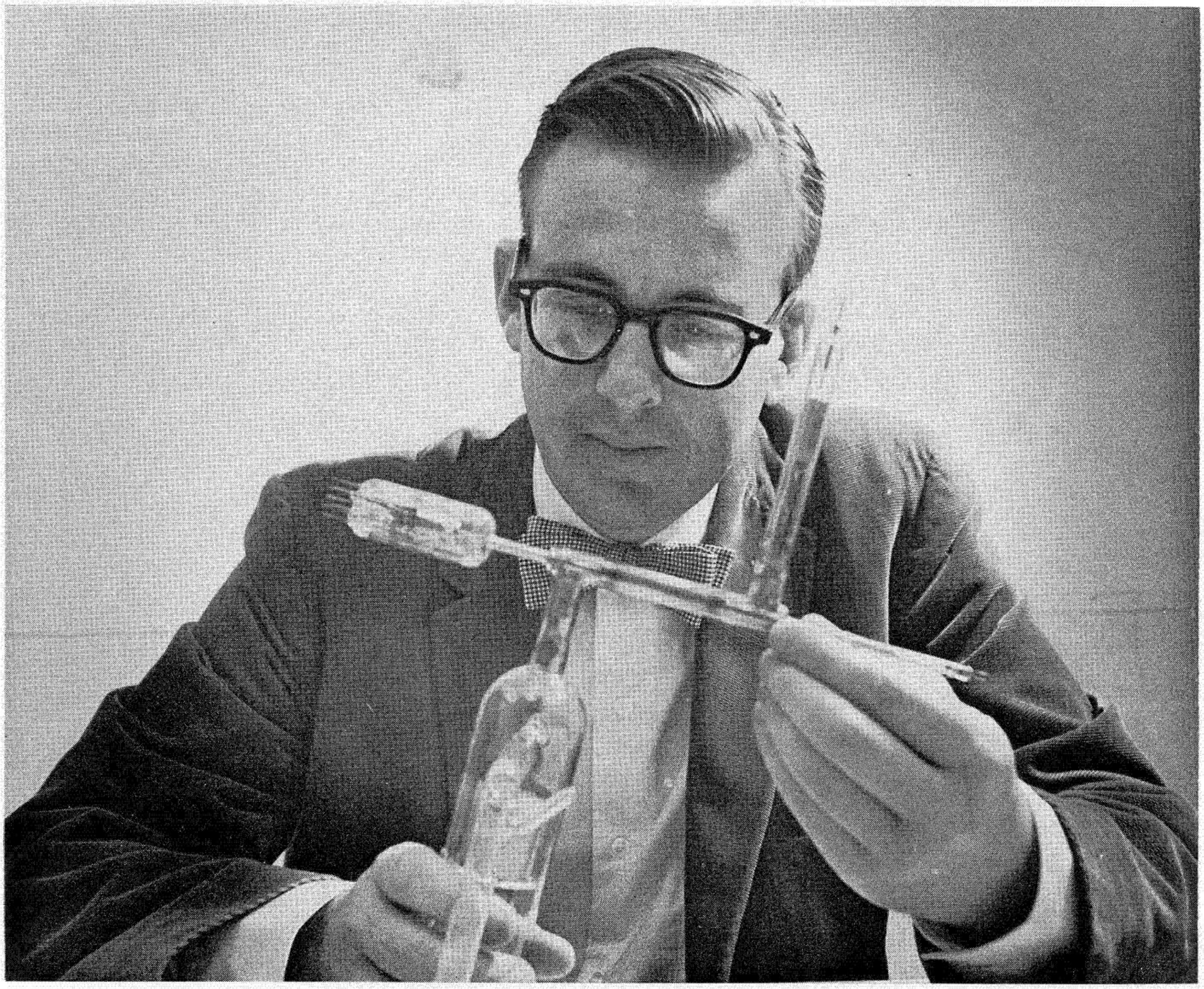


*Plasmas are harnessed for research in amplifier held by Roy Gould, associate professor of electrical engineering.*

# Plasma — The Fourth State of Matter

*by Gary Boyd*

On our earth, we are accustomed to dealing with matter in just three states – solid, liquid and gas. Yet a fourth state exists called plasma. A plasma is formed when a gas is raised to such a high temperature that its atoms come apart, forming a neutral mixture of positive ions and electrons.

The corona of the sun is a good example of a plasma, as is the ionized gas found in fluorescent light bulbs and mercury arc street lamps.

The new and exciting field of radio astronomy is concerned with the radio frequency phenomena found in the combination of research by astronomers on the swirling masses of ionized gases or plasmas in the heavens, and by engineers on the propagation of radio waves through the ionosphere.

Plasmas are also playing a fundamental part in the experimental fusion machines which may eventually harness the power of the H-bomb for peaceful purposes.

