Aurora

Auroras are caused by intense storms on the sun. These storms produce clouds of plasma that strike Earth's magnetic field and then cause high-energy electrons to enter the atmosphere. These electrons collide with atoms of oxygen and nitrogen and create the beautiful colors and shapes we see in the aurora borealis (Arctic) and aurora australis (Antarctic). When the electrons collide with the oxygen and nitrogen atoms, most of the atoms do not get 'shattered', but some atoms can lose their electrons and become ionized. What you then have in these aurorae is a mixture of electrons, ions, and ordinary atoms, which is the definition of a plasma. The interesting thing is that these kinds of plasmas are called cold plasmas because to create them, high temperature collisions between the atoms were not necessary. The high-energy electrons provide the energy while the atoms stay at temperatures of only a few thousand degrees.

Figure 6. A typical aurora borealis (Credit: Elizabeth Macdonald/NASA Aurorasaurus)

Neon Signs

When neon gas is stimulated by an electrical current passing through it, the electrons in the current can collide with the electrons in the neon atoms. This produces the typical red light we see. Because neon also gives off some light at other wavelengths as part of its 'fingerprint', we can filter out these lines to produce other colors like yellow, blue or green. The neon gas is mostly neutral atoms, but some of the atoms become ionized from the energy of the electrical current so that the neon tube is filled with a plasma.

Figure 7. A typical neon advertising sign.

Halogen car lamp

The temperature of the gas inside a halogen car lamp can be higher than 1000 °F which is enough for the collisions to produce some ions, and so the 'high beams' of your car are producing a bit of plasma inside the lamp, along with lots of light.

Figure 8. A halogen car lamp in action.

Gas-discharge lamps.

These include the 'flash lamp' used in some old-style cameras, high-intensity lighting used in theaters such as carbon-arc or 'Klieg' lights, and even the lamps used in antique celluloid movie projectors. In the early 1940s, carbon arc lamps were in common usage for street lighting. A pair of carbon electrodes were placed a few millimeters apart. A very high-voltage current was connected between them that ionized the carbon atoms as they left each electrode, forming a brilliant glowing plasma in between them. These electrodes had to be replaced frequently because over time they eroded.

Figure 9. A gas-discharge light that includes a plasma. This is a typical streetlamp used in the 1940s.

The Sun

Our sun is hot enough that its interior is a plasma. Most atoms collide so violently that they are ionized. However, the surface we see (called the photosphere), only four atoms out of 10,000 are ionized. There's just so much material there that the surface of the sun is a plasma, too.

An important feature of plasma is that it is electrically charged. When a plasma is in motion, it acts like an electric current and generates its own magnetic field. The balance between the forces produced by these magnetic fields and the gravity of a star lead to many different kinds of phenomena such as solar flares, prominences, and the ejection of clouds of plasma called coronal mass ejections. The interaction between plasma, magnetic fields, and gravity accounts for essentially all of the interesting details we see on the surface of our Sun. Without these dynamic phenomena, there would be no sunspots, or even a magnificent corona to see during a total solar eclipse.

