PLASMOIDS

These little pieces of plasma (a gas of electrons and ions) are created in the laboratory with an electrical gun. They have an unexpected capacity for maintaining their identity

by Winston H. Bostick

In physics laboratories of several countries—notably the U. S., Great Britain and the U.S.S.R.—man is feeling his way gingerly toward harnessing thermonuclear power. The studies are centered on small "bottles" of hot gas which correspond to tiny samples of the sun (though they are not nearly so hot or dense). The gas is called a plasma. It is a collection of electrons and ions (electrically charged atoms). The behavior of this assemblage of particles is at once very simple and very complex. It challenges all the mathematical and experimental ingenuity of modern physics, and it has ushered us into a world of unexpected and exciting phenomena. This article is an account of some recent experiments which have generated remarkable bodies that we call plasmoids.

The properties of these bodies stem basically from two familiar phenomena of nature, both of which, oddly enough, go back to the same discoverer—William Gilbert, Queen Elizabeth's physician, who will forever be a great name in physics. In 1600 this imaginative experimenter placed an electrically charged knob of metal close to a flame and found that the metal lost its charge: the heated air had carried it away. Thus Gilbert discovered that a gas (an ionized gas, as we know now) can conduct electricity. The other physical phenomenon that governs the behavior of plasmoids is magnetism—a field in which Gilbert was also the first experimenter. Ionization and magnetism combine to produce what have recently become known as magnetohydrodynamic effects, and plasmoids are a magnetohydrodynamic phenomenon [see "Electricity in Space," by Hannes Alfvén; SCIENTIFIC AMERICAN, May, 1952].

The late Irving Langmuir of the General Electric Company began to study plasmas as long ago as 1921. Plasmas,

TWO PLASMOIDS are fired at each other in a vacuum chamber containing a strong magnetic field. The initial bursts from the guns are marked by the bright spots at left and right. The luminous streaks are the subsequent paths of the plasmoids. It can be seen that they repel and veer away from each other, so that each of the strange gaseous shapes retains its separate identity.

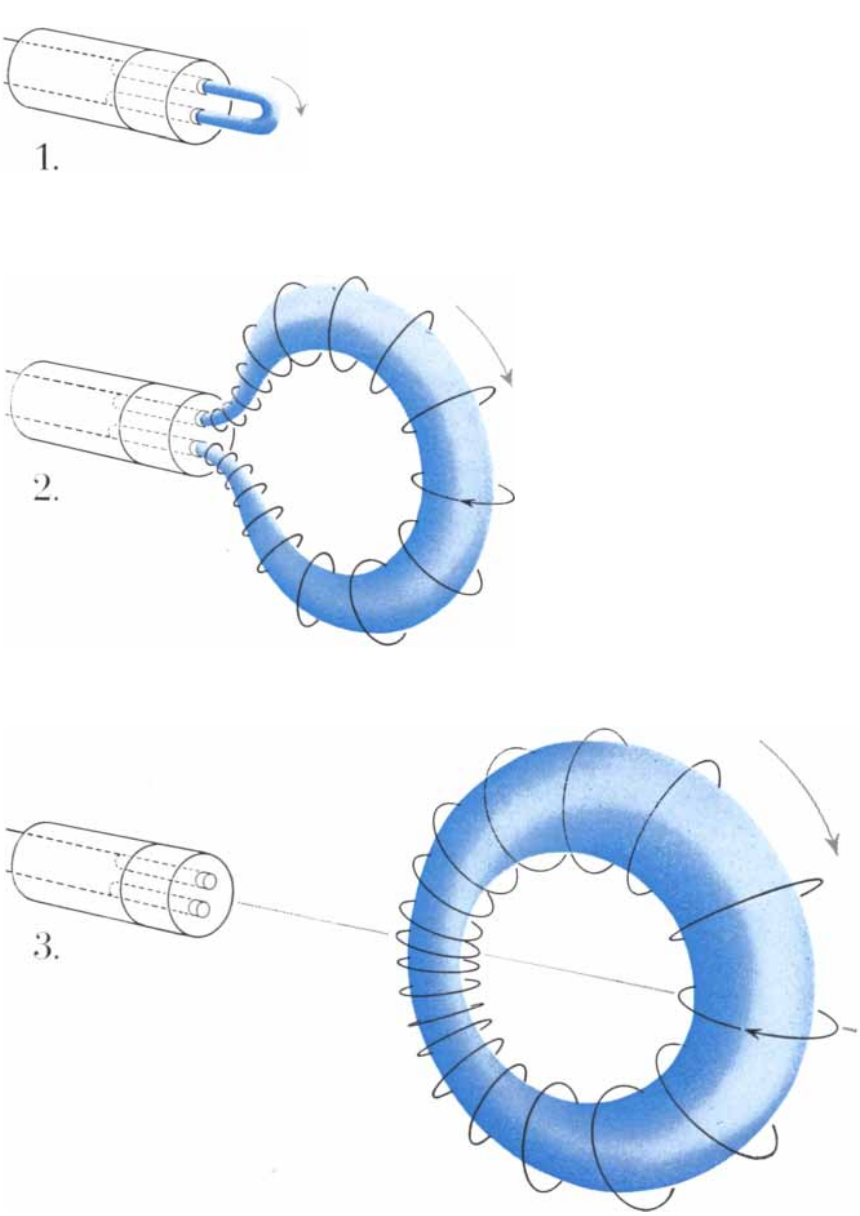
of course, are nothing new: whenever we look at a neon sign we see a plasma. It is produced by an electric discharge, which knocks electrons from the gas atoms in the tube; the released electrons collide with other atoms and produce more ions. This process continues until there are enough liberated electrons to make the gas a good electrical conductor.

