Antimatter and the Development of the Metagalaxy

H. ALFVÉN
Royal Institute of Technology, Stockholm, Sweden

Elementary particle physics has demonstrated the complete symmetry between particles and antiparticles. From this follows the equivalence between matter and antimatter. It is very unsatisfactory that current cosmological theories are not symmetric with respect to matter and antimatter.

It is postulated that a cosmological theory should be matter–antimatter symmetric, and introduce no *ad hoc* laws of nature. These postulates form part of Klein's theory, but are not satisfied by the "expanding universe" or "continuous creation" theories.

Essential properties of an "ambiplasma" consisting of matter and antimatter are studied. It is shown that it emits radio waves but no detectable γ rays. If initially the plasma contains equal amounts of matter and antimatter, the two ingredients can be separated by electromagnetic and gravitational forces. In the present state of the universe there may be coexisting regions of matter and antimatter, separated by thin "Leidenfrost" layers.

Klein's theory of the metagalaxy is reviewed and developed. The "initial condition" is supposed to be an extremely thin plasma of matter and antimatter which contracts under the action of gravitation. When the density has reached about 10^{-2} particles cm^{-3}, annihilation produces a radiation pressure which transfers the contraction to the present expansion. The theory leads to a relation between the average density and the Hubble parameter which is in satisfactory agreement with observations.

Different ways of detecting antimatter are discussed. It is possible that radio stars consist of ambiplasma. The enormous energy quantities emitted from some celestial objects may be supplied by annihilation.

Outside our metagalaxy there may exist other similar systems. The possibility of observing them is discussed.

I. THE COSMOLOGICAL PROBLEM

I. Introduction

About forty years ago it became evident that the spiral nebulae were galaxies of essentially the same size and structure as our own galaxy. Further it was found that the spectral lines from distant galaxies had a redshift which, if interpreted as a Doppler effect, indicated that they move away from us with a velocity proportional to their distance from us (Hubble's law). All the observed galaxies (together with a multitude of still not discovered galaxies) are considered to be part of an enormous system called the metagalactic system.

Models of the development and structure of the metagalactic system have essentially followed two different lines of approach [see, for example, McVittie (1961)]. According to the "expanding universe" theory, the metagalactic system is identified with the whole universe. It is supposed that the universe "originated" at a certain instant as a very dense lump of matter which exploded, and the galaxies were emitted in all directions. On the other hand, according to the "steady-state" theory the universe should be homogeneous and in a steady state. In this theory it is assumed that matter should be continuously created.

In connection with serious objections against both these models an alternative approach has been attempted by O. Klein (1953, 1958, 1961, 1962), who assumed the "initial state" to be an extremely dilute cloud consisting of protons and electrons, a part of which contracted under the action of gravitation and later formed the metagalactic system. The theory, in which no new physical laws were introduced, led to a new interpretation of Eddington's relations between atomic and cosmological quantities. As a necessary consequence of the basic arguments it was later assumed that the initial cloud was a mixture of equal amounts of particles and antiparticles. Arguments for assuming such a symmetry were forwarded by many physicists (among them O. Klein) immediately after the discovery of the positron more than thirty years ago, and they have been strengthened by the recent development in elementary particle physics which has demonstrated the most perfect symmetry between particles and antiparticles. It now seems logically unsatisfactory that the cosmological theories should be based on the assumption that the universe contains only matter and no antimatter.

Klein's line of approach demands the existence of an efficient mechanism of separating matter and antimatter [since statistical fluctuations cannot produce a sufficient separation, Goldhaber (1956), Alpher and Herman (1958)]. It further requires that in the present state of the metagalaxy there must exist regions containing matter and other regions containing antimatter, and these regions must be separated by thin sheaths.

2. Properties of Antimatter

Dirac's theory of the electron and the discovery of the positron gave rise to a general belief that all particles should have corresponding antiparticles. This belief has been confirmed by the discovery of the antiproton. Also, all other elementary particles seem to have antiparticles. From this one can conclude that "antiatoms" may exist which are similar to the ordinary atoms of all elements, but their nuclei consist of antiprotons and antineutrons and are surrounded by positrons. Such antiatoms should have the same properties as ordinary atoms. For example they could build up chemical compounds similar to ordinary chemical compounds, and they should emit spectral lines of exactly the same wavelengths as ordinary atoms. Magnetic or electric fields should produce Zeeman or Stark effects which are the same as for ordinary matter under the condition that the direction of the fields are reversed.

From this follows that we cannot *a priori* exclude the existence of celestial bodies consisting of antimatter. From the study of the light from a celestial body it is impossible to ascertain whether the body consists of matter or antimatter (in case we do not know the direction of the magnetic field). Also, the nuclear properties of matter and antimatter are similar, so that in a star consisting of antimatter there would be an energy release due to fusion.

If a particle is hit by its antiparticle annihilation may take place. An electron and a positron annihilate each other under the emission of (usually) two photons with an energy of 0.5 MeV each. A proton hitting an antiproton produces a number of mesons rapidly decaying into electrons, positrons, photons, and neutrinos, so that after some microseconds the net result is a few positrons and electrons with energies of the order of 10^8 eV and a few photons and neutrinos with energies of the same order of magnitude. The electrons and positrons may later annihilate each other if brought together.

Together with the reaction to an electric or magnetic field with *known* direction, the annihilation reaction is the only way of distinguishing between matter and antimatter. Thus in order to ascertain whether a celestial body consists of matter or antimatter we must either study, e.g., the Zeeman effect of a spectral line when the emitting atom is subject to a magnetic field with known direction, or study the reaction when it is hit by a lump of matter (or antimatter).

Hence, by *direct* observation it is at present impossible to decide whether a distant celestial object consists of matter or antimatter, and we cannot exclude the possibility that, e.g., half of the celestial objects in universe consist of antimatter. (Indirect arguments for and against the existence of antimatter are considered in Sec. II.6, and in Sec. IV.)

