Anti-Matter

The discovery of the anti-proton and the anti-neutron raises the following question: Do anti-atoms made of these and other anti-particles exist in the universe?

by Geoffrey Burbidge and Fred Hoyle

Ever since the discovery of the positron—the opposite number of the electron—physicists have speculated about the possible existence of anti-matter. If an anti-electron could exist, why not an anti-proton and an anti-neutron? Within the last three years the Bevatron, the great accelerator at the University of California, has indeed produced anti-protons and anti-neutrons [see "The Antiproton," by Emilio Segrè and Clyde E. Wiegand; SCIENTIFIC AMERICAN, June, 1956]. Since electrons, protons and neutrons are the basic building stones of atoms, we have strong grounds for asking: If anti-particles, why not anti-atoms—that is to say, anti-matter which is the symmetrical opposite of the matter we know?

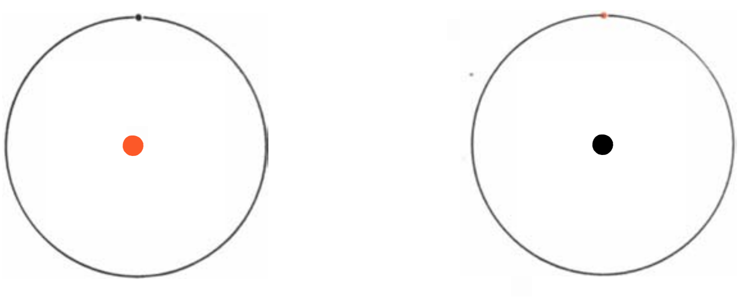
There can be no anti-matter on the earth, because particles and anti-particles annihilate each other the instant they meet. If there is anti-matter in space, we cannot recognize it with our telescopes, for anti-matter should look exactly like ordinary matter. But the problem of looking for evidence of anti-matter in the universe is not entirely hopeless. We shall consider here some possible indirect evidence on the subject. Such inquiries are not altogether academic, for, although the question of the existence of anti-matter has no practical importance to us on the earth, it does raise fundamentally important questions in modern physics and cosmology.

Our starting point is the known fact, established by laboratory experiments, that when a particle and an anti-particle collide they destroy each other, converting the entire mass of both particles into energy. The energy released by such an annihilation amounts to two times mc^2, in accordance with Einstein's famous equation for the conversion of mass into energy. The mutual annihilation of a proton and an anti-proton meeting at low velocity, for example, releases about 1.8 billion electron volts of energy. This energy emerges first in the form of mesons, but the mesons speedily decay and the ultimate carriers of the energy are gamma rays, neutrinos and very high-speed electrons and positrons [*see diagram on next page*].

If we could find evidence of such annihilations going on somewhere in the universe, we might have a proof of the existence of anti-matter. Let us examine our own galaxy, the Milky Way, and start with the gas in its interstellar space. Assume that this thinly dispersed gas, made up mainly of hydrogen at an average density of only one atom per cubic centimeter, contains some anti-protons. Would the annihilating collisions between these anti-protons and protons produce any observable effects on the interstellar gas?

About 90 per cent of the energy generated in an annihilation is carried by gamma rays and neutrinos. Almost all of this energy would escape from our galaxy into outer space, for the chances of gamma rays or neutrinos being intercepted and absorbed by the atoms in the thin gas are exceedingly small. The situation is otherwise, however, for the electrons and positrons that carry the remaining 10 per cent of the energy from annihilations. These charged particles would be trapped inside our galaxy by its magnetic field: there is considerable evidence that our galaxy does possess a weak magnetic field.

Now the high-energy electrons and positrons would gradually give up their energy to the gas as a whole—mainly by exciting and ionizing the atoms and by electron-positron annihilations. This injection of energy would have the effect of heating the gas and generating turbulent motions. We know that there are other processes which heat and stir up the interstellar gas in our galaxy. But suppose we assume, for the sake of putting an outside limit on the total possible amount of anti-matter in our galaxy, that all the energy of the gas is generated by annihilation of anti-matter. We know from various observations what the total energy of the gas in the galaxy is—it amounts to about one 100-billionth of an erg per cubic centimeter. On this basis we can calculate that the ratio of anti-matter to ordinary matter in our



ANTI-HYDROGEN ATOM (*right*) would have an anti-proton (*black circle*) and positron (*colored dot*). Hydrogen atom (*left*) has a proton (*colored circle*) and electron (*black dot*).