Langmuir was interested in learning, among other things, the energy of agitation, or "temperature," of the electrons. The wall of the neon tube is cool, and so are the ions and gas atoms in the tube, because comparatively few atoms are ionized and the ions quickly distribute their energy among the neutral atoms. But the electrons are so much lighter that they lose little energy in rebounding from the more massive atoms or the tube wall. By ingenious experiments Langmuir measured the electrons' temperature and found that it amounted to about 20,000 degrees Fahrenheit—about twice as hot as the sun's surface.

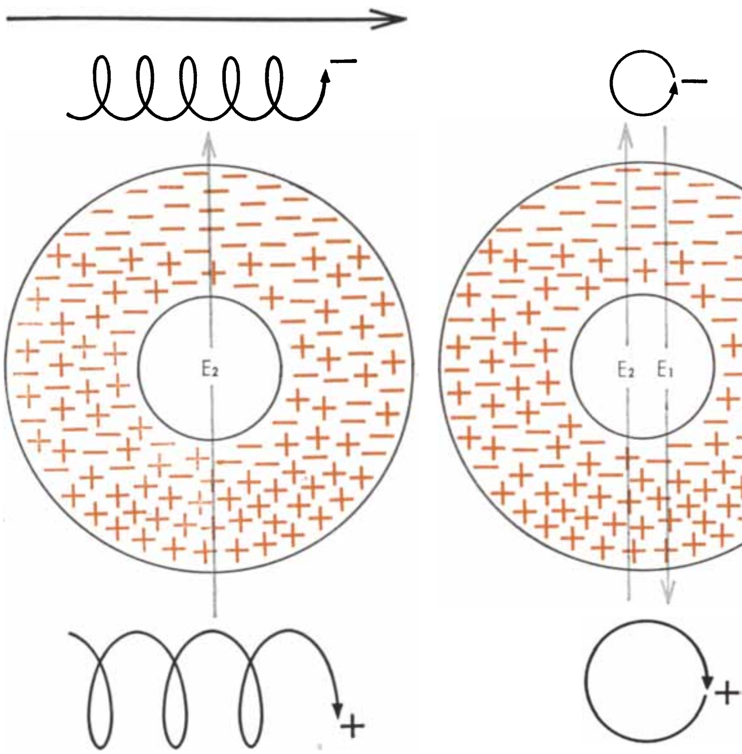
This high figure explains the interest in plasmas on the part of physicists who are now studying the possibilities for achieving controlled thermonuclear fusion. To fuse atoms of deuterium (heavy hydrogen) on a large scale requires a temperature of about 300 million degrees centigrade. Such a temperature is far beyond our reach in the laboratory, nor could a dense gas at this temperature be contained by any method we know at present. But for exploratory experiments it should at least be possible to raise a plasma to a temperature of scores of thousands of degrees, and the plasma can be contained if its density is sufficiently low.

The difficulty is that in a low-density gas, energized ions and electrons do not collide with one another often enough to raise the temperature greatly; instead they lose their energy in collisions with the walls of the container. But as everyone who has followed events knows, a beautiful solution to this problem has been found. It is the magnetic "bottle." Within a magnetic field, which swings the electrified particles in circular orbits, the plasma can temporarily be held in thrall as tightly as by any material container. The electrons and atoms collide only with one another, and the plasma becomes fully ionized.

In the University of California Radiation Laboratory at Livermore and at the Stevens Institute of Technology we have been studying magnetically confined plasmas with the help of a special plasma gun. It generates a plasma of deuterium, the potential fuel of thermonuclear fusion. There are two electrodes, made of titanium with deuterium atoms absorbed in them [*see diagram at left*]. A pulsed arc current of several thousand amperes, each pulse lasting about half a microsecond, is passed across the gap between the electrodes. This high current evaporates electrons and ions from the two electrodes. It also generates a magnetic field which, like a girdle, pinches the plasma into a slender column. The special feature of our gun is that the plasma emerging from the two "mouths" is bent into a loop, and it fires doughnut-shaped blobs of plasma. Just as, when a spring is bent, the turns of the wire are crowded closer on the inside of the loop than on the outside, so the magnetic field lines of the loop of plasma emerging from our gun are more crowded on the inside than on the outside. The strong magnetic pressure on the inside of the loop blows the plasma forward at high speed—up to 120 miles per second! Considering that the gun is smaller than a thimble and that the driving energy stored in the capacitor is only six joules—no more than is needed to



FORMATION OF PLASMOID is diagrammed schematically. In drawing 1 a burst of plasma emerges from the electrodes of an arc gun. The gray arrow shows direction of current flow in the ionized gas. Loop enlarges (2) and breaks off (3). Black circles around the doughnut-like body are magnetic lines of force set up by current in the plasmoid itself.



