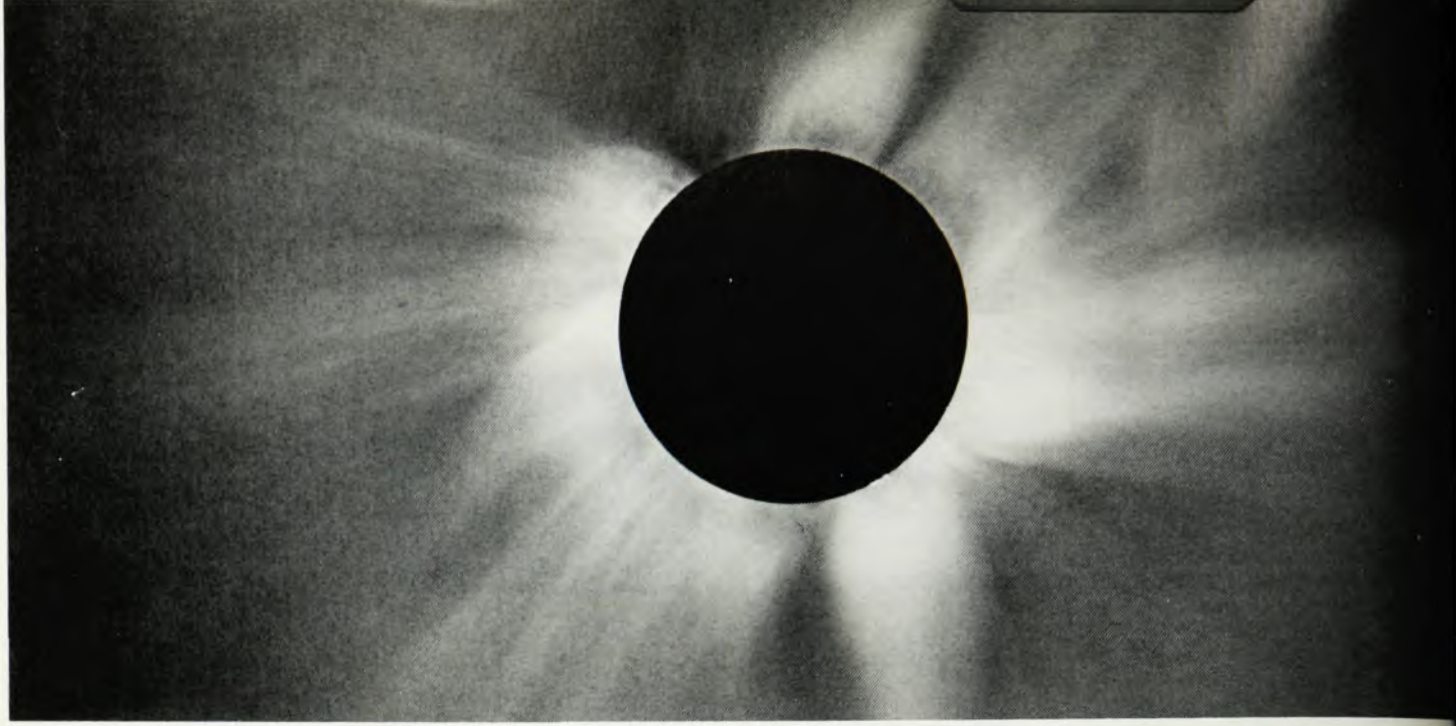


Plasma physics applied to cosmology

Hannes Alfvén

The study of astrophysics in modern times should essentially involve the application of laboratory results to cosmical problems, with help from theoretical physics. In the realm of plasma physics, there appears to be no reason why known basic laws, formulated in the laboratory, should not hold just as well at the astrophysical and cosmological scale.

It is possible that there are some basic laws of physics that we have not found in the laboratory but that could be discovered by cosmological research, as is claimed by some cosmologists. I do not think this is very likely. To me the most promising approach appears to be to learn how to apply the laws of physics already discovered in the laboratory, rather than to speculate about undiscovered laws. With this approach we are led to study cosmology along the lines of Oskar Klein; he postulates symmetry between ordinary matter and antimatter throughout the cosmos, and a metagalaxy with an initial state of contraction giving way to the expansion we are observing now. To follow this theory into all its consequences we need to know a great deal more about the properties of ambiplasma (mixed matter and antimatter) than we do now. Before long we will find ourselves involved also in nuclear and particle-physics problems of a kind that has not yet been studied.