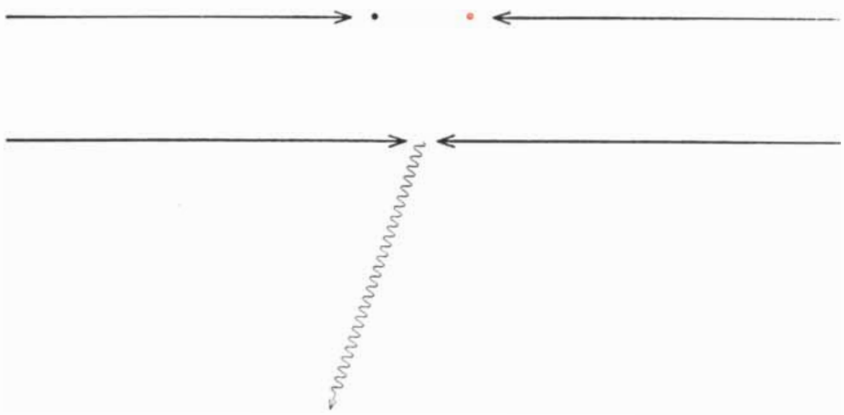
interstellar gas cannot possibly be more than one part in 10 million, spread thinly through the galaxy. From this small proportion we must deduce, incidentally, that even if anti-matter can somehow segregate itself from ordinary matter to form stars, it is extremely unlikely that there are any stars of anti-matter in our galaxy.

The establishment of a maximum figure for the amount of anti-matter does not prove that it is present, but it enables us to go on to an interesting speculation. This has to do with the recently discovered radio waves in space, stemming from so-called radio "stars" and from our galaxy as a whole. We know that electrons and positrons accelerated by a magnetic field emit a type of radiation called synchrotron radiation. This radiation can take the form of radio waves. The question then arises: Is annihilation of anti-matter responsible for some of the mysterious radio broadcasts we are receiving from space?

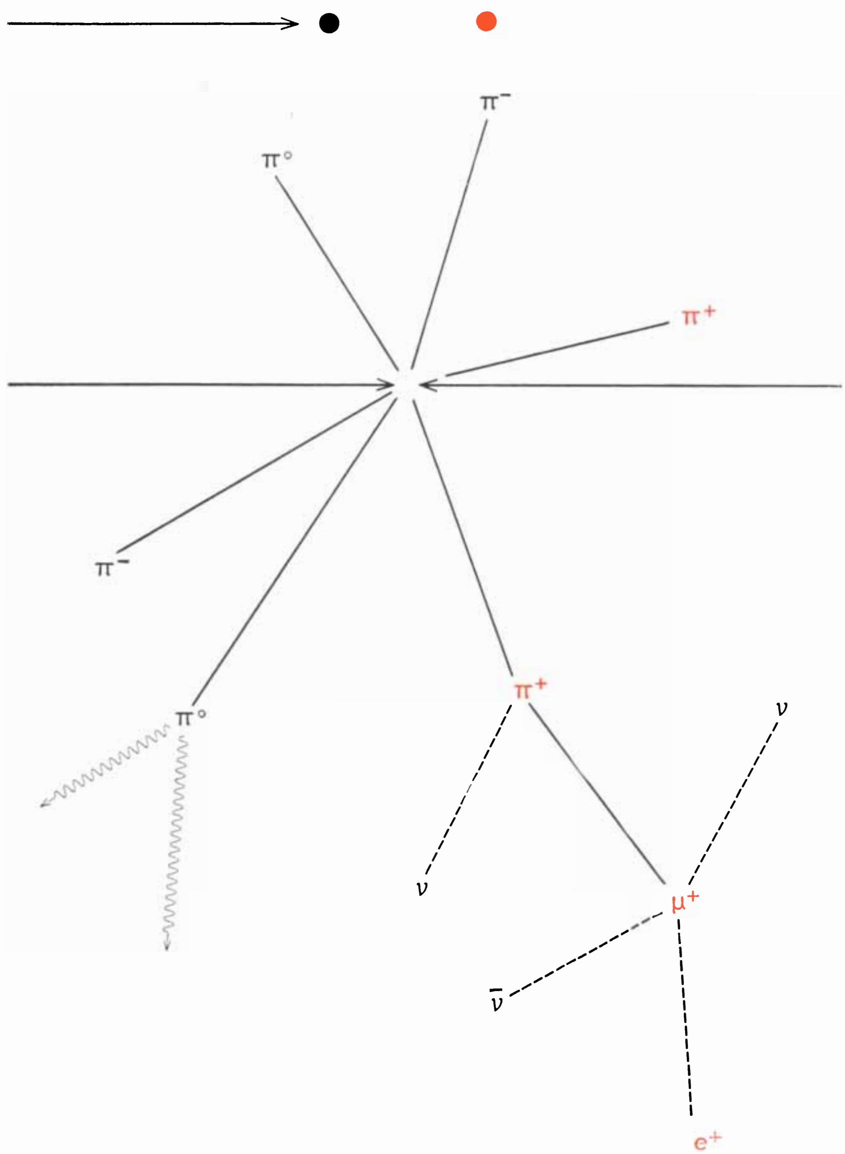
A particularly good subject for examining this question is the famous Crab Nebula, one of the strongest radio emitters in our galaxy. There is persuasive evidence that the radio emission and most of the light from this remnant of a supernova are synchrotron radiation [see "The Crab Nebula," by Jan H. Oort; SCIENTIFIC AMERICAN, March, 1957]. The Nebula appears to have a comparatively strong magnetic field and particles traveling at extremely high speeds. It is therefore conceivable that the radio emission of the Crab Nebula arises from electrons and positrons which have been created by annihilation of anti-matter. Calculating how much radio energy would be generated if one part in 10 million of the interstellar gas were anti-matter, we arrive at a figure which is close to the actual radio output of the Nebula (about 10^{33} ergs per second). The synchrotron radiation at visible wavelengths may arise from acceleration of some of the electrons and positrons to very high speeds by fast-moving gas clouds in the Nebula.