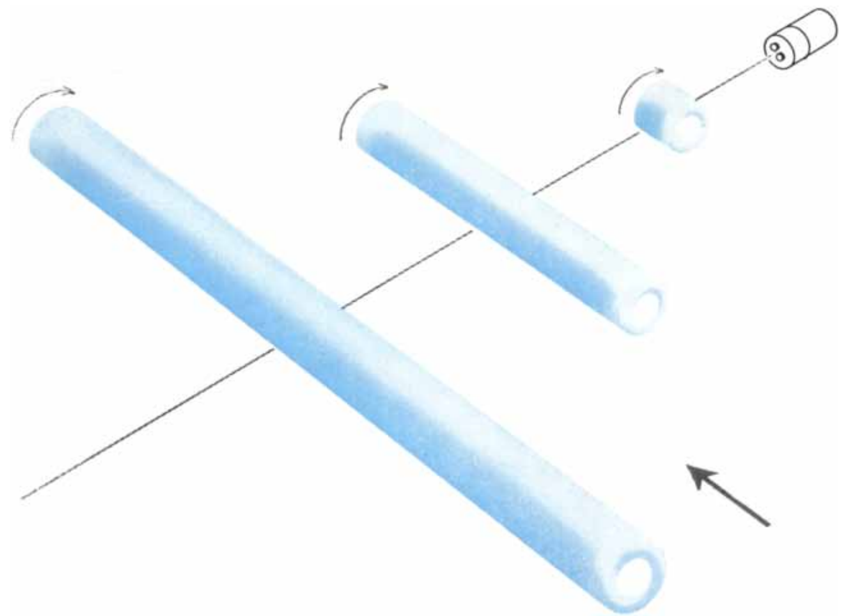
MOTION OF CHARGES in plasmoid moving across a magnetic field is seen in two frames of reference. In laboratory frame (*left*) the black arrow indicates motion of the loop across a magnetic field directed vertically up from the page. The gray arrow (E_2) shows the electric field produced by separation of charges. The upper curve is path of electrons; the lower curve, path of positive ions. In the plasmoid frame of reference (*right*) E_2 is offset by the charge-separating voltage E_1, and the charges have simple circular orbits.

light a six-watt bulb for one second—this is a truly remarkable performance. A velocity of 120 miles per second for deuterium ions represents a temperature of four million degrees. It suggests that with larger plasma guns of this kind we might begin to approach thermonuclear temperatures.

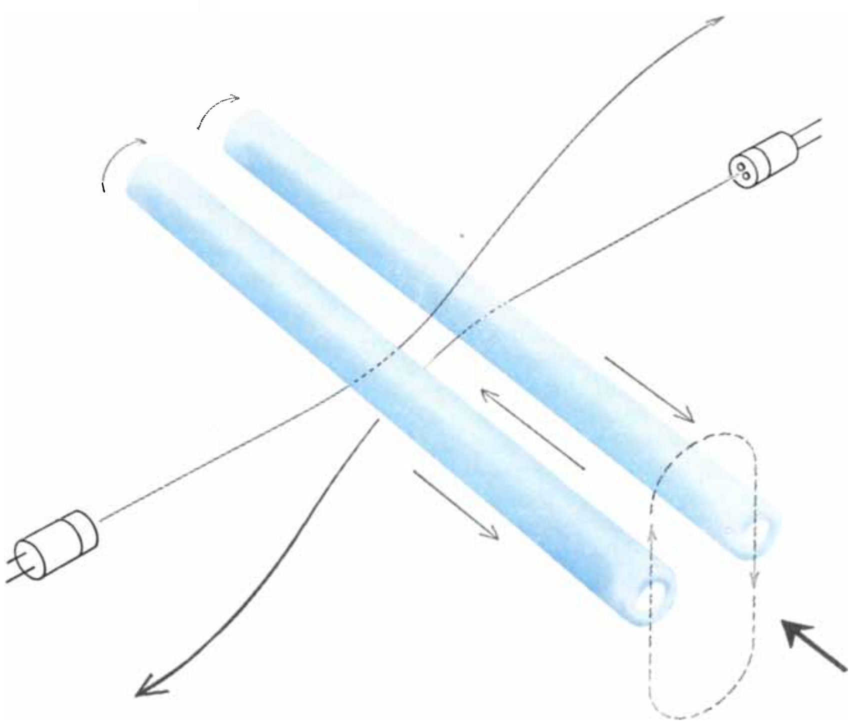
The velocities of the plasma bodies shot from our gun are comparable to the speeds of stars in galaxies and of flares shooting out from the sun. It seemed worthwhile to follow up the analogy. Would the high-speed plasma serve as a kind of laboratory model to throw light on the magnetohydrodynamic processes operating in the universe? We have studied it from this point of view, with what seem to me interesting and significant results.

Let us see first what happens when we fire a piece of plasma into a vacuum under an external magnetic field (that is, a field applied from outside the plasma itself, which is bottled within its own self-excited field). Although the plasma darts through our chamber at a speed in the neighborhood of 120 miles a second, fortunately it leaves a luminous wake which can be photographed with a high-speed camera, so that we can see its track. Now we would expect the electrons and ions in the plasma to be thrown into circular orbits as soon as they enter the externally applied magnetic field, so that the plasma would not move more than a very short distance from the gun. But the camera discloses the somewhat shocking fact that the plasma crosses the magnetic field with ease! How does it get through the field?

To follow our explanation the reader is advised to consult the accompanying diagrams [*above*]. As the plasma starts to move across the magnetic field, the electrons curve upward and the positive ions downward. This effect essentially produces an electromotive force, just as copper wires moving across a magnetic field do in an ordinary dynamo. An electromotive force can be thought of as the electric pressure exerted by an electric pump. If there is no outlet (such as an electric toaster) for the pump, no current will flow. Similarly this little piece of plasma has no outlet in the vacuum chamber, and no current can flow. Its



PLASMOID STRETCHES into a cylinder as it travels through a magnetic field. In this drawing the travel is in a straight line away from the gun at upper right. Curved arrows show direction of the plasmoid's spin; heavy gray arrow gives the direction of the field.



MUTUAL REPULSION of approaching plasmoids is presumably due to a strong magnetic field created between them. In this diagram a pair of plasmoids avoid each other, the plasmoid from the left moving up and the plasmoid from the right down as they approach. The magnetic field arises from a current (*oval broken line*) produced by the plasmoids' internal electric fields. The resulting magnetic field (*light straight arrows*) adds to the external field (*heavy arrow*) in the space between the plasmoids and subtracts in the space outside.

pump pushes against closed valves, so to speak, and merely creates an electrical pressure opposing that of the pump. Within the plasma frame of reference the direct and opposing electric fields cancel each other, and the magnetic field swings the electrons and ions in perfectly circular orbits. But from our outside point of view we can see that the opposing electric field (E_2), in conjunction with the magnetic field, moves the orbits, so that the plasma travels across the magnetic field. The particle orbits trace a track such as a marker at one point on the edge of a merry-go-round would leave on the ground if the merry-go-round were dragged along by a tractor while it was turning.