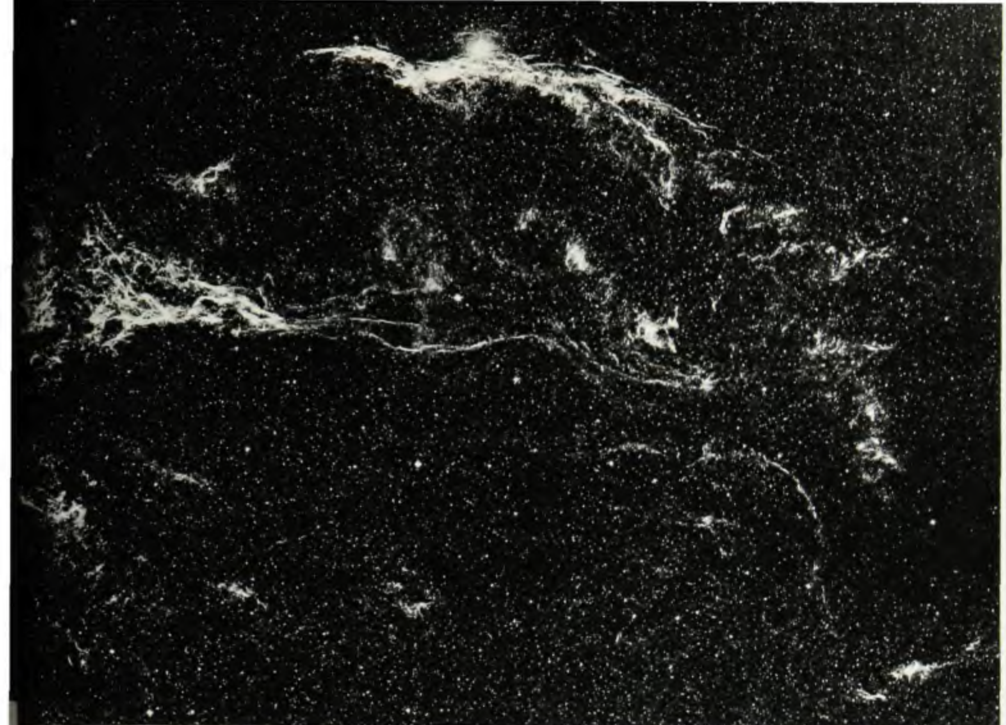
Hannes Alfvén was awarded last year's Nobel prize in physics (shared with Louis Néel) for his work in plasma physics. He is a professor of plasma physics at the Royal Institute of Technology, Stockholm, and at the same time professor in residence at the University of California, San Diego.

New laws or old ones?

Historically, the development of the physical sciences has been characterized by fruitful interactions among laboratory physics, theoretical physics, and astronomy (or astrophysics). For the start of the scientific avalanche, some three hundred years ago, the astronomical problem of planetary motion was essential. The first proof that the velocity of light is finite also came from astronomy.

Since then it has been the dream of many an astrophysicist to discover new basic laws of nature by astrophysical investigations. Connections between magnetization and rotation of celestial bodies, cosmological changes in the physical constants, continuous creation of matter, the existence of quarks and magnetic monopoles, and so on, have been suggested, but none of these hypotheses has been confirmed. This lack of success does not mean that we should take for granted that no new basic laws of physics could be discovered by astrophysical investigations. We should always keep an open mind in this respect. But it does mean that we should investigate to what extent we can understand astrophysics with the help of the basic laws we have discovered in the laboratory. This will be the background of my discussion here. In view of the rather chaotic state of cosmology at present, I believe that it is essential to define our approach in this way.

However, even if we do agree to start from the basic laws discovered in the laboratory, it is not at all easy to see how they should be applied. In astrophysics, matter is often in a state that we can not study in the laboratory. For example, even if we can not clarify the nature of nuclear forces by studying superdense stars, such as pulsars, we must learn to apply nuclear physics to problems of which we have no direct experience in the laboratory. Similarly, there is no reason why the basic laws of



Cosmical plasma structures. At left is the solar corona photographed during the 7 March, 1970 eclipse with a radially symmetric neutral-density filter to emphasize detail in the coronal structure. Photograph on right is part of the gaseous nebula in Cygnus. Many celestial objects show a pronounced "hairy" structure, as in these two examples. According to the "first approach" to cosmical electrodynamics these regions are approximated as homogeneous media (sometimes as turbulent media) in spite of the fact that few people would apply such theories to their own hair. According to the "second approach" the filamentary structure is produced by electric currents and is basic to the understanding of the physical state of the medium. (Eclipse photo by Gordon Newkirk Jr and L. Lacey, High Altitude Observatory, National Center for Atmospheric Research. Nebula photo from the Hale Observatories.) Figure 1

is time for a fresh approach to cosmical ectrodynamics. Instead of searching for new laws f physics we should be trying to find ıt how to use the laws we already know.

plasma physics should not hold good in the cosmos, yet the application of plasma physics to cosmical problems, often involving collective phenomena, is still in such a state that comparatively few of the published papers have any permanent value.

Two lines of attack

The study of plasma physics developed along two parallel lines. The first one, originating about a century ago, comprised investigations into electrical discharges in gases. This approach was, to a great extent, experimental and phenomenological; only very slowly did it reach some degree of theoretical sophistication. Most theoretical physicists looked down on this field, which was complicated and awkward. The plasma exhibited striations and double layers; the electron distribution was non-Maxwellian; there were all sorts of oscillations and instabilities. In short, it was a field not at all suited for mathematically elegant theories.