This is still no proof of the existence of anti-matter, because the original explosion of the supernova might account for its high-energy electrons and positrons. All that can be said is that the items of evidence we have considered are consistent with the possible presence of some anti-matter in our galaxy.

We come now to the wider scene. Are there, outside our own galactic system, galaxies entirely composed of anti-



ELECTRON-POSITRON annihilation occurs when particle and anti-particle collide. If the annihilation occurs in the field of an atom, the mass of the particles may be converted into only one photon (*wavy line*). If it occurs in free space, two photons will be emitted.



PROTON–ANTI-PROTON annihilation converts the particles to pi mesons (π), which decay as indicated at bottom. In this purely schematic diagram the Greek letter ν represents a neutrino; the same letter with a line over it, an anti-neutrino; the letter μ, a mu meson.

ANNIHILATION OF AN ANTI-PROTON made by the Bevatron at the University of California is recorded by these tracks in a liquid-propane bubble chamber. The event is outlined in the drawing at right. The anti-proton is annihilated by an encounter with a proton in a carbon nucleus. The short track to the left of the "star" of pi mesons is a fragment of the nucleus. At lower left a proton matter? If there are, we might possibly detect their existence if we saw an ordinary galaxy and an anti-galaxy in collision: this should be a really violent event. Here again we have one or two interesting cases for study.

Some astronomers believe that the extraordinary object called Cygnus A is a pair of galaxies in collision [see "Colliding Galaxies," by Rudolph Minkowski; SCIENTIFIC AMERICAN, September, 1956]. We are getting exceptionally strong radio signals from this object, even though it is very far away—at least 270 million light-years. The two colliding galaxies might be systems of matter and anti-matter, but suppose we make the less radical assumption that both consist predominantly of ordinary matter and each contains one part in 10 million of anti-matter. Assuming further that the magnetic fields of the two galaxies have combined to accelerate electrons and positrons, we can calculate that the annihilation of anti-matter in the colliding galaxies would generate a total of about 10^{44} ergs per second of radio energy. According to the measurements of radio astronomers, Cygnus A is actually emitting radio energy at precisely this rate!

The case of the galaxy known as Messier 87, another strong radio emitter, is even more interesting—indeed, it was M 87 that first aroused the speculation that a galaxy might contain anti-matter. M 87 looks like an unusually bright but normally shaped galaxy; there is no evidence that it represents a pair of galaxies in collision. However, it is emitting very powerful synchrotron radiation at radio wavelengths and has a bright jet or streak emitting such radiation at wavelengths of visible light [*see photograph at bottom of page 39*]. Astrophysicists have been at a loss to account for its extremely strong radiation, and it is tempting to suppose that the energy is coming from the galaxy's capture of a gob of anti-matter from an anti-galaxy.