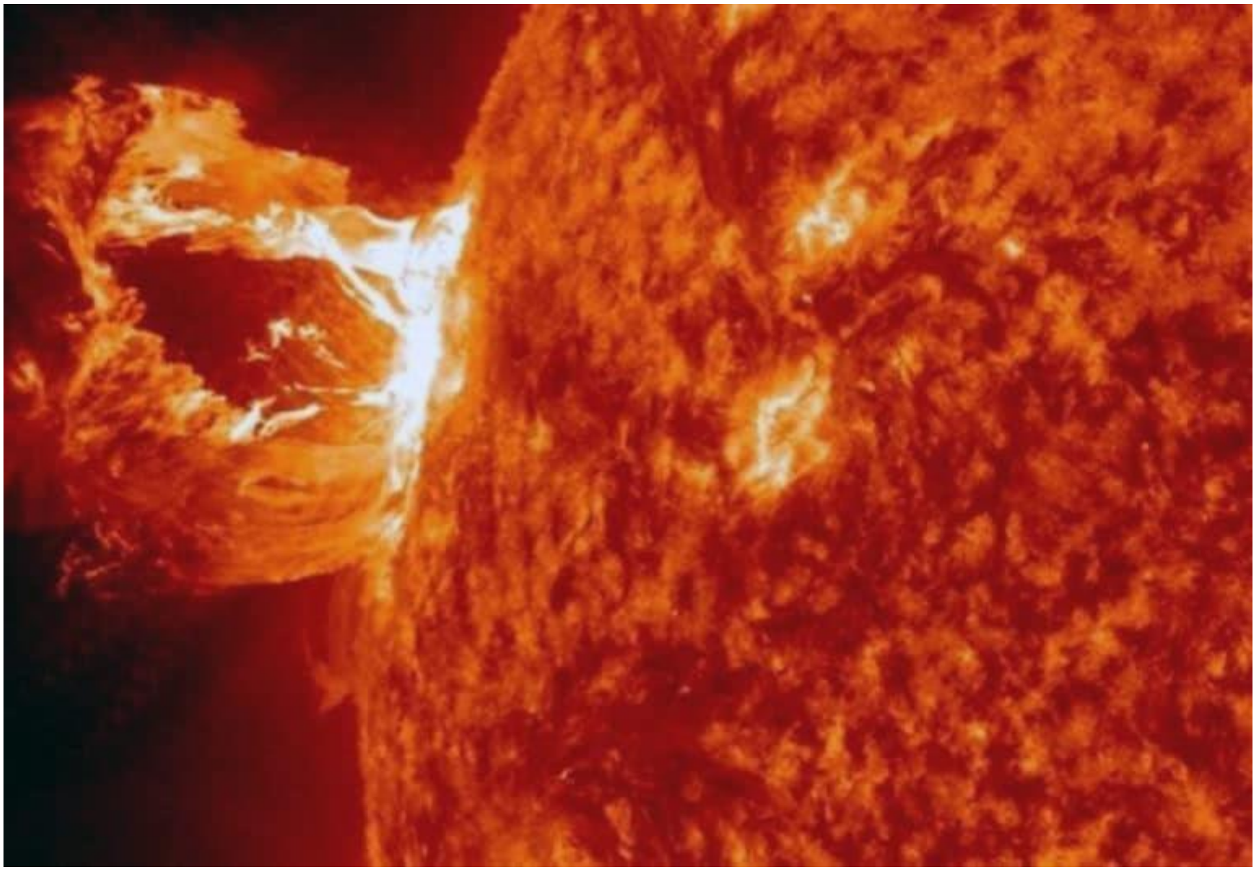


Figure 8. A coronal mass ejection produced by magnetic fields on the Sun reconnecting to form a cloud of plasma over 100,000 kilometers in diameter and traveling at 1,000 km/sec. (Credit: NASA/SDO).

Stars

The coolest stars called brown dwarfs have surface temperatures of only a few thousand degrees, but some of the hottest stars tip the temperature scale at over 50,000 °C. This range by itself is more than enough to keep the surface gases in stars in the plasma state. The interiors of stars are even hotter and can reach over 500 million °C. So, every star you can see in the sky is literally a massive ball of plasma. In fact, if you were to take an inventory of all the visible matter in our Milky Way galaxy, 99.9% of the mass would be in the form of plasma and not ordinary 'neutral' matter.

Figure 9. Stars are balls of plasma that emit light. The star cluster NGC 1850 (Credit NASA/Hubble)

Things that are hot that don't produce plasma

A common feature of many plasmas is that they produce their own light so long as the source of energy that is heating them continues. There are, however, many other kinds of things that although they are hot and produce light, are not a mixture of ions, electrons and neutral atoms.

Candle flames

Candle flames can be very hot. The hottest part of a candle flame (blue part) burns at around 1400°C, while the average temperature is usually 1000°C. An ordinary wood fire burns at around 600°C. Most of what you see in the flame are the microscopic ash particles from the combustion that are like little marbles glowing at these temperatures. The nearby gas atoms of oxygen and nitrogen, however, are generally too cool to collide with enough energy to ionize themselves.

Flashlights

These are either produced by incandescent bulbs or by LEDs. Neither of these provide enough heat to produce ions and electrons.