The other approach to plasma physics came from the highly developed kinetic theory of ordinary gases. It was thought that with a limited amount of work this field could be extended to include ionized gases as well. The theories were mathematically elegant, and the consequences of them showed that it should be possible to produce a very hot plasma and confine it magnetically. This was the starting point of thermonuclear research.

However, the theories had initially very little contact with experimental plasma physics, and all the awkward and complicated phenomena that had been treated in the study of discharges in gases were simply neglected. The result of this was what has been called the "thermonuclear crisis," some ten years ago. It taught us that plasma physics is a very difficult field, which can only be developed by a close cooperation between theory and experiments.

Cosmical plasma physics is far less advanced. It is to some extent the playground of theoreticians who have never seen a plasma in a laboratory. Most of them still believe in formulas that we know, from laboratory experiments, to be wrong. The astrophysical correspondence to the thermonuclear crisis is just beginning.

The need for a second approach

I think it is evident now that in certain respects the first approach to the

Koinomatter and antimatter

Koinomatter is "regular" or "ordinary" matter, as distinct from antimatter. According to symmetrical theories of the cosmos, such as that postulated by Oskar Klein, there is no reason to suppose that this kind of matter is any more "ordinary" than antimatter; both kinds exist in equal amounts. Then the term "antimatter" can be thought of as a short form for "antikoinomatter."

Ambiplasma consists of both koinomatter and antimatter. For *quasineutrality* of a hydrogen ambiplasma we require:

$$n(p^+) + n(e^+) = n(p^-) + n(e^-)$$

In a neutral koinoplasma:

$$n(p^-) = n(e^+) = 0$$
$$n(p^+) = n(e^-) \neq 0$$

In a neutral antiplasma:

$$n(p^+) = n(e^-) = 0$$
$$n(p^-) = n(e^+) \neq 0$$

In a symmetric ambiplasma:

$$n(p^+) = n(p^-)$$
$$n(e^+) = n(e^-)$$

physics of cosmical plasmas has been a failure. It turns out that in several important cases this approach has not given even a first approximation to the truth; instead, it has led us into dead-end streets from which we now have to turn back. The reason is that several of the basic concepts on which the theories are founded are not applicable to the conditions prevailing in the cosmos. These concepts are "generally accepted" by most theoreticians, and they are developed with the most sophisticated mathematical methods. But the plasma itself does not "understand" how beautiful the theories are and absolutely refuses to obey them. It is now obvious that we have to start a second approach from widely different starting points.[1] The two different approaches are summarized in Table 1. Two examples of cosmical plasmas where the second approach appears necessary are shown in figure 1.

If you ask where the border between the first approach and the second lies today, an approximate answer is that it is given by the range of spacecraft. In every region where we have been able to explore the state of the plasma by magnetometers and particle analyzers we find that, in spite of all their elegance, the first-approach theories have very little to do with reality. It appears that the change from the first approach to the second is the astrophysical correspondence to the thermonuclear crisis.

Cosmologies

Few astrophysicists believe that we can discover new basic laws of physics in our nearby environment in space—in the magnetosphere, in interplanetary space, or even in our galaxy. But as we look further out opinions begin to divide. When we reach what are called "cosmological distances" we find phenomena that are difficult to understand, either because we do not know how to apply the well known basic laws, or because there are new basic laws of nature governing the phenomena there. To one group of astrophysicists the charm of cosmology seems to be the hope of discovering new basic laws. I must confess that I find this activity rather uninteresting; I do not believe that regions which are so difficult to investigate are well suited to such an activity. I am more attracted by the attempts to clarify to what extent astrophysical phenomena can be explained by the laws of physics we have already discovered in the laboratory.

This approach to cosmology has been advocated very clearly by Oskar Klein.[2] He thinks that it is extremely important to draw a clear line between theories of this kind and speculations about new basic laws of physics. I completely agree with him.