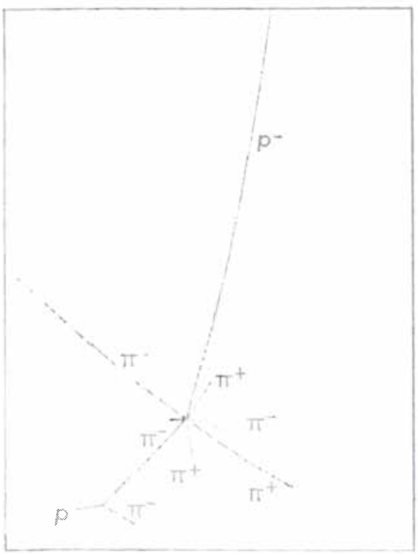
Yet notwithstanding the evidence tending to uphold the idea of the existence of anti-matter on the cosmic scale, most physicists, including the authors of this article, do not look too favorably on the hypothesis. Let us consider some of the difficulties.

In all present theories of the history of the universe—evolutionary or steady-state—symmetry arguments demand that if anti-matter exists both matter and anti-matter must be created in equal amounts. The evolutionary theory would require that the original nucleus from which the universe expanded must have contained both kinds of matter in equal parts; the steady-state hypothesis of the continuous creation of matter would imply that matter comes into being as pairs of particles and anti-particles. In either case, atoms and anti-atoms must somehow be separated selectively if they are to condense into stars and galaxies—otherwise they would destroy each other. It appears that the only way they could be so separated is by a gravitational force of repulsion between atoms and anti-atoms—in short, by anti-gravity, as opposed to the gravitational attraction that operates between atom and atom of ordinary matter.

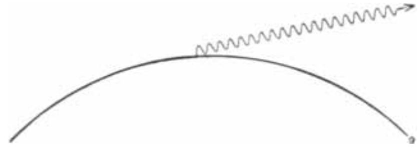
It is upon this rock that the anti-matter ideas have foundered. For the idea of anti-gravity cannot be accepted without destroying basic principles of the general theory of relativity. The successes of the relativity theory are so great that most scientists are not prepared at the present time to consider with equanimity the very considerable upheaval that would come about if it had to be abandoned or drastically modified.

Experiments designed to look for the existence of anti-gravity are possible in principle and may be worth doing. One obvious test would be to generate a beam of anti-protons in an accelerator and project it over a path parallel to the earth to see whether it would rise or fall; if the beam rose, it would indicate that anti-gravity was operating.

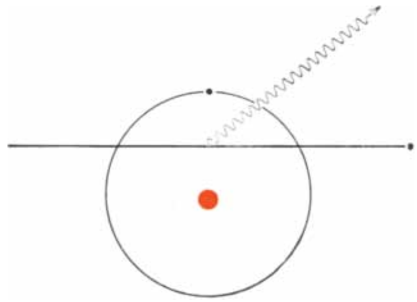
Maurice Goldhaber of the Brookhaven National Laboratory has speculated on the possible existence of two separate



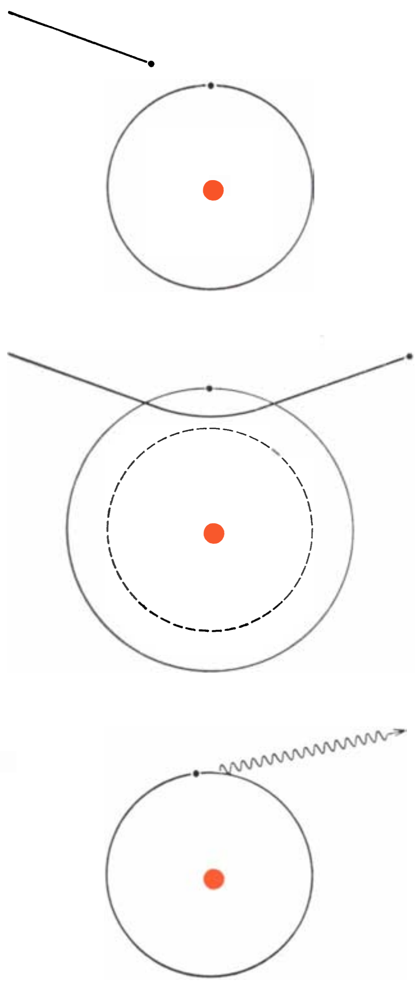
(P) recoils from a collision with a pi meson. The experiment was performed by groups under W. M. Powell and Emilio Segrè.