3. Physics and Cosmology

Ordinary physics is essentially based on observations in the laboratory. In many cases the laws derived by theoretical deduction from laboratory experiments have been successfully checked by astronomical observations. The astronomers have not made any observations which now definitely call for the introduction of new physical laws. There is not a single astronomical fact in definite disagreement with quantum theory or the theory of relativity. This does not mean that we can be sure that the usual laws of nature (which of course include the general theory of relativity) hold up to such linear distances and intervals of time as are dealt with in cosmological theories. Since we are approaching such questions as the possible limitation in space and time of our universe, we should not be surprised if we had to introduce new physical laws. However, one is naturally rather reluctant to accept new physical laws until one feels convinced that an observed phenomenon cannot possibly be explained according to laws for which there are satisfactory proofs in other ways.

This means that one should prefer a cosmology introducing no new laws of nature to one which is founded on *ad hoc* assumptions. As a general rule an *ad hoc* assumption should never be made until it is obvious that other ways of approach are excluded. From this point of view there is no reason to accept the hypothesis of a "continuous creation."

The concept of antimatter in the universe cannot be considered an *ad hoc* assumption. The perfect symmetry between particles and antiparticles is a result of elementary particle physics and if there should be any logical connection between cosmology and the fundaments of physics one cannot avoid assuming even a cosmological symmetry between matter and antimatter. It is the usual assumption that the universe consists only of matter and contains no antimatter which should be classified as an *ad hoc* assumption. The main purpose of the present paper is to demonstrate that there does not exist any decisive support for this conventional view.

In this connection it should be observed that even if no new laws of physics are introduced, a cosmology can never avoid making assumptions about the "initial state." It is obviously an advantage if the initial state is assumed to be very simple.

4. Klein's Model of the Metagalaxy

In Klein's model the "initial state" is supposed to be a thin plasma consisting of a homogeneous mixture of matter and antimatter. The density is extremely low, much lower than the present average density in the metagalactic system. Hence the initial state is very simple and the model is perfectly symmetric with regard to matter and antimatter. The rate of annihilation is very slow, due to the low density. The plasma occupies a volume which is very much larger than the present dimensions of the metagalactic system. Due to gravitational instability a certain part of the plasma begins to contract. A large quantity of initial gravitational energy can be released. For the case of simplicity the contracting plasma is assumed to be a sphere. The development of the sphere under the action of gravitation is studied and only ordinary laws of physics (including, of course, the theory of relativity) are assumed to be valid. It is shown that the development

Table I. Annihilation lifetimes.

n	10^{-6}	10^{-4}	10^{-2}	1 particle per cm^3
T_0	4.3×10^{12}	4.3×10^{10}	4.3×10^{8}	4.3×10^{6} years

of the contracting sphere may lead to a state similar to the present state of the metagalactic system.

In principle there may be several condensations of the initial plasma so that there may be other metagalactic systems in the universe. A discussion of the universe outside the metagalactic system is reserved for Sec. V.

II. ON THE PROPERTIES OF AN AMBIPLASMA

1. Introduction

Klein's model of the metagalaxy has directed attention to the importance of studying the properties of a plasma consisting of a mixture of matter and antimatter. We shall call such a plasma an *ambiplasma* (ambi = both), and discuss some of its properties in the following paragraphs.

In general, an ambiplasma may contain a mixture of all elements and antielements. In order to simplify the treatment we shall confine ourselves to the case when it has only four constituents, n_p^+ protons, n_p^- antiprotons, n_e^+ positrons, and n_e^- electrons per unit volume. As all cosmical plasmas it is magnetized (field = B), and it may be acted upon by gravitation g. The quasineutrality condition requires

$$n_p^+ + n_e^+ = n_p^- + n_e^-. \tag{II.1}$$

There are three important special cases:
Matter:

$$n_p^+=0, \qquad n_e^+=0, \qquad n_p^+=n_e^-; \tag{II.2}$$

Antimatter:

$$n_p^+=0, \qquad n_e^-=0, \qquad n_p^-=n_e^+; \tag{II.3}$$

"Symmetric ambiplasma":

$$n_p^+=n_p^-, \qquad\qquad n_e^+=n_e^-. \tag{II.4}$$

According to the model, the metagalaxy consisted initially of a symmetric ambiplasma. One of the main problems is to study how this can be separated into matter and antimatter. It is also important to investigate what radiation it emits.

2. The Annihilation Reactions

A proton and an antiproton may annihilate each other. The annihilation results in mesons, neutrinos, and high-energy γ rays. After the π and μ decays there are, on the average, about two electrons and two positrons per annihilation, and their energy is about 100 MeV.

If we introduce the "classical radius of the electron"

$$d=e^2(mc^2)^{-1}=2.8\times10^{-13}\text{ cm}$$

and

$$\sigma_0=\pi d^2=2.5\times10^{-25}\text{ cm}^2 \tag{II.5}$$

we can write the average lifetimes T_p^+ and T_p^- of a proton and an antiproton

$$T_p^+=(n_p^- c\sigma_0)^{-1}k_p, \tag{II.6}$$

$$T_p^-=(n_p^+ c\sigma_0)^{-1}k_p, \tag{II.7}$$

and similarly for electrons and positrons

$$T_e^-=(n_e^+ c\sigma_0)^{-1}k_e, \tag{II.8}$$

$$T_e^+=(n_e^- c\sigma_0)^{-1}k_e. \tag{II.9}$$

We have

$$c\sigma_0=0.75\cdot10^{-14}\text{ cm}^3\text{ sec}^{-1}. \tag{II.10}$$

In these formulas k_p is a function which is of the order unity up to relativistic energies. Further k_e approaches unity for nonrelativistic energies, but increases logarithmically for relativistic energies. The value of

$$T_0=(nc\sigma_0)^{-1} \tag{II.11}$$

is shown in Table I. Since k_p and k_e are of the order unity, T_0 gives the order of magnitude of the lifetimes. The table shows that if we have a homogeneous mixture of matter and antimatter with the present average density of the metagalaxy ($\sim10^{-6}$ cm^{-3}) the annihilation goes very slowly ($T_0=4.3\times10^{12}$ years), but if the density is of the order 10^{-3} cm^{-3} the decay time becomes of the order of billion years, which compares with the ordinary time-scale in cosmological theories. The interstellar medium (inside a galaxy) is supposed to have a density of 1 particle/cm^3, which means that an antiparticle there would decay after about 5 million years.