Lava

The intense red-hot glow of molten lava comes from the surface of the rock heated to about 1,300 to 2,200ºF. The light you see is the same kind of light you get from your stove top and is not hot enough to heat the air to create a plasma.

Volcanic plumes

These look very spectacular and gaseous, but in fact what you see is something very much like a candle flame. The red glows come from heated dust particles whose surfaces are ‘red hot’. This is too cool and dilute to produce a plasma in the air that it passes through.

Firework sparklers

Sparklers are pretty dramatic. They work by a chemical reaction and cause metal flakes to glow red- and white-hot. What you see is not a plasma but a ‘gas’ of heated iron particles.

Words to Use with Students about Plasma

Current – A flow of charged particles such as electrons and is measured in units called amperes. This is like the amount of water that flows over a waterfall.

Voltage - The difference in energy between two points, usually provided by a battery. This is like a very tall waterfall producing a faster water flow than a short waterfall.

Discharge – The sudden release of electric charges into a current that forms a spark.

Ion – An atom in which one or more of its electrons has been removed so that the atom has a positive charge.

III. Basic Plasma Safety

- ❖ **Is plasma dangerous?**
- ❖ **How can I safely experiment with plasma?**

Under the conditions that students will be observing plasmas in these activities, plasmas will not be harmful. In this guide, learners will observe plasmas that emit light, which means that they might possibly be bright enough to produce a temporary persistent image if students stare at the light source long enough. The same warning that would be relevant to working with ordinary light sources such as reading lamps, car headlights, or flashlights would also apply here.

IV. Introductory Activities

❑ Experiment E1 - Recognizing plasma as a state of matter

- ❖ **Overview**: A plasma can be recognized by four common properties.
- ❖ **Objective**: Students observe several objects and are able to identify which of them could be a plasma.
- ❖ **Assessment**: Students find examples of objects that meet the criteria of a plasma

Background: Explain to students that plasma can be recognized through its four main properties:

1) It resembles a gas and is not a solid or a liquid.
2) It gives off its own light.
3) It can be hot to the touch.
4) It requires energy to sustain itself.

Materials: Each student will need a table to record results.

Procedure: Have students look at the objects in Table 1 and use the criteria above to identify the objects that represent plasma. They will record objects that represent plasma and then check the criteria each object satisfies in Table 2.

Table 1. Common objects

Pencil	Mirror	Flat-screen TV	Fog
Aurora borealis	Reading lamp	DVD disk	Birthday balloon
Lawn sprinkler	Crayon	Clouds in the sky	Hammer
Snowball	Flashlight	Tree	Firefly
Fluorescent light	Textbook	Glue gun	Streetlight
Ice cream	Meteor tail	Lightning	Moon
Laser beam	Welding arc	Disco ball	Candle flame
Neon sign	Lava	Rocket exhaust	Gold
Sparkling diamond	Stove hot plate	Sun	Fireworks
Spray paint	Smartphone	Waterfall	Spark
Stars	Firecracker	BBQ charcoals	Jet engine exhaust

Gathering Data: In Table 2, have students write the name of the objects that satisfy the plasma criteria they found in each row. Each column represents one of the four criteria. For each object, the student will check the criteria that the object satisfies.

Table 2. Candidate objects that could be plasma

Object	**Looks like gas**	**Gives off light**	**Might be hot**	**Requires energy**

Explanation: Most of the objects are clearly solid or liquid. Some of these, like a stove top or a smartphone, either emit light or reflect light (diamonds, DVD disk) but are not plasma because they are solid objects. Objects such as flashlights emit light but are not gaseous. Firecrackers and fireworks produce light chemically and do not reach temperatures high enough to create plasmas. Some flat-screen TVs called 'plasma screens' contain tiny pockets of gas in each image pixel, and when a voltage is applied to them, they turn into a plasma state. But this is an old technology and since 2007 modern flat-screen TVs use LCD cells and do not use plasma.

The items that are plasma are: aurora borealis, neon sign, stars, welding arc, lightning, Sun, spark, meteor tail. Some streetlights involve plasma but the vast majority use ordinary incandescent bulbs and are not examples of plasma.

The Sun, meteor trails, and aurora are interesting cases of things that give off light, but learners may not recognize them as examples of plasma because they are unfamiliar objects. This could lead to some interesting discussions and searches for new information about them on which a decision can be made.