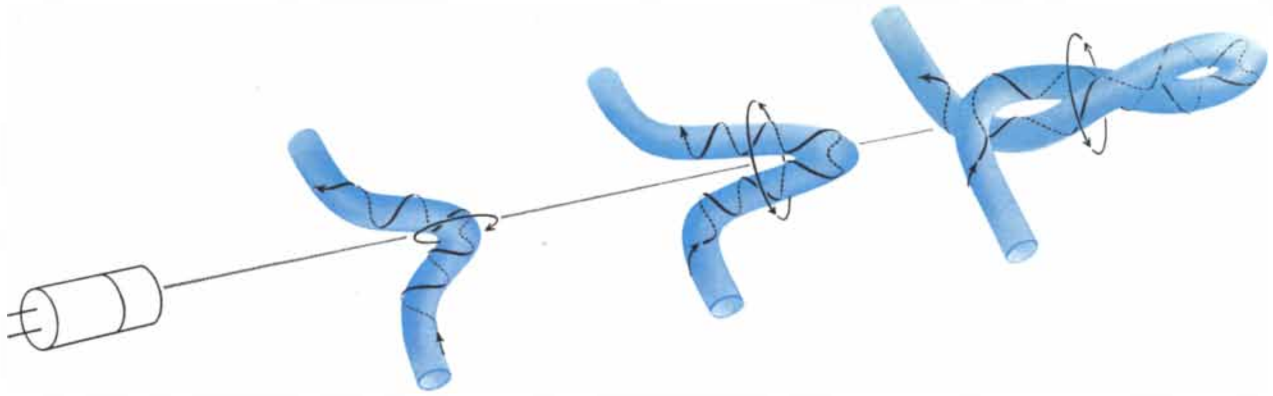
Apparently some ions and electrons in the plasma, escaping the full effect of electric field E_2, stay behind in stationary circular orbits. These ions and electrons recombine and give off light. Their luminous tracks are, in a manner of speaking, the funeral pyres of the particles which were sacrificed in laying down the electric field E_2 so that the main body of the plasma might pass across the magnetic field.

We can actually draw current from the primary electric field produced by the little dynamo contained in this plasma. If we put two small stationary probes connected by a resistance in the chamber (equivalent to plugging in a toaster), we get a pulse of current of about one ampere as the two regions of the plasma pass simultaneously over the probes.

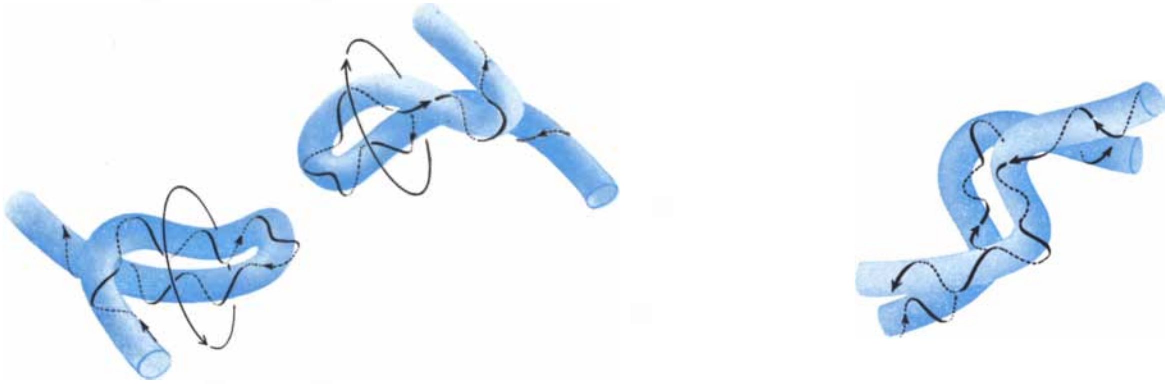
Further measurements with probes show that the plasma forms an ever-elongating hollow cylinder as it proceeds across the magnetic field [*see upper diagram at left*]. It is to this type of plasma—a self-generating, shaped body—that we have given the name plasmoid. And plasmoids, under laboratory manipulation, display some fascinating behavior.

What will happen if we fire two plasmoids at each other from opposite directions? We might suppose that when they meet their transverse electric fields will cancel each other so that both plasmoids stop dead. But in fact they bounce off each other like billiard balls! Apparently each dynamo acts as an outlet or short-circuit for the other, and a substantial current (several amperes) flows briefly. The current gives rise to a "cushion" of high magnetic-field pressure between the two plasmoids which pushes them away from each other.