3. Radiations From an Ambiplasma

The electrons and positrons, which are the result of the proton–antiproton annihilation have energies of the order 10^8 eV. All cosmic plasmas we know are magnitized and there is no reason to suppose that the case we treat should be different. In a magnetic field B the electrons and positrons spiral and emit synchrotron radiation. The decay time is

$$T_s=\frac{5\times10^8}{B^2}\frac{1}{1+(W/W_0)}\text{ sec} \tag{II.12}$$

[see, for example, Alfvén and Fälthammar (1963), p. 69], where W is the kinetic energy and $W_0=m_ec^2$. If $W=100$ MeV$=200W_0$ we obtain

$$T_s=2.5\times10^6B^{-2}\text{ sec}=0.08B^{-2}\text{ years}. \tag{II.13}$$

If $T_s \ll T_0$ the electrons and positrons radiate most of their energy as synchrotron radiation before they annihilate (see Table II). If, on the other hand, $T_s \gg T_0$ very little synchrotron radiation is emitted. If for example the electron–positron density is 10^{-2} cm^{-3}, the condition for a great fraction of synchrotron radiation is $B > 10^{-5}$ G.

The energy maximum of the spectrum of the synchrotron radiation is

$$\nu_{max} = (eB/2\pi mc)(W/W_0)^2 = 3\times10^6(W/W_0)^2 B. \quad \text{(II.14)}$$

With $W/W_0 = 200$ we have

$$\nu_{max} = 10^{11} B \text{ sec}^{-1}. \quad \text{(II.15)}$$

It should be observed that if the particles spend most of their time in a field B_0, but 1% of their time in a field $B_1 = 10B_0$, half of their energy is radiated in the stronger field. Hence both for the calculation of the lifetime and the maximum of the spectrum one should use rather the maximum field than the average field.

Compared to the synchrotron radiation, the Bremsstrahlung is usually negligible.

Hence under the assumption

$$T_s \ll T_0 k_e \quad \text{(II.16)}$$

the net result of an annihilation is the emission of four γ photons of energy $\sim$200 MeV, and the emission of about 300 MeV in the form of radio waves. Moreover neutrinos are emitted.

For each γ photon the radio-wave energy of 75 MeV is emitted, which equals 1.2×10^{-11} J.

With present technique [see Kraushaar *et al.* (1965)] it is possible to detect a 200-MeV photon flux of about 1 photon m^{-2} sec^{-1} ($=10^{-4}$ cm^{-2} sec^{-1}) $=3.2\times10^{-11}$ Wm^{-2}. On the other hand, it is possible to detect a flux of radio-wave energy of the order of 10^{-18} Wm^{-2} (bandwidth 10^8, sensitivity 10^{-26} Wm^{-2} Hz^{-1}). [See, for example, Ryle (1963).] Hence, our instruments to detect the radio waves from an ambiplasma are more than 10^7 times more sensitive than the γ-ray detectors.

A cosmic ambiplasma would manifest itself as an emitter of radio waves. A measurable flux of γ rays would occur only if the radio flux exceeds 8×10^{-11} Wm^{-2} or, with a bandwidth of 10^8 Hz, 8×10^{-19} Wm^{-2} Hz^{-1}.

As a comparison the strongest radio stars emit 3×10^{-22} Wm^{-2} Hz^{-1}. If a radio star consists of an ambiplasma, and both the γ rays and radio waves reach us without absorption, the γ-ray intensity would be 10^3 times too weak to be detected with present technique.

The positrons and electrons also annihilate with the emission of photons exceeding 0.5 MeV. Their number is about the same. Moreover, an ambiplasma emits neutrinos, but they are of course impossible to detect. Finally, the ambiplasma may emit light and all other types of radiation that characterize a cosmic plasma.

In an infinite plane layer of thickness Δ the total energy per cm^2 is

$$W_M = 2m_p c^2 n_p \Delta. \quad \text{(II.17)}$$

This energy is radiated during a time $T_p = (n_p c\sigma_0)^{-1} k_p$. The energy flux ϕ per unit time is

$$\phi = W_M/T_p = 2m_p c^3 \sigma_0 n_p^2 \Delta \cdot k_p^{-1} \quad \text{(II.18)}$$

or

$$\phi = 2.2\times10^{-17} n_p^2 \Delta k_p^{-1} \text{ erg cm}^{-2} \text{ sec}^{-1}. \quad \text{(II.19)}$$

It should be kept in mind that what has been said holds only if $T_s \ll T_0 k_e$. If on the contrary $T_s \gg T_0 k_e$ more energy is emitted in γ rays than in radio waves, but the γ emission is not more easily detected unless $T_s > 10^7\, T_0 k_e$.