Even in the field of aeronautics, engineers are studying plasmas for a clue to solving the problems of re-entry to the earth's atmosphere at the high velocities of intercontinental ballistic missiles.

A plasma has a finite electrical conductivity due to collisions of electrons and ions with the un-ionized gas molecules. The electrons and ions are in continuous milling motion due to the random distribution of their thermal energies — just like the molecules of an un-ionized gas such as air.

## *Plasma oscillations*

A plasma medium is capable of plasma oscillations. Such oscillations result from a displacement of a group of electrons from their equilibrium position. Since the ions in the plasma are much more massive than the electrons, the ions tend to be relatively fixed in position. Therefore a local displacement of a group of electrons leaves an excess of positive charge (ions) which exerts an attractive force to return the electrons to their equilibrium position. Such a force imparts energy to the group of electrons and they tend to overshoot their equilibrium position and thus oscillate about it.

This natural resonance or plasma oscillation frequency of the electrons is proportional to the square root of the electron density in the plasma. In some respects these plasma oscillations can be likened to the shaking of a bowl of jelly. In electric arc discharges made in the laboratory, such oscillation frequencies are often in the microwave region of 1,000 megacycles per second. In the solar corona they are in the range of 10 to 1,000 megacycles.

Plasma oscillations can be caused by a radio wave passing through the medium. When one is considering experiments such as the interaction of radio waves with plasmas it is possible to show that the effect of such a plasma is mathematically equivalent to a charge-free medium with a dielectric constant different from free space. Of course, the index of refraction of a material is proportional to the square root of the dielectric constant.

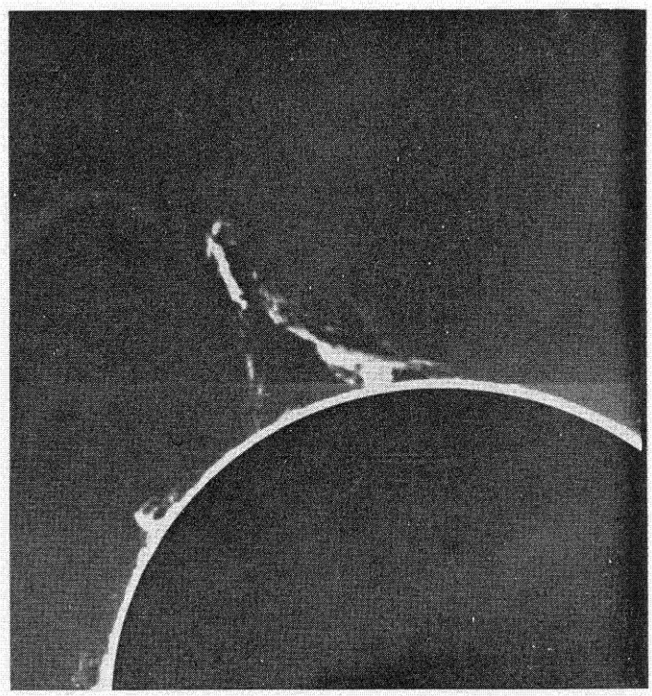
All such known dielectric mediums as glass, water, diamond, ceramic, plastic and the like have relative dielectric constants several times that of free space. None have dielectric constants less than the free space value. A plasma, however, has a relative dielectric constant which is always less than unity and may even become negative if the plasma oscillation frequency exceeds the frequency of the radio wave in the medium. Radio waves traveling in a medium of positive dielectric are reflected at the interface with a medium of negative dielectric.

On the basis of this description of a plasma we are able to appreciate the relationship between plasma physics and the propagation of radio waves through the ionosphere. The ionosphere is actually just another example of a plasma. The theory of radio wave propagation through the ionosphere is complicated, however, by the effects of the earth's magnetic field on the dielectric properties of the ionosphere. The magnetic field causes the dielectric constant to be anisotropic — meaning that the dielectric constant differs in different directions.

In the electrical engineering laboratories at Caltech, engineers are investigating radio frequency phenomena with an electron tube called a plasma amplifier. This tube sends a modulated electron beam through the plasma of an electric arc discharge. If the natural plasma oscillation frequency corresponds to the modulation frequency on the electron beam, then upon demodulating the electron beam one finds that the output signal is larger than the input signal and thus amplification has resulted.

The interest of astronomers and engineers in radio astronomy has led to intensive study of the properties of plasmas. As all of us are aware, many heavenly bodies emit electromagnetic energy in the visible light frequency range. Many also emit energy in the radio frequency range. In the past decade, considerable attention has been devoted to theories concerning the means of generation of radio frequency energy in heavenly bodies such as our own sun.