RADIATION from electron in curved path transfers energy to the surrounding gas.



ENERGY TRANSFER also takes place by means of radiation emitted when an electron passes through the field of an atom.

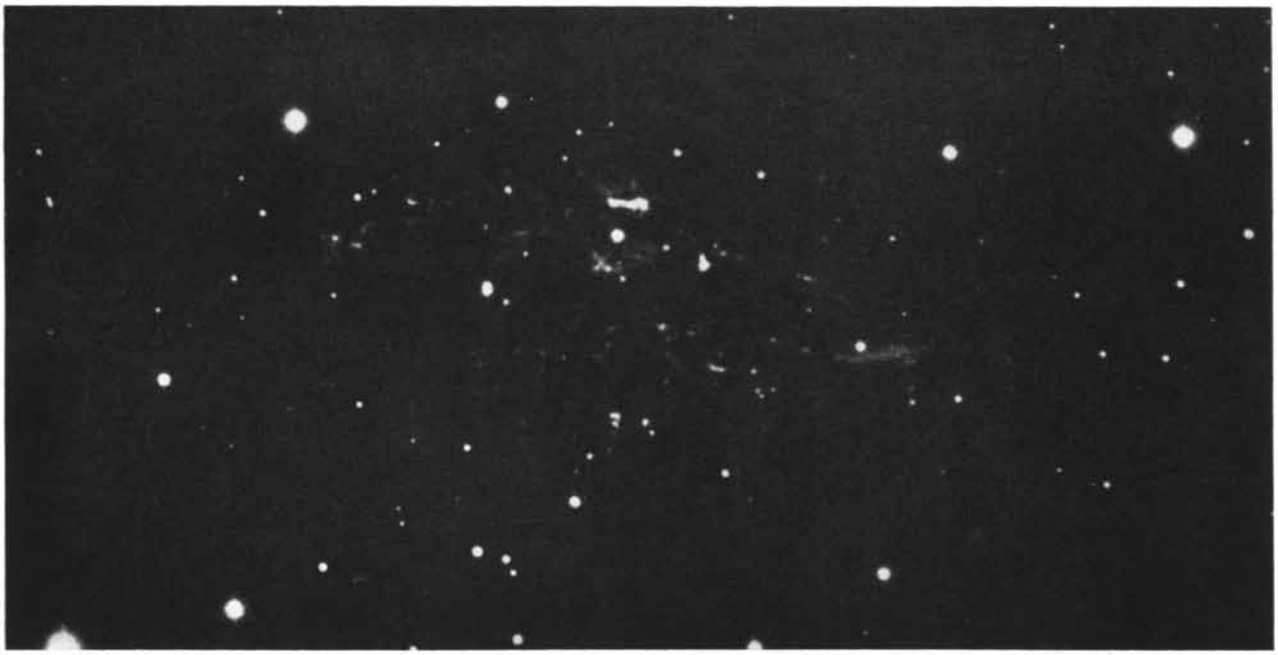


EXCITATION of atomic electron to higher energy level is a third way to take energy from free electrons. When the excited electron drops back to orbit, it radiates energy.

worlds—one composed of matter and the other of anti-matter. Inspired by the primeval atom of Abbé Georges Lemaître, he suggests that the universe originated from a single "particle" called the "universon." This divided immediately into a pair of "particles"—the "cosmon" and the "anti-cosmon." They flew apart with great kinetic energy (by some unspecified process) and eventually decayed, one giving rise to the cosmos we know, the other to an anti-cosmos beyond reach of our observation. Goldhaber goes on to speculate on whether some anti-matter from the anti-cosmos may have been injected into our cosmos; possibly this would be the source of the radio energy being emitted by some of our galaxies and gas clouds.