4. An Ambiplasma in a Gravitational Field

In this paragraph we neglect the annihilation and the radiation in order to study the plasma properties of the matter–antimatter gas. Suppose that in a unit volume there are n_p^+ protons, n_p^- antiprotons, n_e^+ positrons, and n_e^- electrons. The number density is so small that annihilation can be neglected. The magnetic field is neglected. The plasma is acted upon by gravitation g in the direction $-z$. In general this will polarize the ambiplasma so that an electric field E is produced. All variables are supposed to depend only on the coordinate z. For each of the components we obtain

$$\partial(nkT)/\partial z = (-g\cdot m \pm eE)n, \quad \text{(II.20)}$$

where k is Boltzmann's constant, T the temperature, m the mass, and e the charge of a particle. We confine ourselves to the case of an isothermal plasma $T=$const. Putting $gm_p/kT = \mu_p$, $gm_e/kT = \mu_e$, and $eE/kT = F$ we obtain

$$(n_p^-)^{-1}(\partial n_p^-/\partial z) = -\mu_p - F, \quad \text{(II.21)}$$

$$(n_p^+)^{-1}(\partial n_p^+/\partial z) = -\mu_p + F, \quad \text{(II.22)}$$

$$(n_e^-)^{-1}(\partial n_e^-/\partial z) = -\mu_e - F, \quad \text{(II.23)}$$

$$(n_e^+)^{-1}(\partial n_e^+/\partial z) = -\mu_e + F. \quad \text{(II.24)}$$

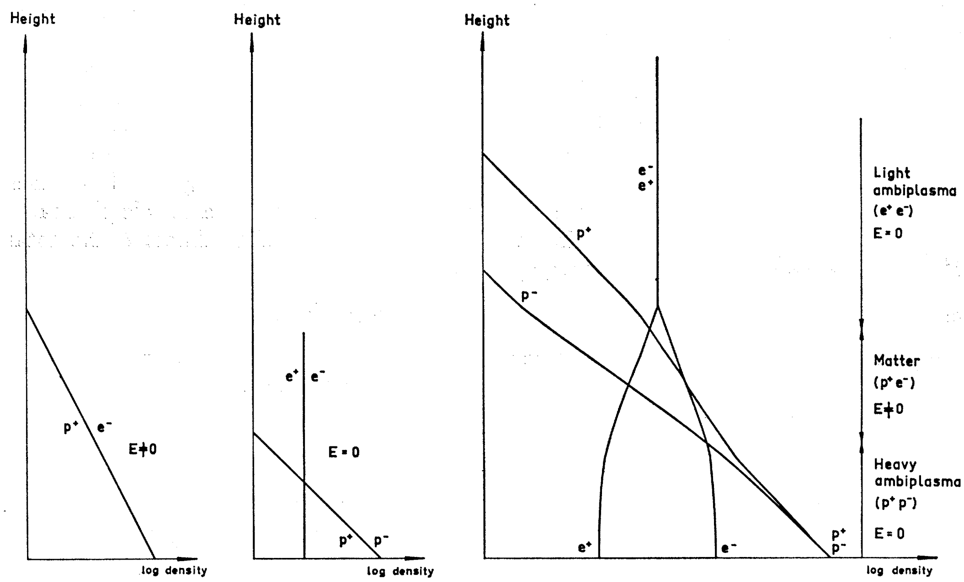
These four equations are combined with the quasi-neutrality condition

$$n_p^+ + n_e^+ = n_p^- + n_e^-. \quad \text{(II.25)}$$

The solution of the system of equations is easily found

TABLE II. Frequencies at energy maximum of the spectra and decay times for synchrotron radiation.

B	10^{-6}	10^{-5}	10^{-4} G
T_s	8×10^{10}	8×10^8	8×10^6 years
ν_{max}	10^5	10^6	10^7 cps



(a) (b) (c)

FIG. 1. Ambiplasma in a gravitational field. (a) Matter alone (or antimatter alone). (b) Symmetric anbiplasma. (c) Asymmetric ambiplasma.

to be

$$n_p^- = \tau_p^{-1}\{\nu_p^-\nu_p^+[1+(\nu_e^+/\nu_p^+)\tau_p]\}^{\frac{1}{2}}[1+(\nu_e^-/\nu_p^-)\tau_p]^{-\frac{1}{2}}, \quad \text{(II.26)}$$

$$n_p^+ = \tau_p^{-1}\{\nu_p^+\nu_p^-[1+(\nu_e^-/\nu_p^-)\tau_p]\}^{\frac{1}{2}}[1+(\nu_e^+/\nu_p^+)\tau_p]^{-\frac{1}{2}}, \quad \text{(II.27)}$$

$$n_e^- = \tau_e^{-1}\{\nu_e^-\nu_e^+[1+(\nu_p^+/\nu_e^+)\cdot\tau_p^{-1}]\}^{\frac{1}{2}} \times[1+(\nu_p^-/\nu_e^-)\cdot\tau_p^{-1}]^{-\frac{1}{2}}, \quad \text{(II.28)}$$

$$n_e^+ = \tau_e^{-1}\{\nu_e^+\nu_e^-[1+(\nu_p^-/\nu_e^-)\cdot\tau_p^{-1}]\}^{\frac{1}{2}} \times[1+(\nu_p^+/\nu_e^+)\cdot\tau_p^{-1}]^{-\frac{1}{2}}, \quad \text{(II.29)}$$

where $\tau_p = \exp(\mu_p \cdot z)$ and $\tau_e = \exp(\mu_e \cdot z)$, and ν means the value of n for $z=0$. We have neglected μ_e in comparison to μ_p.

If no antimatter is present ($\nu_p^- = \nu_e^+ = 0$), we have

$$n_p^+ = n_e^- = n \quad \text{(II.30)}$$

and

$$n = \nu/\tau_p^{\frac{1}{2}} = \nu \exp(-\tfrac{1}{2}\mu_p z).$$

A constant electric field

$$E = \tfrac{1}{2}(m_p g/e) \quad \text{(II.31)}$$

is produced. The gravitation does not separate the heavy and light component, but produces an electric field (the Rosseland field).

The same is the case for pure antimatter, but the electric field is reversed.