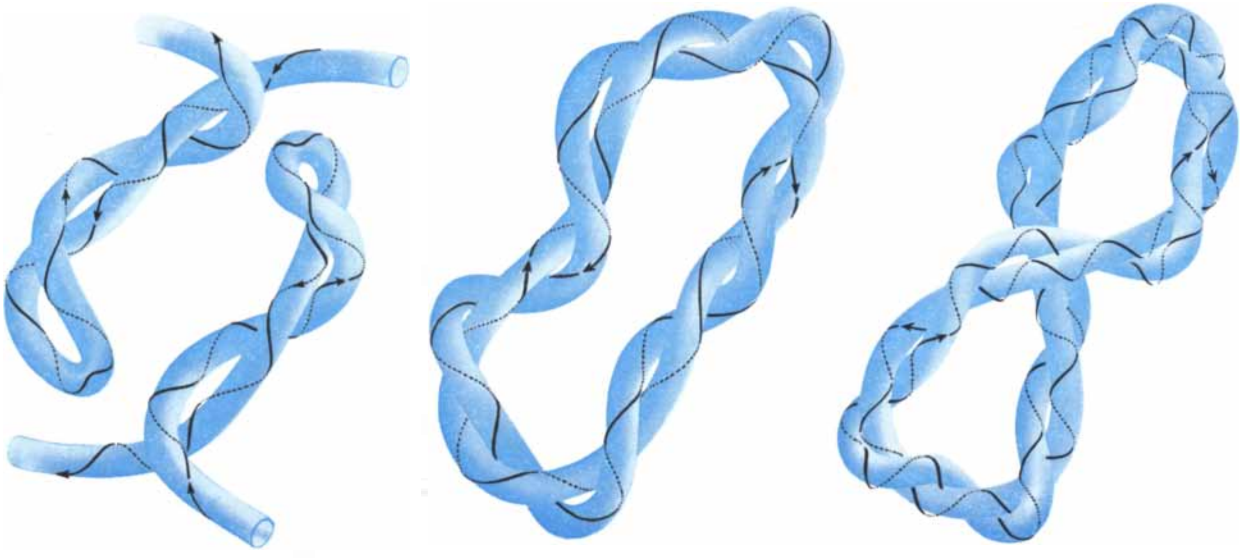
Occasionally two plasmoids crashing



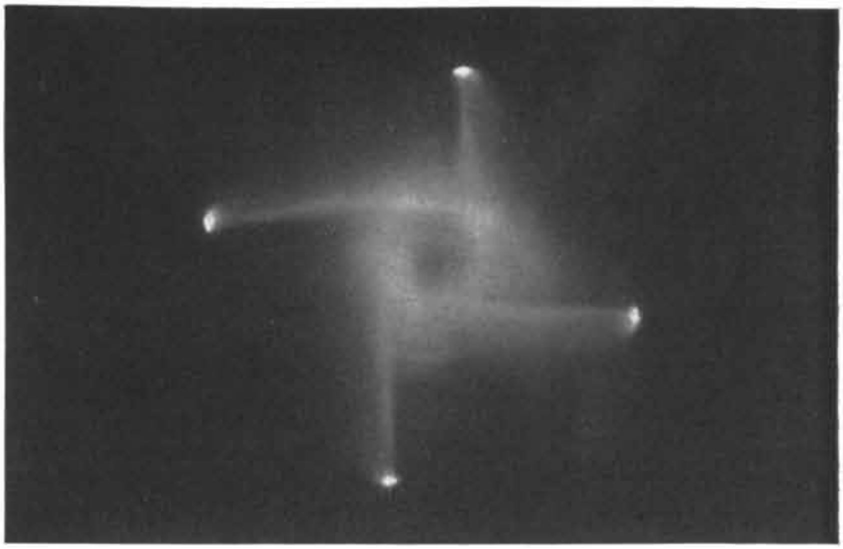
PLASMOID TWISTS when it is fired into a gas which slows it down. The helical arrows give direction of plasmoid's internal magnetic field. The ellipses give direction of the magnetic field produced by the plasmoid around itself and the direction of its spin.



PLASMOIDS MAY LINK TOGETHER if they approach each other in such a way that they can interchange portions of their internal magnetic fields. In this diagram a pair of twisted plasmoids meet one another head to head, blending into a new unit.



RING IS FORMED when a pair of twisted plasmoids meet head to tail, thus joining together at two points. Because of the electromagnetic forces which exist within this ring-shaped structure, it subsequently twists itself around its mid-point, forming a figure 8.