Some cosmologists have become more receptive to the idea of two separate universes since the recent overthrow of the parity principle—that is, the discovery that certain particles of our universe are unsymmetrical, in the sense that they have a particular "handedness." It be-

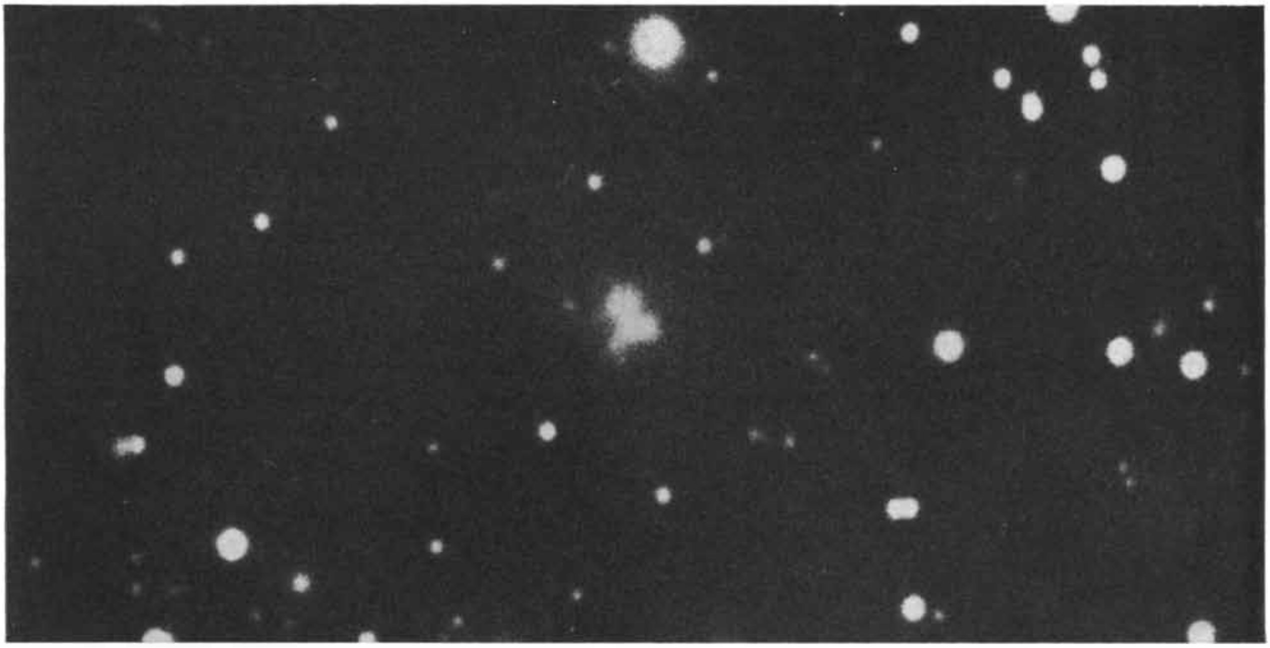
CRAB NEBULA is the remnant of a supernova which occurred in 1054. Its light comes from highly accelerated charged particles, which may have been created by the annihilation of anti-matter. This photograph is from the 100-inch telescope on Mount Wilson.



CASSIOPEIA A, the strongest isolated source of radio waves in the sky, is seen as a series of faint luminous wisps in this photograph from the 200-inch telescope on Palomar Mountain. It is probably also the remnant of a supernova and may contain anti-matter.

comes reasonable to ask whether symmetry may be preserved after all by the existence in some other part of the universe of an equal amount of anti-matter with the opposite "handedness."

We may sum up as follows. Anti-matter may exist in our galaxy, but it cannot exceed about one part in 10,000,000 of ordinary matter if it is there. It is most unlikely that any of the stars in our galaxy can be made of anti-matter. Outside our galaxy, other galaxies in remote parts of the universe may consist entirely of anti-matter. The nearest approach to direct proof of the existence of such bodies is the presence of strong radio sources whose energy is difficult to explain by any known process but might be explained by the annihilation of anti-matter. On the other hand, if anti-matter does exist in the universe, we do not understand at present how the bulk of it became separated from matter. To explain this would apparently require a revolution in our thinking on cosmological problems.



CYGNUS A, a strong emitter of radio waves, may be a pair of colliding galaxies which appear as the blob in the center of this 200-inch-telescope photograph. Its observed radio energy can be calculated if the galaxies are assumed to contain some anti-matter.

MESSIER 87 is apparently a single galaxy, but the radiation of light and radio waves by the bright jet at right is unusually strong. This radiation may be caused by the annihilation of anti-matter in the jet. The photograph was made with the 200-inch telescope.