If the plasma contains equal amounts of matter and antimatter ("symmetric ambiplasma"), we find

$$n_p^- = n_p^+ = \nu_p/\tau_p = \nu_p \exp(-\mu_p z), \quad \text{(II.32)}$$

$$n_e^- = n_e^+ = \nu_e/\tau_e = \nu_e \exp(-\mu_e z). \quad \text{(II.33)}$$

The electric field is zero, and there is no coupling between the heavy component and the light component. The scale height of the electron–positron gas is 1840 times larger than the scale height of the proton–antiproton gas. The total number of protons–antiprotons is independent of the total number of electrons–positrons.

In an asymmeteric ambiplasma, which, for example, contains more matter than antimatter, there are typically three different regions. The lowest region and the highest region contain a symmetric ambiplasma with no electric field, but the intermediate region has a Rosseland field and contains almost no antimatter.

Almost all the antiprotons are accumulated in the lowest region together with an equal number of protons. Since we have assumed that in the whole volume there is more matter than antimatter, there is an excess of protons, and they occupy the intermediate region together with electrons. In the upper region practically all the positrons are accumulated together with an equal number of electrons.

Hence if we place an asymmetric ambiplasma (containing, for example, more matter than antimatter) in a gravitational field, it tends to split up into three different parts (see Fig. 1). The lowest part is a symmetric ambiplasma containing the heavy particles, the highest part is a symmetric ambiplasma containing the light particles. These are separated by a medium part in which almost all the excess of one component (in our example matter) is concentrated (see Table III).

In an ordinary plasma the positive ions and the electrons cannot easily be separated. Our analysis has shown that an ambiplasma is different in this respect. Under the action of gravitation, the light component

TABLE III. Parameter μ of the increase with height z defined by $n_0 \exp(\mu z)$. ( ) means that the percentage is small; (( )) means that the percentage is very small.

	Antiprotons	Protons	Electrons	Positrons	Electric field
Lowest region	$-\mu_p$	$-\mu_p$	$(-\mu_e)$	$((-\mu_e))$	0
Medium region	$(-\frac{3}{2}\mu_p)$	$-\frac{1}{2}\mu_p$	$-\frac{1}{2}\mu_p$	$(+\frac{1}{2}\mu_p)$	$\frac{1}{2}m_p g/e$
Highest region	$((-\mu_p))$	$(-\mu_p)$	$-\mu_e$	$-\mu_e$	0

has a tendency to separate from the heavy component. Moreover, if the ambiplasma contains an excess of either matter or antimatter, it has a tendency to separate this from the rest of the ambiplasma, and dispose it in a certain region. We have neglected magnetic fields. It is well known that a magnetic field does not change the equilibrium state of an isothermal atmosphere.

5. Separation of Matter and Antimatter

Gravitation alone cannot separate an initially symmetric ambiplasma (containing equal quantities of matter and antimatter) into matter and antimatter. However, in principle, this is possible under the action of electromagnetic effects [Alfvén and Klein (1962)].

In order to demonstrate this let us assume that in the symmetric ambiplasma considered in the preceding paragraph there is an electric current antiparallel to g. This will remove positive charge from the top of the atmosphere, and since the highest region contains mainly positrons and electrons, it is essentially the positrons that are removed. Simultaneously the current will remove negative charge from the base of the atmosphere, and since the lowest region contains mainly heavy particles, the result will be essentially a loss of antiprotons. Hence the current will remove antimatter, leaving an asymmetric ambiplasma with an excess of matter, and this will be located in the intermediate region.

Similarly, a vertical current parallel to g will cause an excess of antimatter. A vertical current may be produced by hydromagnetic effects which are caused by motion of magnetized ambiplasma during the development of the metagalaxy, or in connection with the formation of galaxies.

It may be objected that a process of this kind is in contradiction to the general laws of statistical mechanics, because it changes a state of disorder—matter and antimatter homogeneously mixed—into a state of higher order. This objection is not valid, because the ultimate source of energy is the gravitation of the whole system. Consider as an analogy water pouring down from a mountain. It is possible to convert its gravitational energy into electric energy by means of a hydroelectric plant, and the dielectric energy can be used to electrolyze part of the water and separate it into hydrogen and oxygen. Our process is similar. In fact, the separation of matter or antimatter out of a symmetric ambiplasma can be considered as a result of electrolysis. The quantity M of matter or antimatter which is separated by a current I flowing during a time T is

$$M=(M_H/e)IT \tag{II.34}$$

in agreement with the ordinary law of electrolysis.

A somewhat similar process has been described already in an earlier publication [Alfvén and Klein (1962)]. Also in this case a current flows perpendicular to the interface between a heavy ambiplasma and a light ambiplasma. At the interface, either matter or antimatter is accumulated, depending on the direction of the current.

As currents are normally produced in a moving magnetized plasma processes of these kinds should occur normally. However, the total quantity which can be separated in a certain closed-current circuit is limited. Suppose that a current $I=\pi r^2 i$ flows along the axis of a circular cylinder with radius r. The magnetic field at the surface of the cylinder is

$$B=2I/cr. \tag{II.35}$$

Combining this equation with (II.34) we obtain

$$\begin{aligned} M&=m_H TcrB/2e\\ &=0.5\times10^{-4}TrB. \end{aligned} \tag{II.36}$$

The magnetic fields in space are usually supposed not to exceed 10^{-5} or possibly 10^{-4} G. As the phenomena we discuss take place in regions where the energy density is large, the magnetic fields may also be large. The time T cannot reasonably exceed 10^{17} sec ($=3\times 10^9$ years). With $B<10^{-4}$ G and $T<10^{17}$ sec we obtain

$$M<0.5\times10^9 r \text{ g}. \tag{II.37}$$

Hence a separation in a galactic scale ($r=10^{23}$ cm) would not suffice to separate one solar mass.