As research with Caltech's plasma amplifier indicates, there is a possible mechanism in the corona of the sun and like bodies for the amplification of radio frequency energy. If a solar eruption sends a high velocity stream of electrons through the sun's corona, we then have a situation capable of amplifying stray signals on the stream. Such amplification



*Solar eruptions are one source of the radio frequency energy studied by radio astronomers. This June 15 eruption reached the greatest height (850,000 miles) observed from Mount Wilson Observatory since 1946.*

occurs at frequencies close to the natural plasma oscillation frequency of the corona. If such energy is radiated into space we might well receive some of it on earth. Of course, there are probably many other sources of radio frequency energy in the heavens.

Other researches in these laboratories on the interaction of microwaves and electron beams with plasmas are concerned with the investigation of the propagation of newly discovered waves on plasma columns. The interaction of electron beams with such waves is interesting since these waves travel at velocities which are small compared to the velocity of light. This means that they can be made synchronous with the electron beam velocity. Also of interest is the use of microwaves as a means of measuring plasma densities and temperatures. Such measurements are particularly important in fusion research.

## *Controlled H-bomb*

Certainly the largest effort today in the field of plasma research is concerned with fusion containment. This is often referred to as the controlled H-bomb. Fusion in this sense means the fusion of two hydrogen ions (normally the heavy isotopes deuterium or tritium) to form a helium ion with the release of a large amount of energy. Since the hydrogen atom has only one electron, its ion is just the nucleus.

In order for two colliding deuteron nuclei to fuse and form helium it is necessary that they collide at a very high velocity. The temperature of the deuteron nuclei must be about 350 million degrees Centigrade, (corresponding to 30,000 electron volts of kinetic energy) for such a process to be self-sustaining and thus produce more energy than it loses to its surroundings. This amount of energy is small compared with the millions of electron volts and in some cases even the billion electron volts of energy supplied to particles in modern particle accelerators, but it is large in the sense that a comparatively large number of particles must be accelerated to this average kinetic energy.

Present efforts at controlled fusion deal with low density deuterium gas which is ionized in some manner to form a plasma. This plasma is contained in a strong magnetic field or magnetic "bottle." An electric discharge formed in such a gas will contain deuterium nuclei with an average random energy of only a few electron volts. It is then necessary to pump energy into this plasma system in some way to raise the average energy of the deuterium nuclei up to approximately 30,000 electron volts. At the present time energies of only 430 electron volts (5 million degrees) or so have been obtained, and then only for a thousandth of a second.

There are several methods of feeding energy into a plasma. One that is widely used is to pass an electric current through a plasma. This heats up the plasma due to the collisional losses of the charged particles with neutral atoms. A second is to use the pinch effect. This method receives its name from the fact that a high current electric arc discharge in an ionized gas will constrict due to its self-magnetic field. As the arc constricts, the average energy of the plasma electrons and ions increases. The third is the magnetic pump, in which the confining magnetic flux is periodically increased and decreased. This will induce a circumferential electric field which acts on the charged particles and heats the plasma.

## *Ballistic missiles*

Another field of interest to plasma research is concerned with missile re-entry problems. When an intercontinental ballistic missile re-enters the earth's atmosphere at approximately 15,000 miles per hour, the velocity is high enough so that a collision of an atom of the atmosphere with the nose of the missile is sufficient to ionize the atom. Thus it might be expected that around the nose of such a missile an ionized gas shock wave will exist — the medium we have now learned to call a plasma.

As a plasma is a dielectric medium because of its radio frequency properties, we immediately face problems relating to the effect of this medium on radar frequency waves that might be sent up to detect the arrival of such a missile. Would it make the missile easier or more difficult to detect? Also, if we remember that a plasma is capable of natural oscillations, the interesting possibility occurs that if this oscillating plasma radiates any of its radio frequency energy, then perhaps this could be detected on the ground by a radio receiver. In other words, will a re-entering missile cause plasma oscillations that can be detected from the ground without the aid of a radar frequency transmitter?

Aside from problems associated with the detection of high speed missiles re-entering the atmosphere, there is the problem of communicating with high speed missiles which are surrounded by this plasma dielectric. If the natural plasma oscillation frequency is greater than the frequency of the incident wave, the dielectric constant becomes negative and the medium will no longer propagate such a radio wave. For similar reasons the antenna radiation pattern of a missile is modified by the rocket flame resulting from turning on the rocket engine.

Another important field of study in plasmas is ion propulsion, a form of propulsion in which a cloud of charged particles, rather than hot expanding gases, is forced out of the rocket engine. Plasmas are also being used to obtain temperatures as high as 15,000° Centigrade for high temperature research (the temperature limit of chemical fuels is approximately 6,000° Centigrade). These are only a few of the many applications found in current plasma research. The future may bring still unimagined opportunities for research in this new frontier of science and engineering.