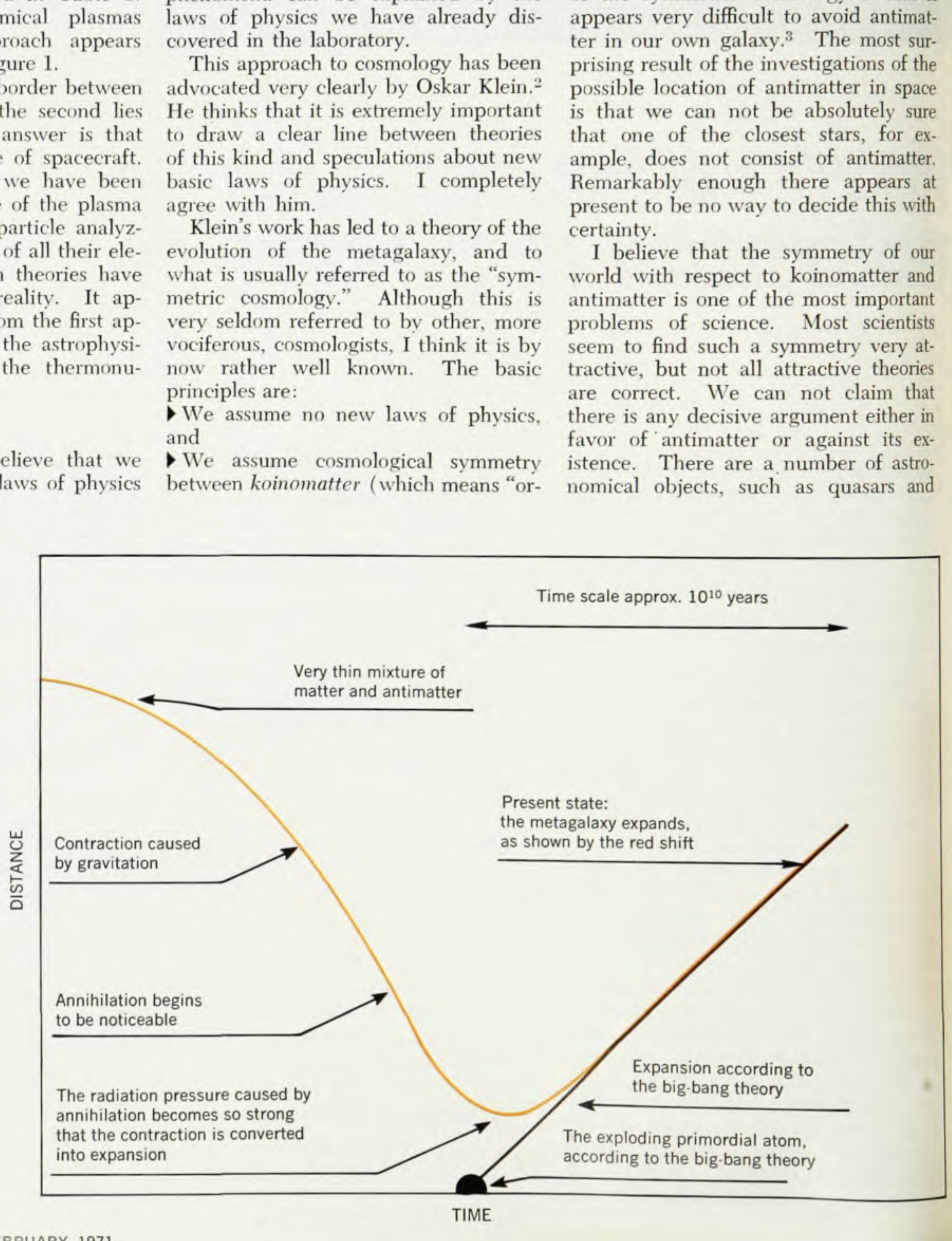
Klein's work has led to a theory of the evolution of the metagalaxy, and to what is usually referred to as the "symmetric cosmology." Although this is very seldom referred to by other, more vociferous, cosmologists, I think it is by now rather well known. The basic principles are:

- We assume no new laws of physics, and
- We assume cosmological symmetry between *koinomatter* (which means "ordinary" matter) and *antimatter*.

He concludes that the only way to reconcile these principles with observations is to assume that the "initial state" of the metagalaxy was a more-or-less homogeneous *ambiplasma* (a mixture of koinomatter and antimatter) with so low a density that annihilation is negligible. From this state the metagalaxy contracts until it reaches a minimum size, at which it commences the present expanding state (see figure 2). The change from contraction to expansion is achieved by a release of annihilation energy that produced a radiation explosion about 10^{10} years ago. This differs from the usual "big bang" by being a "bigger big bang." The minimum size of Klein's metagalaxy is 10^9 light years.

One of the interesting consequences of the symmetric cosmology is that it appears very difficult to avoid antimatter in our own galaxy.[3] The most surprising result of the investigations of the possible location of antimatter in space is that we can not be absolutely sure that one of the closest stars, for example, does not consist of antimatter. Remarkably enough there appears at present to be no way to decide this with certainty.

I believe that the symmetry of our world with respect to koinomatter and antimatter is one of the most important problems of science. Most scientists seem to find such a symmetry very attractive, but not all attractive theories are correct. We can not claim that there is any decisive argument either in favor of antimatter or against its existence. There are a number of astronomical objects, such as quasars and



Evolution of the metagalaxy. Gravitational attraction of the original matter–antimatter mixture leads to a condition where annihilation causes the expansion now observed by the red shift. Expansion according to the big-bang theory is shown for comparison by the black line. Figure 2 some galactic nuclei, that emit such enormous quantities of energy that it is rather difficult, although perhaps not impossible, to find other energy sources than annihilation. There has been a flow of papers stating that the existence of antimatter is in conflict with some authors' pet theories, but so far there appears to be no *observational* results that conflict with the theory. Much more work is needed before we can expect a decision. Certainly we know enough already to state that most of the "anti-antimatter" letters to *Nature* are nonsense, but the real question is how to develop this field of research in a systematic way.

We need many more astronomical observations and we need to investigate the properties of an ambiplasma before we can draw any conclusions on how to detect it or how to prove its absence. Unfortunately it is impossible to study an ambiplasma in the laboratory. Many of its basic properties could no doubt be treated theoretically, although any ambiplasma is certainly more complicated than an ordinary plasma.