The process is much more efficient in a small scale. If the medium has a density nm_p the mass is nm_pr^3. Hence a total separation can be obtained if

$$nm_pr^3=0.5\times10^{-4}TrB \tag{II.38}$$

or

$$r^2=[(0.5\times10^{-4}TB)/m_pn]=3\times10^{19}(BT/n). \tag{II.39}$$

The time T is limited by annihilation. Introducing T_0

from (II.11) we obtain

$$r = 0.63\times10^{17}B^{\frac{1}{2}}n^{-1}. \tag{II.40}$$

With $B<10^{-4}$ and $n=10^{-2}$ we obtain

$$r<10^{17}\ \mathrm{cm}$$

and $M<m_p n(10^{17})^3<10^{25}$ g.

Hence a "small scale" turbulence with elements of 0.1 light year or less may produce a high degree of separation between matter and antimatter. The mass separated by each turbulence element may not be very large, but the total mass may be a large fraction of the whole ambiplasma. Whether a separation in a galactic scale is possible should be regarded as an open question.

6. On the Coexistence of Matter and Antimatter

The average density in the metagalaxy is estimated to 10^{-6} particles cm^{-3}. According to Table I a homogeneous ambiplasma of this density has a very large lifetime. Within a galaxy the average density is of the order of one particle cm^{-3}. This means that if our galaxy consisted of homogeneous ambiplasma, it would have annihilated long ago. Antimatter can exist in a galaxy only if it is separated from matter. We discuss here the interface between matter and antimatter.

If in the kitchen a teaspoon of water is placed on a plate with a temperature somewhat above 100°, it evaporates very rapidly. However, if the plate is very hot the water may remain during five or ten minutes (especially if the plate is a little concave). The evaporation of the water produces a thin layer of vapor which isolates the water from the hot plate. In text books in physics the phenomenon is referred to as the "Leidenfrost phenomenon." In high temperature boilers it is of technical importance.

If matter and antimatter are brought together an analogous phenomenon may occur. At the interface between matter and antimatter annihilation produces a very hot layer which separates matter from antimatter in the same way as the water vapor in the Leidenfrost layer separates the water from the hot plate.

Let us consider the simple case when in a homogeneous magnetic field B in the z direction there is matter to the left of the surface $x=-\Delta/2$ and antimatter to the right of the surface $x=+\Delta/2$. The layer between $-\Delta/2$ and $+\Delta/2$ contains an ambiplasma. The three media are in hydrostatic equilibrium so that the gas pressure in all of them are equal. Since the pressure can be transferred between the media by electromagnetic forces, collisions between the particles are not essential.

In the annihilating ambiplasma, the gas pressure is essentially given by the 10^8-eV electrons and positrons which are produced by the p_+p_- annihilation. If we denote the number density of 10^8-eV particles by n_e and the gas pressure in the matter and antimatter regions by $p=n_0eV_0$ we have

$$n_e = n_0V_0/V \tag{II.41}$$

with $eV=10^8$ eV$=1.6\times10^{-4}$ erg. If we have $n_0=1$ particle cm^{-3} and $eV_0=1$ eV, which is typical in interstellar space, we obtain $n_e=10^{-8}$ cm^{-3}. The Leidenfrost layer must have a thickness of at least a few times, say ν times, the radius of curvature ρ of a 10^8-eV electron in the magnetic field B. Hence we obtain $\Delta\geq\nu\rho=\nu V/B$. The total number of electrons per unit surface is $N=\Delta\cdot n_e=10^{-8}\ \nu V/B$. With, for example, $\nu=10$ and $V=10^8$ eV$=0.33\times10^6$ esu and $B=10^{-5}$ G we obtain $N=3000$ particles cm^{-2}. Since according to Table II the particles must be renewed ones in 8×10^8 years due to new annihilation one γ photon per $8\times10^8/3000\approx0.3\times10^6$ years must be emitted. Hence the γ radiation from a Leidenfrost layer with the assumed properties is negligible. The radio emission is $3\times10^3\times10^8\times1.6\times10^{-12}\times(2.5\times10^{18})^{-1}=2\times10^{-17}$ erg cm^{-2} sec^{-1}. As a comparison it is possible to detect a flux of radio-wave energy if it exceeds 10^{-18} Wm$^{-2}=10^{-15}$ erg sec^{-1} cm^{-2} (see Sec. II.3). Hence, the radio emission from the layer we have considered is also negligible.

Our simple discussion has demonstrated that regions of matter and antimatter may coexist, separated by sheaths parallel to the magnetic field. At the boundary there is a thin layer of very hot ambiplasma which need not radiate with a detectable intensity. However, the stability of such a configuration is still an open question. Further, in the direction parallel to the magnetic field the separating layer cannot have the same structure. The geometry of the interface between matter and antimatter must probably be intimately connected with the shape of the magnetic field.

The annihilation in a Leidenfrost layer produces an apparent repulsion between matter and antimatter. Suppose that a small-scale separation process (of the kind discussed in Sec. II.5) has produced a number of small regions of matter intermingled with small regions of antimatter. Then there is a repulsion between the matter and the antimatter regions, but no repulsion between regions with similar content. It is possible that this may lead to the coalescence of the small regions to larger volumes of matter and antimatter. Hence possibly a small-scale separation process may ultimately result in large masses of pure matter and pure antimatter. A closer study of such processes is of fundamental importance to the understanding of the separation of matter and antimatter. However, a satisfactory theoretical analysis of this process is likely to be difficult and an experimental investigation cannot be made at present.

III. THE DEVELOPMENT OF THE METAGALACTIC SYSTEM

1. Contracting Sphere of Ambiplasma

To specify the "initial conditions" in more detail we consider a sphere containing a homogeneous mixture of protons and antiprotons [Alfvén and Klein (1962)].