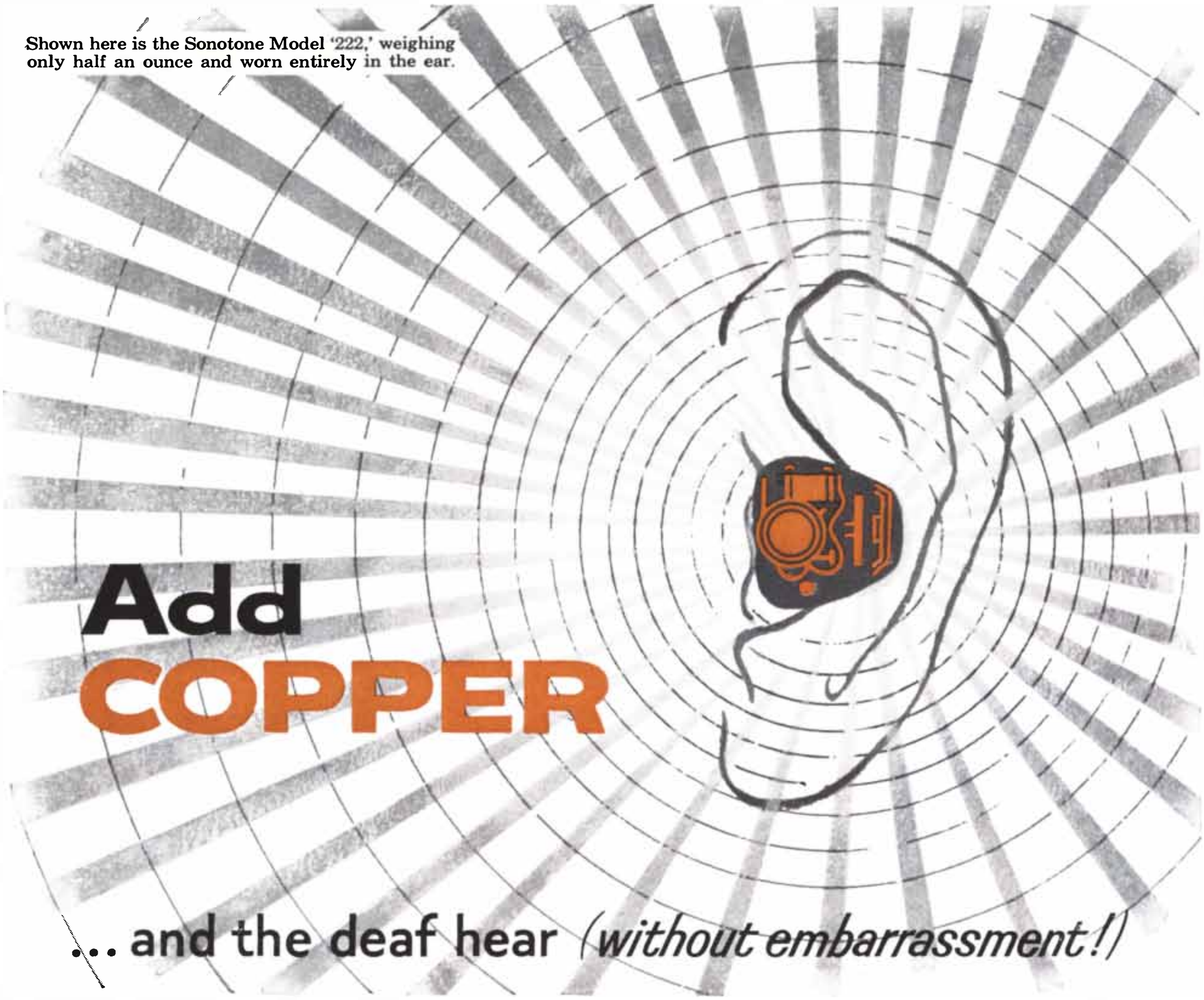
SPIRAL GALAXY SHAPE is produced when four plasmoids are fired simultaneously through a magnetic field toward a common center. The field is perpendicular to the page.

head on break into fragments, but even these fragments seem to behave as entities. In other words, we appear to be dealing with bodies which have strong powers of self-organization and preservation. We find these powers still more strikingly demonstrated when we go on to further experiments.

Suppose we fire a plasmoid not into a vacuum but into a thin gas. We introduce into the chamber a little deuterium gas, amounting to a pressure of about one micron. Now when a plasmoid is fired into the chamber through a magnetic field, the gas, which becomes somewhat ionized by the firing, allows current to flow. The current slows the movement of the plasmoid and also twists its path and its shape. When we fire four (or eight) plasmoids at one another from different directions, upon meeting near the center they whirl and form a ring with spiral arms [*see photograph above*]. The formation looks strikingly like a photograph of a spiral galaxy. If we fire two plasmoids at each other head on, they form an S-shaped figure resembling a "barred" spiral galaxy [*see photograph below*].

Just how are these interesting shapes formed? We can explain them on the basis of complicated interactions between the plasmoids and the magnetic field, which are diagrammed here for readers versed in electricity and magnetism who may be interested in the

BARRED SPIRAL results when two plasmoids are fired at each other. The photograph at the top of the page is a time exposure; the one at bottom is a two-microsecond "snapshot."



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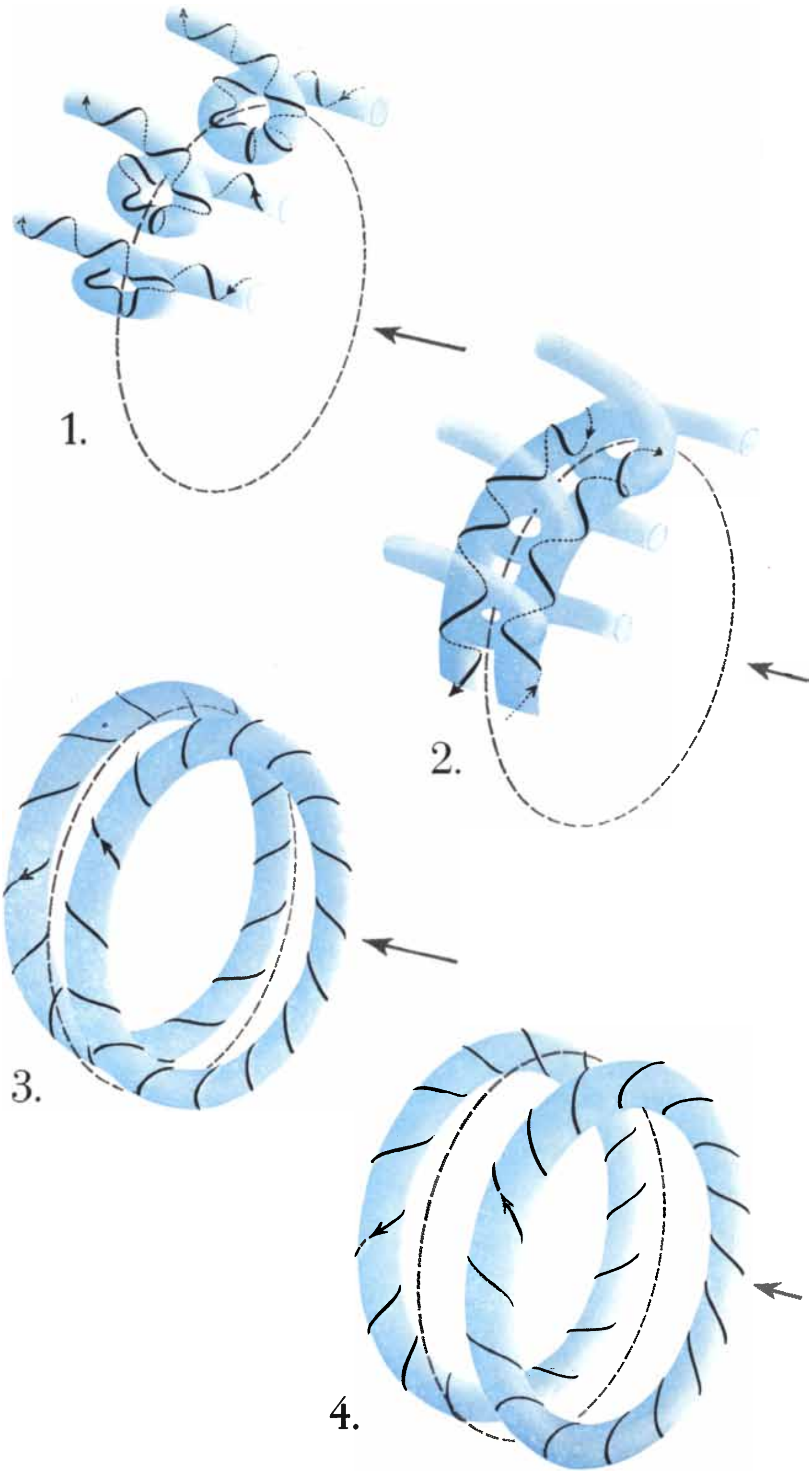