Table 1. Cosmical electrodynamics

First approach	Second approach
Homogeneous models	Space plasmas often have a complicated inhomogeneous structure
Conductivity $\sigma = \infty$, electric field $E_{\parallel} = 0$	σ depends on current and often suddenly becomes zero, $E_{\parallel}$ often $\neq 0$
Magnetic field lines are "frozen in" and "move" with the plasma	Frozen-in picture often completely misleading
Electromagnetic conditions illustrated by magnetic-field line picture	It is equally important to draw the current lines and discuss the electric circuit
Electrostatic double layers neglected	Electrostatic double layers are of decisive importance in low-density plasmas
Filamentary structures and current sheets neglected or treated inadequately	Currents produce filaments or flow in thin sheets
Theories are mathematically elegant and very well developed	Theories are still not very well developed and partly phenomenological

Properties of an ambiplasma

For a quasi-neutral plasma, we require

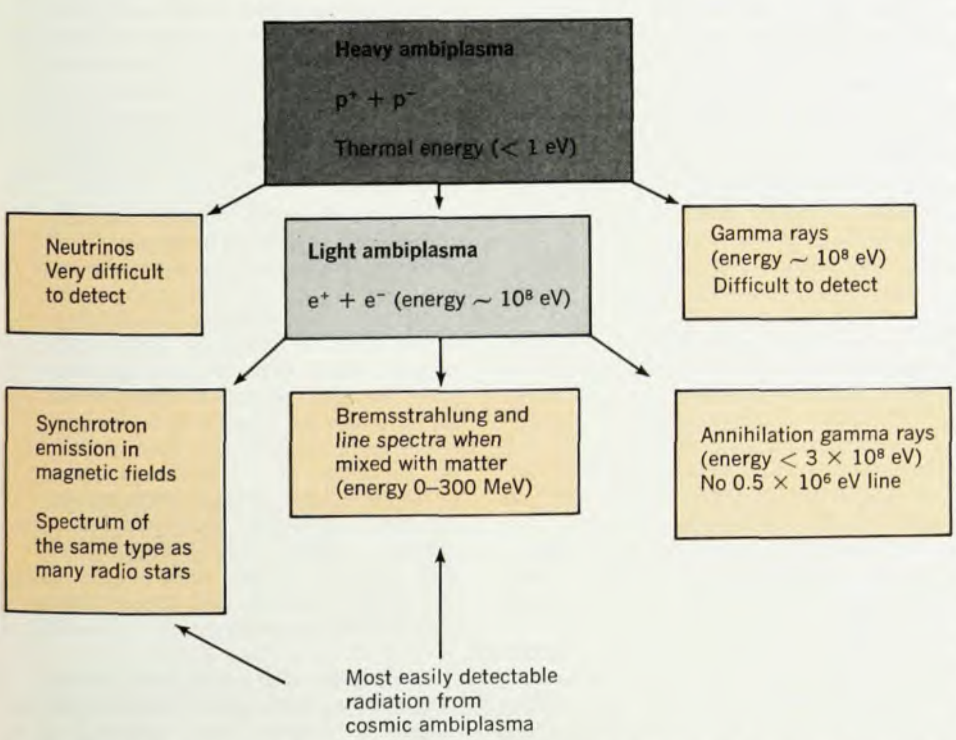
$$n(p^+) + n(e^+) = n(p^-) + n(e^-)$$

where the four terms refer to the densities of ions, positrons, anti-ions and electrons respectively. Taking the simplest case, that is, a homogeneous, completely ionized, hydrogen ambiplasma (see the box on page 29), we learn from particle physics that the annihilation will produce a constant decrease in $n(p^+)$ and $n(p^-)$, which after a very shortlived intermediate state results in an increase in $n(e^-)$ and $n(e^+)$. Furthermore there will be a decrease in $n(e^-)$ and $n(e^+)$ due to electron-positron annihilation. Some important properties of ambiplasmas are shown in figure 3.

Very soon we meet a difficulty. Although particle physics is a highly developed field of research, the simple problem of how protons and antiprotons annihilate appears not to be sufficiently well known for our purposes. Certainly the reactions in the MeV and GeV ranges are very well studied, but the cross sections for reactions between thermal particles—those with energies of 1 eV or less—appear not to have attracted very much attention.

Our next question is, under what circumstances does an ambiplasma become explosive, in the sense that a shock wave will be amplified? We want to know what observable phenomena are produced in this way. One of the applications is the change from contraction to expansion in the metagalaxy. Further, if we start with a symmetric ambiplasma, that is, $n(p^+) = n(p^-)$, the final result will be a complete annihilation; but if $n(p^+)$ is greater than $n(p^-)$ initially, the burnout will result in an ordinary koinoplasma. As, according to Klein, a symmetric ambiplasma is the only reasonable starting condition in the metagalaxy, and as a koinoplasma is characteristic of the present conditions on our part of the universe, one of the basic problems is how to make $n(p^+)$ greater than $n(p^-)$ locally. In other words, how can we obtain a partial separation of an ambiplasma that was initially homogeneous?