We need not specify the temperature except that it must not be zero, because we shall consider collisions between protons and antiprotons. Further, since magnetic fields will be important, we can not allow the initial magnetic field to be zero. It may also be essential that there is a certain degree of turbulence initially.

Collisions between protons and antiprotons give rise to annihilation, resulting in electrons, positrons, and photons. We may assume that already in the initial state electrons, positrons, and photons are present, but this is not essential because these particles are in any case produced by annihilation.

Starting from a state of extremely low density the sphere contracts uniformly under the influence of its own gravitation which is proportional to the distance r from the center. At the beginning of the contraction, relativity effects may be neglected and the velocity of a particle at the distance r from the center will be given by the free-fall velocity

$$v=\eta r, \qquad \text{(III.1)}$$

where

$$\eta=\tfrac{2}{3}(t_0-t)^{-1}. \qquad \text{(III.2)}$$

The free-fall produces a variation in the density ρ which is easily found to be

$$\rho=(6\pi\gamma)^{-1}(t_0-t)^{-2}, \qquad \text{(III.3)}$$

where γ is the gravitational constant. The constant t_0 is the time at which all particles would reach the center if the contraction continued unchanged until that time.

During the contraction phase, electromagnetic radiation will be produced because of collisions between the electric particles of the cloud and also by the acceleration of the electrons in the magnetic field. Also, the radiation will be further increased by means of scattering by moving electrons. These sources of radiation are likely to be small compared to the annihilation and we shall, in this preliminary investigation, neglect them. The annihilation on the other hand will act as a radiation source, the density of which is constant within the sphere as long as the decrease in mass attributable to annihilation can be neglected. A constant radiation source produces a flux of radiation outwards from the center. (We neglect here the time needed to establish this state.) The radiation pressure stops the inward motion and converts it into the outward motion which according to Hubble characterizes the present state of the metagalaxy.

The energy production from proton–antiproton annihilation within the sphere of radius r is

$$P=(4\pi/3)r^3n_p2m_p(c^2/T_p)=(8\pi/3k_p)m_pc^3n_p^2\sigma_0r^3 \qquad \text{(III.4)}$$

(compare Sec. II, Eq. (II.6)), and the resulting stationary outward flow of momentum per cm^2 (neglecting the time lag in its establishment) is

$$F=P/4\pi r^2c=(1/6k_p)(c^2\rho^2\sigma_0/m_p)r. \qquad \text{(III.5)}$$

The annihilation results in mesons, neutrinos, and high-energy γ rays (from π^0 decay). After the π and μ decays there are about four $\pm$ electrons per annihilation process of around 100 MeV each. These will spiral in the magnetic field and emit synchrotron radiation until they annihilate under emission of γ rays. If all the energy flow F were carried by low-energy electromagnetic radiation, its pressure effect on the gas would be given by the Thomson cross section, $\frac{8}{3}\sigma_0$, of the electrons. However, for γ rays approaching 1 MeV, the cross section decreases by about one order of magnitude until above 10 MeV it increases again because of pair production. Further, a considerable fraction of the energy goes into neutrinos. Hence, if we put the force per electron equal to $f_e=\epsilon\frac{8}{3}\sigma_0F$, taking both these circumstances into account, we should expect ϵ to be between 0.1 and 1. With (III.5) this gives

$$f_e=(4\epsilon/9k_p)(\rho^2/m_p)\sigma_0^2c^2r. \qquad \text{(III.6)}$$

Because of the magnetic field this force is transmitted to the whole gas. Hence the radiation pressure subjects a volume element dV at the distance r from the center to the outward force $f_r dV$, where

$$f_r=(8\epsilon\rho^2n_e/9k_pm_p)\sigma_0^2c^2r. \qquad \text{(III.7)}$$

This force opposes the gravitational force per unit volume

$$f_g=-\gamma(4\pi/3)\rho^2r, \qquad \text{(III.8)}$$

and we get the following equation of motion:

$$\rho[(\delta v/\delta t)+(\delta v/\delta r)]=f_r+f_g, \qquad \text{(III.9)}$$

where v is the radial velocity taken positive in the outward, and negative in the inward, direction. We put again $v=\eta r$ with η independent of r. Hereby η is given by (III.2) for early times and should go over to the Hubble parameter for t=present time. With (III.7) and (III.8) we get

$$\dot{\eta}+\eta^2=\tfrac{4}{3}\pi\gamma\rho[\tfrac{2}{3}\pi(\epsilon/k_p)(c^2d^4/\gamma m_p)n_e-1]. \qquad \text{(III.10)}$$

To this equation we have to add the equation determining the change of ρ caused by the added effects of the motion and the annihilation and the corresponding equation for the change of n_e with time. Before coming to this we shall introduce the following convenient units. (These units were introduced by Klein in connection with his interpretation of the Eddington relations and were later seen to fit the annihilation processes as well.)

Length:	$c^2d^2/\gamma m_p=6.3\times10^{26}$ cm.	(III.11)
Time:	$cd^2/\gamma m_p=6.7\times10^{8}$ year.	(III.12)
Mass:	$c^4d^2/\gamma^2m_p=8\times10^{54}$ g $=4\times10^{21}M_{\text{sun}}$.	(III.13)
Mass density:	$\gamma m_p^2/c^2d^4=3.2\times10^{-26}$ g/cm^3.	(III.14)