Candle flames may or may not contain plasma depending on their temperature. The flame itself consists of innumerable carbon soot particles flowing from the wick with different temperatures that cause the familiar flame colors. The hottest part of the flame nearest the wick is blue in color and can reach a temperature of 1,600^{o} C. This is not quite hot enough to create plasma. Other flames, such as those from propane (2,000^{o}C) or oxyacetylene (2,200 C) 'blow torches,' can be hot enough to produce small quantities of plasma. The highlighted objects in Table 3 are examples of the plasma state. Table 3. Answer key for common objects that contain plasma.

Table 3. Which of these are plasmas?

Pencil	Mirror	Flat-screen TV	Fog
Aurora borealis	Reading lamp	DVD disk	Birthday balloon
Lawn sprinkler	Crayon	Clouds in the sky	Hammer
Snowball	Flashlight	Tree	Firefly
Fluorescent light	Textbook	Glue gun	Streetlight
Ice cream	Meteor tail	Lightning	Moon
Laser beam	Welding arc	Disco ball	Candle flame
Neon sign	Lava	Rocket exhaust	Gold
Sparkling diamond	Stove hot plate	Sun	Fireworks
Spray paint	Smartphone	Waterfall	Spark
Stars	Firecracker	Bar-B-Que charcoals	Jet engine exhaust

Assessment: Learners should find one or two additional objects that meet all of the criteria, then compare their answers with each other to accept or reject the possible candidates based on a classroom discussion.

Additional ideas:

✓ This lab could be easily turned into a game. One idea is turning the pictures into playing cards and having an image of every object on the front with its name on the back. You play with one other person, split the deck in half, and then each player flips over 1 card at a time. If you have plasma, that goes in your 'win' pile; if it's not plasma, it goes in the losing pile. Ties go in the win pile. Play until someone runs out of cards, then reshuffle the win pile and play again.

- ✓ You could also print pictures of these objects, tape them around the room, and have learners record their thoughts on a clipboard as they circulate!

- ✓ You could also ask students to pick one type of plasma to research and present on as the assessment piece.

❑ Experiment E2 - Can you find the plasma?

- ❖ **Overview**: A plasma can be created anytime you have a source of energy that can heat a gas to high enough temperatures. There are many places in your everyday environment where this can occur.

- ❖ **Objective**: Students will recognize that plasmas can be found in many different circumstances. By studying photographs of everyday situations, students will be able to see examples of plasmas in many different forms.

- ❖ **Assessment**: Students will identify examples of all four states of matter including the plasma state in a series of photographs

Background:

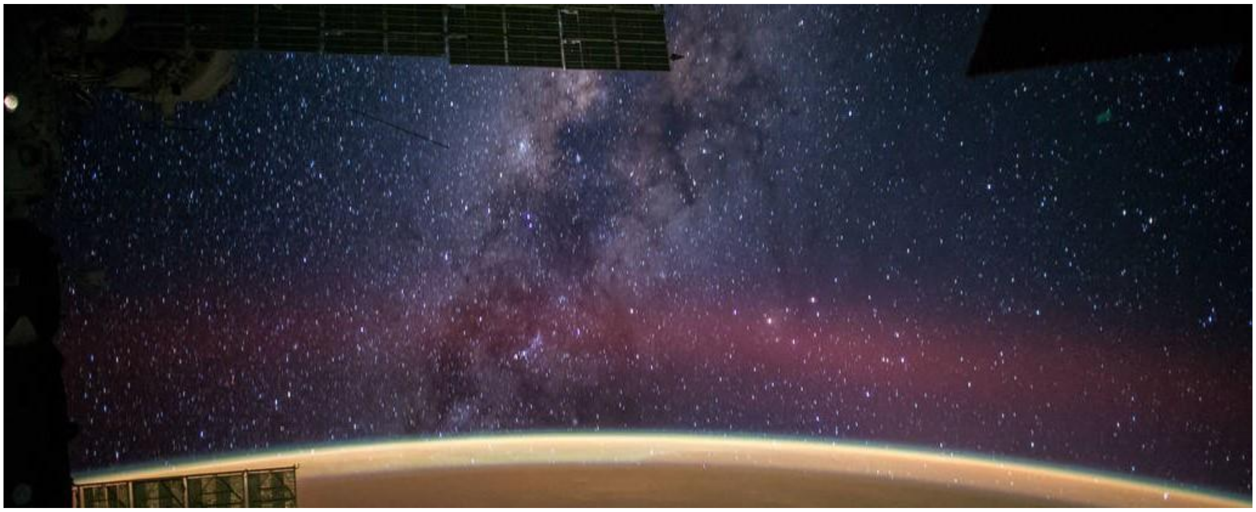
A plasma is a very hot gas that can produce its own light. This is not a very common phenomenon to observe in our everyday life, but there are some examples that you can discover with a bit of detective work. The first three states of matter, solid, liquid, and gas, are pretty easy to spot and can be found in nearly every picture you take. A plasma, however, requires energy to maintain itself, such as extreme heat or currents of electricity. Wherever these sources of energy exist, you will usually see a plasma nearby.