This separation of an ambiplasma into a koinoplasma and an antiplasma is clearly one of our basic problems. It is easy to show that an electric current flowing parallel to a gradient in $n(p^+) - n(p^-)$ will produce a partial separation (see figure 4), and there are also a few other separation processes. But the more general problem of separation has not yet been taken up in a really ambitious way. Is it possible that under certain conditions an ambiplasma becomes unstable, in the sense that regions of koinomatter and antimatter are automatically produced?



Annihilation in heavy and light ambiplasma produces radiation of various kinds by which we might hope to detect these processes occurring in the cosmos. Figure 3

Does annihilation power quasars?

One attractive aspect of the concept of a symmetrical universe containing equal amounts of koinomatter and antimatter is our ability to explain the observed properties of quasars, or quasi-stellar objects, starting from this concept. Quasar structure, the vast quantity of energy emitted, variations in the energy flux and in the direction of polarized components, spectral distribution and radiofrequency emission can all be explained by this simple model.

First we must decide whether a symmetrical universe contains koinomatter and antimatter components separated by cosmological distances, or whether there is comparatively "local" symmetry. After considering all alternatives we find we have no choice but to assume that all galaxies contain the two kinds of matter in equal proportions. Other possibilities (with widely separated components) require new mechanisms or new laws of physics, for which we have no basis, to explain how one galaxy could be created out of koinomatter alone and another out of antimatter alone, or to explain a large-scale separation of the two kinds of matter since the galaxies were formed.

We then interpret quasars as being very young galaxies representing an early phase in the evolution from the protogalaxy into various types of radio galaxies and finally to normal galaxies. Typical quasar phenomena will become evident by the time a dense nucleus is formed. At this stage cells of koinomatter and antimatter are mostly small, and collisions between the two kinds of matter are much more frequent than they are for a stable galaxy, especially in the dense nucleus. As time goes on the cells grow rapidly and the galaxy evolves towards a more stable state.

Energy emitted by quasars. If we assume that the very large red shifts of quasar spectra indicate that they are at cosmological distances, the emitted energies must be very large. For the best-known object, 3C 273, the emitted energy is of the order of 2×10^{47} erg/sec. For typical quasars we can assume the emitted energies lie in the range $10^{46.5 \pm 1.0}$ erg/sec.

There appears to be no other energy source than annihilation of koinomatter and antimatter that could deliver these enormous energies.

Disregarding the unobservable energy of neutrinos, we find that the annihilation of one solar mass per year will release on the average 3×10^{46} erg/sec. The mass of a typical galaxy is 10^{11} solar masses. Hence even a quasar emitting the equivalent of 10 solar masses per year could proceed at this rate for 10^{9} years without losing more than 10% of its mass.

The energy release necessary to turn the initial contraction of the metagalaxy into an explosion 10^{10} years ago (see figure 2) is 4×10^{59} erg/sec. The average energy release for each of the 10^{10} galaxies in the metagalaxy is therefore 4×10^{49} erg/sec, or a hundred times the output of an energetic quasar. Hence the quasi-stellar sources as we observe them today emit much less energy per unit mass than the metagalaxy emitted at the time its contraction turned into expansion.

Structure. We suppose a quasar to consist of a large number of regions, each containing mainly one kind of matter only. The interstellar gas in each region is condensing into stars.

The rate of annihilation and radiation from active layers between unlike cells will be small or moderate. But in the nucleus of the system, where densities and relative velocities are higher, collisions between stars will not be rare. Sometimes two colliding stars will be composed of opposite kinds of matter, and a sudden release of annihilation energy will then accompany the collision.

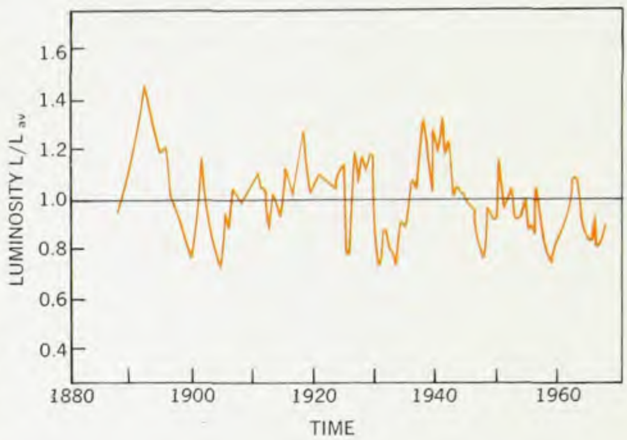
Observation shows that, in a typical quasar, much of the energy is released within a very small volume, probably in the nucleus of a more extensive system. Thus in the center of 3C 273 there is a radio source smaller than 0.0006 sec of arc, or 5×10^{15} cm, together with other components about 3 and 30 times larger.

Considerable variation in the optical magnitudes and radio flux densities are common properties of quasars. Long-term variations and sudden "flashes" have been observed. In our model, collisions between stars of opposite kinds of matter would produce such sudden and violent energy outbursts, with annihilation in nonseparated ambiplasma producing at least part of the steady (or slowly varying) emission.