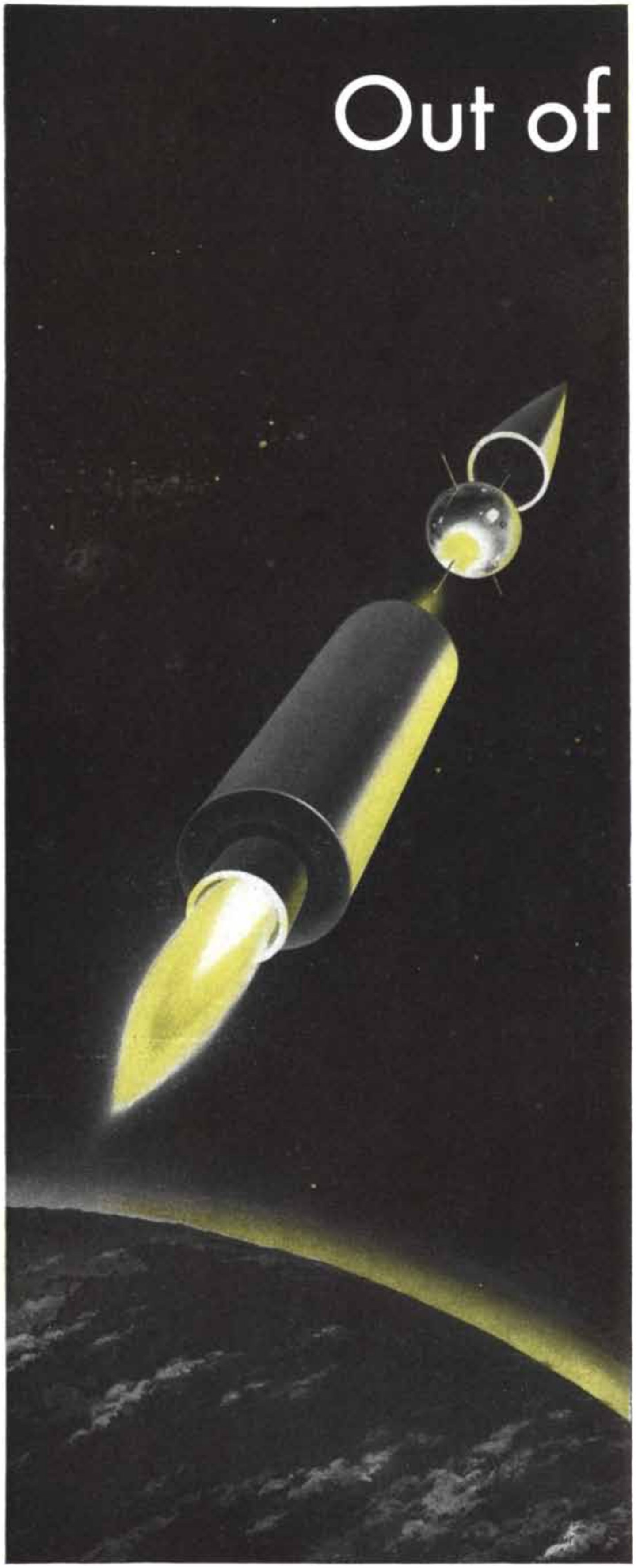
PAIRS OF RINGS, moving in opposite directions, may be formed by the merging of separate looped plasmoids as indicated in these drawings. Helical arrows show direction of the internal magnetic fields; the heavy gray arrows, the direction of the external field. Broken gray ellipse represents the center plane between the rings, from which each moves away.

mechanism [*see diagrams on page 91*]. A barred spiral, it appears, may be formed by plasmoids joining head to head; a ring spiral, by plasmoids joining head to tail. When the ring is oval-shaped, part of it flips over and forms a figure 8.

Photographs of plasmoids in three dimensions show that as a plasmoid moves across the magnetic field it is twisted into the shape of a left-handed screw [*see diagram at top of page 91*]. It is amusing to speculate on the possible relation of this fact to the recent breakdown of the parity principle, when it was found by particle experiments that the matter of our universe has a preferred left-handed spin [see "The Overthrow of Parity," by Philip Morrison; SCIENTIFIC AMERICAN, April]. If we reversed the poles of the magnetic field and the sign of the current in our plasma gun, our plasmoids would be right-handed instead of left-handed. The tempting speculation is that the matter of our galaxies may have been formed under the influence of vast galactic magnetic fields of one predominant orientation, which gave our matter a left-handed bias.