Are plasmas dangerous? Yes they are, but fortunately they are very, very hard to produce. The temperature of a plasma is usually above 2,000^{o}F. Even the very small plasma in some electronic candle lighters will cause a painful sting (like a bee sting) if you touch them because they will burn your skin in a pin-prick area. Large quantities of plasma are even used to cut through solid steel!

Materials:

A series of ten photographs of ordinary scenery is provided here. These can be printed and circulated, provided digitally to students, or projected on a screen for group study.

Picture 1. Candles on the water (Credit: WallpaperAbyss)



Picture 2. The Milky Way (Credit: NASA/ISS/Reid Wiseman)

Picture 3. Aurora over snow (Credit: Wikipedia/Joshua Strang)

Picture 4. Downtown in the rain (Credit: Joseph Haubert)

Picture 5. Volcanic eruption (Credit: Sigurdur Stefinsson)

Picture 6. Cooking soup (Credit: ChefSteps.com)

Picture 7. Lightning over a lake (Credit: Wikipedia)

Picture 8. Downtown at night with streaked car headlights (Credit: International Dark Sky Association)

Picture 9. Sunrise on the beach (Credit: Jooin)

Picture 10. Crackling electricity (Credit: Wikipedia)

Procedure:

Have the students carefully look at each picture and list the objects that are examples of solids, liquids, gases, and plasmas using the definitions provided.

Gathering Data:

Create a table where the rows represent each picture and the columns represent each of the four states of matter. In each row, identify the state of matter that the object represents.

Picture	Solids	Liquids	Gases	Plasmas
1 – Candles on the water				
2 – Milky Way				
3 – Aurora over snow				
4 – Downtown in the rain				
5 – Volcanic eruption				
6 – Cooking soup				
7 – Lightning over a lake				
8 – Downtown at night				
9 – Sunrise at the beach				
10 – Crackling electricity				

Assessment:

Students will examine each image and list at least one or two items they spotted in each ‘state’ category. They should be able to explain why their choices are representative of each state, especially why the gas and plasma states appear differently, such as stating that plasmas are so hot they are self-luminous (electrical sparks, lightning, stars and the Sun in the sky). Candles however are generally not hot enough to produce a plasma even though their flames are hot and gaseous. The following table shows the recommended answers.

Picture	Solids	Liquids	Gases	Plasmas
1 – Candles on the water		Water	Atmosphere	
2 – Milky Way				Stars
3 - Aurora over snow	Snow		Atmosphere	Aurora
4 – Downtown in the rain	Pavement	Rain puddles	Atmosphere	Neon signs
5 – Volcanic eruption	Mountain		Plume	Lightning
6 – Cooking soup	Ground	Soup in kettle	Steam	

7 – Lightning over a lake	Mountains	Lake water	Atmosphere	Lightning
8 --Downtown at night	Pavement	Rainwater	Atmosphere	
9 --Sunrise at the beach	Beach	Ocean	Atmosphere	Sun
10- Crackling electricity	Tower		Atmosphere	Sparks

National Aeronautics and Space Administration
Goddard Space Flight Center
9432 Greenbelt Road
Greenbelt, MD 20771
https://nasa.gov/goddard/
www.nasa.gov

NP-2021-10-697-GSFC