Light emission. The optical spectra of quasars contain broad emission lines, with the width of the lines differing from one object to another. The optical continuum shows a strong excess in the ultraviolet, and usually an excess in the infrared.

In the annihilation model intense local heating would give rise to the ultraviolet continuum, with broad spectral lines coming from somewhat cooler regions. If the source is surrounded by a layer of dust a large fraction of the energy may finally be emitted in the infrared.

Polarization. If a small star penetrates the outer parts of a larger star during an annihilating collision, the explosion will produce a massive jet of hot plasma ejected radially from the star. Electron scattering and optical synchrotron radiation may give highly polarized radiation from such a jet. Each new explosion would result in a new direction for the polarized component of the radiation, corresponding to the fluctuations observed by astronomers.



Random fluctuations in the luminosity of quasar 3C 273. The luminosity is here compared with the average L_{av}. (Adapted from James Terrell and Kenneth Olsen, Astrophys. J. **161**, 399, 1970).

Radio emission. Some quasars are among the strongest radio sources so far known. For others no radio emission has been observed. The flux density from radio quasars varies considerably; each outburst appears to start at the shortest wavelengths and occurs later at longer wavelengths—up to 40 cm.

The annihilation model suggests that a large fraction (perhaps 17%) of the energy goes into electrons and positrons at 100 MeV. Some of these particles are annihilated immediately; others form a cloud of light ambiplasma, which expands, moving away from the star where it was formed. Stellar magnetic fields may be dragged out in this motion and the particles will probably, at a later stage, spiral around the lines of force emitting synchrotron radiation at radio wavelengths. The energy maximum will shift towards larger wavelengths as the cloud expands and moves away from the active region. —JTS

* * *

This material is a condensed version (prepared by PHYSICS TODAY) of reference 2 (Teller) and reference 3 (Alfvén and Elvius).

Another basic problem concerns what happens at the interface between a region of koinoplasma and a region of antiplasma. It appears likely that the annihilation produces a very hot intermediate zone, a "Leidenfrost layer," which separates koinomatter and antimatter. Such layers could be very thin (cosmically speaking), and space may be divided into a large number of compartments containing either koinomatter or antimatter. The radiation from such layers may be too weak to be detected, with the result that it would be very difficult to detect if our galaxy has a patchy structure of koinomatter and antimatter.

When this idea was proposed some years ago, it was not very well received. Now we know, however, that very thin current-carrying layers are common in space. Examples are the magnetopause, the tail sheet in the magnetosphere, and the so-called "sector boundaries" in interplanetary space. At such layers, the magnetic field often flips through 180 deg. There had been no indication of their existence until spacecraft crossed them. Similar structures in our galaxy may very well keep regions of different kinds of matter apart.

Nuclear-physics problems

So far I have mentioned problems that belong essentially to plasma physics, but there are other problems where nuclear physics and particle physics are important (see Table 2). If there are antistars with planetary systems somewhere in the neighborhood, we should expect meteoric antimatter to be ejected, some of it in the direction towards our solar system. How far can an antimeteor travel before it burns out? Does an interstellar koinoplasma stop it? If a piece of antimatter was to fall through the Earth's atmosphere, as has been suggested by Konstantinov and Bredov in Leningrad, what phenomena would we expect? The answers to these questions require the treatment of the interaction between, for example, a solid piece of anti-iron and koinonitrogen gas. To my knowledge this problem, which is not at all trivial, has never been studied. The reactions between heavy nuclei of different kinds of matter appear to be *terra incognita.*

Table 2. Important antimatter problems

Nuclear and particle physics

1. **Lifetime of thermal ambiplasma[4]**
   Cross section of annihilation for particles <1 eV
2. **Reactions between heavy nuclei of opposite kind**
   Example: Anti-iron and koinonitrogen

Solid state

1. **How rapidly will a solid body of given size be fragmented by annihilation reactions at its surface?**
   Example: How far can an antimeteoroid move in interstellar koinomatter?