Under certain conditions our plasmoids form a pair of rings, which do not stay in the center of the chamber but move away from each other in opposite directions [*see diagrams at left*]. We believe that these rings are basically similar to magnetohydrodynamic whirls which, according to Alfvén, are apparently formed in pairs in the interior of the sun and may be responsible for sunspots. However, our plasma rings are not whirls in a fluid but are separate, independent "bodies." As such they represent a form of ordered organization by nature of which we have not been fully aware until now. Here is a case of electrons and ions collaborating with a magnetic field to form bodies which, though inanimate, assume orderly, characteristic shapes and possess a firm integrity.

We can look upon the combination of plasma and a magnetic field as a kind of self-shaping putty. Perhaps study of the forms assumed by this putty may help us to understand configurations such as the stars and galaxies. It may also throw light, at the other end of the scale, on the construction of fundamental particles such as the electron, the proton, mesons and neutrinos. They, too, may be made of a self-organizing putty: a putty composed of the electromagnetic field and its own gravitational forces, which, working together, create the bodies we know as particles.



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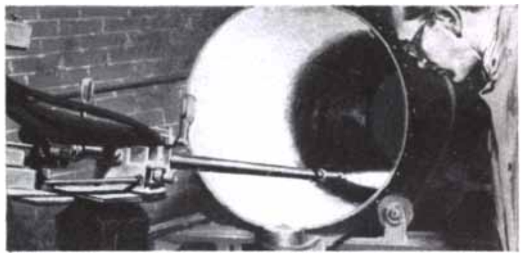

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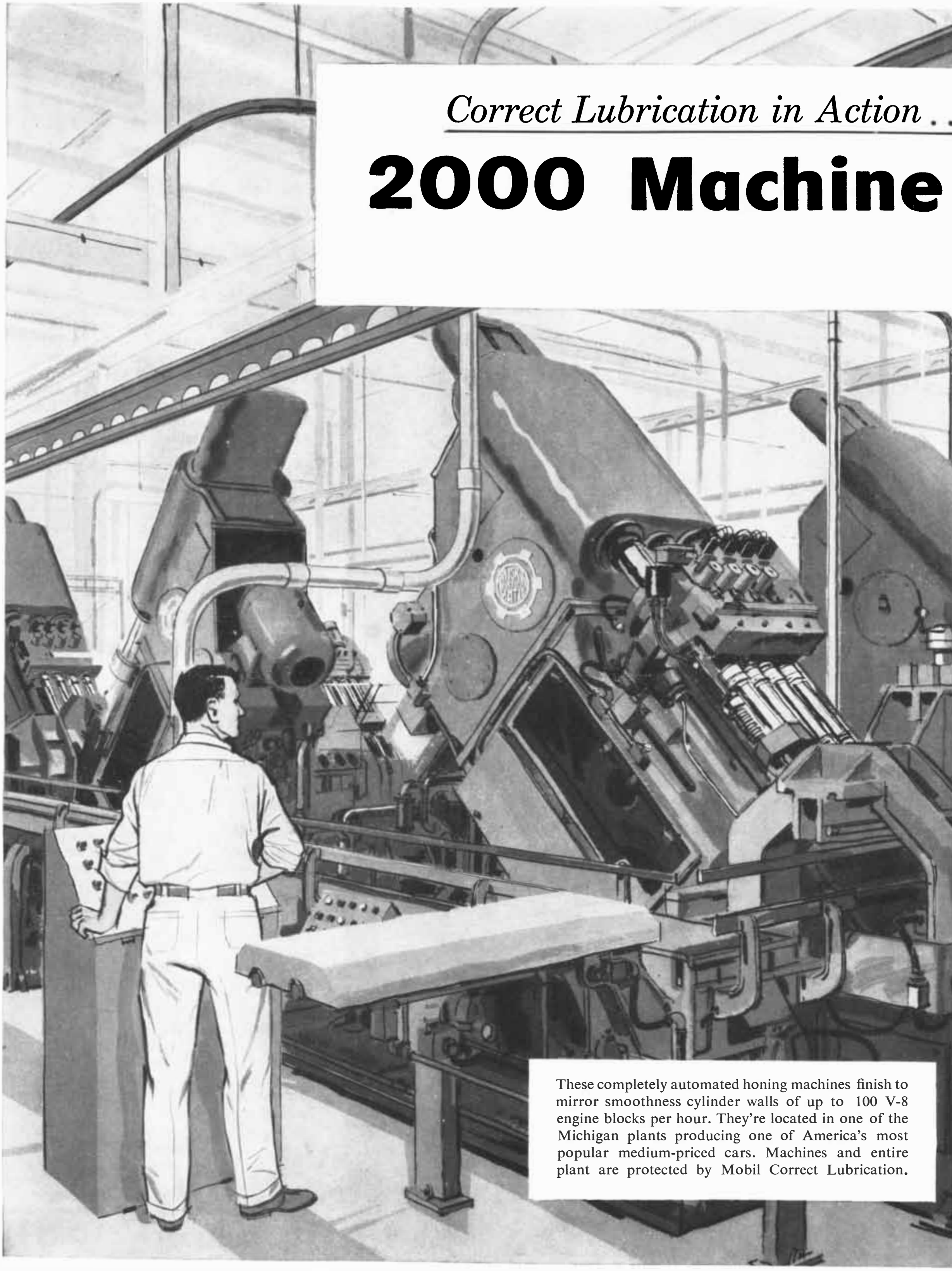

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