Plasma physics

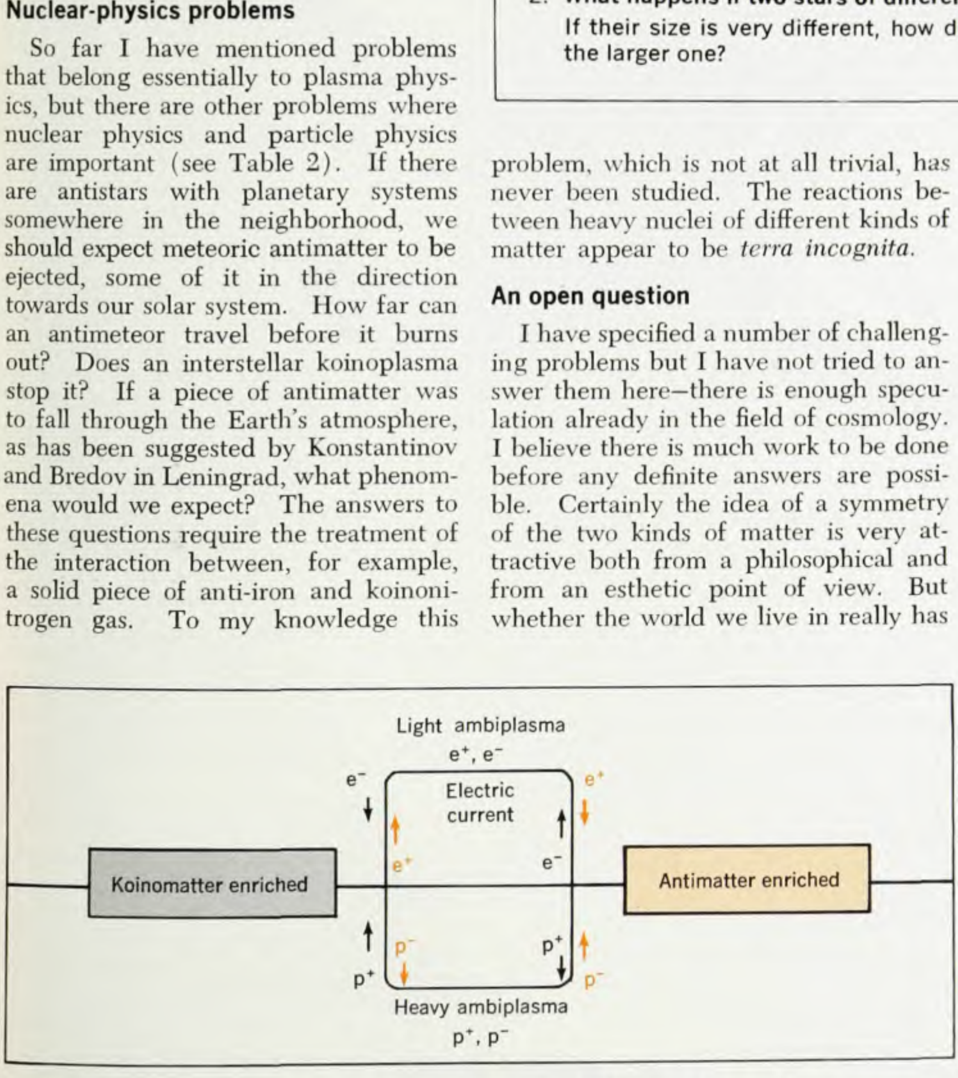
1. **Evolution of a magnetized homogeneous ambiplasma**
   Spectrum of emitted radiations as functions of magnetic fields and plasma densities
2. **Interface between koinoplasma and antiplasma**
   Structure of "Leidenfrost layer," radiations, stability
3. **Separation of an ambiplasma**
   Under what conditions does it "coagulate" into regions of partially separated koinoplasma and antiplasma?
4. **Shock waves in ambiplasma**
   Under what conditions is it "explosive"?

Complex problems (involving several different fields of physics)

1. **What happens if an antimeteoroid hits the Earth's atmosphere?**
2. **What happens if two stars of different kind collide?**
   If their size is very different, how deep can the smaller body penetrate into the larger one?

An open question

I have specified a number of challenging problems but I have not tried to answer them here—there is enough speculation already in the field of cosmology. I believe there is much work to be done before any definite answers are possible. Certainly the idea of a symmetry of the two kinds of matter is very attractive both from a philosophical and from an esthetic point of view. But whether the world we live in really has such a property is an open question—one of the most challenging questions of today's physics. It can be solved only by joint work of plasma physicists, nuclear physicists and, of course, astronomical observers. When the cosmical existence of antimatter is clarified we will have a much better foundation for cosmological applications.



A simple separation process. Here an electric field flowing parallel to a gradient in $n(p^+) - n(p^-)$ will produce a partial separation. Figure 4

References

1. H. Alfvén, "The Second Approach to Cosmical Electrodynamics," in the *Proceedings* of the Birkeland Symposium, Sandefjord, Norway (1967), published in Ann. Geophysique **24**, 361 (1968); H. Alfvén, C. G. Fälthammer, *Fundamental Principles of Cosmical Electrodynamics,* Oxford U.P. (1963).
2. O. Klein, Nature **211**, 1337 (1966); H. Alfvén, O. Klein, Arkiv Fysik **23**, 187 (1962); H. Alfvén, Rev. Mod. Phys. **37**, 652 (1965); H. Alfvén, *Worlds–Antiworlds,* Freeman, San Francisco (1967); B. Bonnevier, Arkiv Fysik **27**, 310 (1964); A. G. Ekspong, N. K. Yamdagni, B. Bonnevier, Phys. Rev. Lett. **16**, 664 (1966); B. E. Laurent, L. Söderholm, Astron. and Astrophys. **3**, 196 (1969); E. Teller, in *Perspectives in Modern Physics* (R. E. Marshak, ed.) Interscience, N.Y. (1966), page 449.
3. H. Alfvén, A. Elvius, Science **164**, 911 (1969).
4. D. L. Morgan, Jr., V. W. Hughes, Phys. Rev. **D2**, 1389 (1970). □