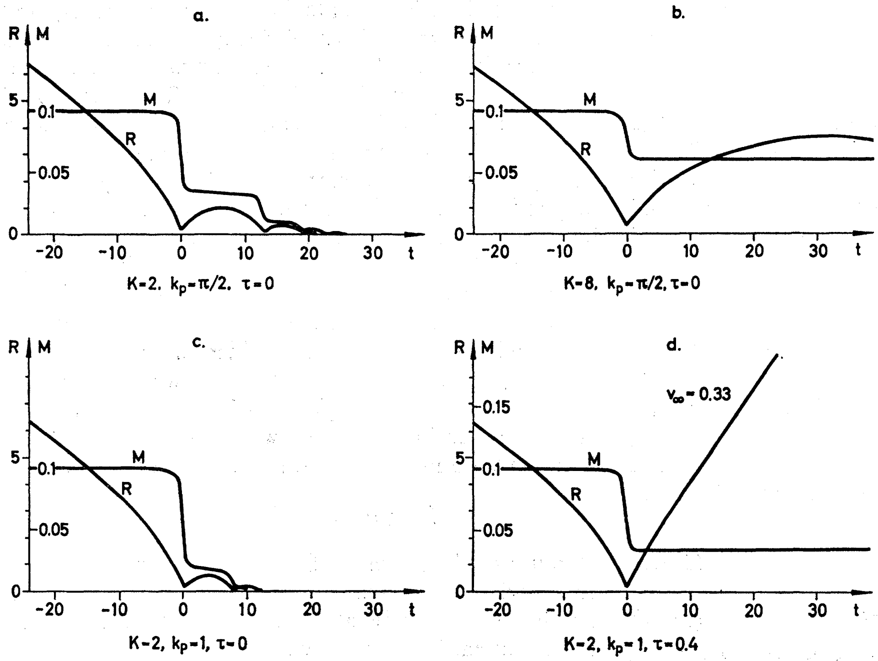


Fig. 2. Time variation of the radius R and mass M of the metagalaxy for different values of the constants K, k_p, and τ. K is proportional to the ratio between the force due to radiation pressure and the gravitational force; k_p is proportional to the annihilation cross section for protons. The constant τ is the time delay. Units: time, 6.7×10^8 year; length 210 Mpc; mass, $4\times10^{21}M_{\text{sun}}$. The figures show how an initial contraction can change into an expansion. Parameter values: (a) $K=2$, $k_p=\pi/2$, $\tau=0$; (b) $K=8$, $k_p=\pi/2$, $\tau=0$; (c) $K=2$, $K_p=1$, $\tau=0$; (d) $K=2$, $k_p=1$, $\tau=0.4$.

Further, we use as unit for particle density the corresponding unit for mass density divided by m_p, which gives

$$\text{Particle density: } \gamma m_p/c^2d^4 = 1.9\times10^{-2}\ \text{cm}^{-3}. \qquad \text{(III.15)}$$

Giving the earlier notations to the dimensionless ratios between the respective quantities and the corresponding units, Eq. (III.10) takes the form

$$\dot{\eta}+\eta^2=\tfrac{4}{3}\pi(\tfrac{2}{3}\pi(\epsilon/k_p)n_e-1), \qquad \text{(III.16)}$$

and the equation for the time change of ρ is given by

$$\dot{\rho}=-3\eta\rho-(\pi/2k_p)\rho^2. \qquad \text{(III.17)}$$

For the time change of n_e we get, similarly,

$$\dot{n}_e=-3\eta n_e-(\pi/k_e)n_e^2+(\pi/2k_p)\rho^2, \qquad \text{(III.18)}$$

the last term representing the electrons created by proton annihilation. When the inward motion is braked, the kinetic energy is converted into increased radiation. This means that f_r should be larger.

2. Discussion of the Equations

In the derivation of the equations (III.16), (III.17), and (III.18) some simplifying assumptions have been made, and some of these may introduce errors. The scattering of the radiation has been neglected. When the outward flow of energy is scattered back by inward moving particles, a Doppler shift takes place and part of the kinetic energy of the particles is transferred into radiation energy. This effect can be taken into account to some extent by increasing the value of ϵ (=efficiency of radiation pressure).

A difficult point in the theory is the value of the magnetic field B. The synchrotron radiation from the high-energy electrons and positrons depends on B, and hence the value of k_e is influenced. Moreover, there is a time delay between the annihilation and the radiation pressure which depends on B. To this time delay should be added the time delay due to the finite finite velocity of light.

Further, if we want to compare the model with the actual metagalaxy we must also take into account that the real metagalaxy is far from homogeneous. At a rather early state of development, a condensation into galaxies, and into stars, takes place, connected with separation of matter and antimatter. This affects the rate of annihilation, and also the efficiency of the radiation pressure.

Our discussion has shown that even if the calculation can be refined very much, we will still be left with a number of uncertain parameters. Therefore, if we want to integrate the equations in order to compare the theory with observations, the best way seems to be to carry out the integrations for a number of values of the parameters.

3. Integration of the Equations

Bonnevier (1964) has integrated the equations numerically with a number of values of the following three parameters:

$$K=\frac{2\pi\epsilon}{3k_p}\left(\frac{k_e}{4k_p}\left\{1+\left[1+\left(\frac{8k_p}{k_e}\right)\right]^{\frac{1}{2}}\right.\right) \qquad \text{(III.19)}$$

is essentially a measure of ϵ. The second parameter k_p is defined above. The third parameter is τ, by which he denotes the time delay between the annihilation and the force excerted on the electrons.

Some of Bonnevier's results are shown in Fig. 2. The solutions are of two different types. In (a) and (c) the metagalaxy shrinks indefinitely with a superimposed oscillation. Almost all the ambiplasma is finally annihilated. In (d) the inward motion is transferred to an outward motion with finite velocity and finite mass for $t \rightarrow \infty$. There is also an intermediate case, close to the solution depicted in (b) when, for very large values of t, the outward velocity goes to zero and the mass to a finite value.

Since at present our metagalaxy is expanding we must be situated somewhat to the right to the minimum of the radius R of the metagalaxy. Since (d) probably best fits the real condition, we have to assume that the set of parameters have such value as to give this type of solution.

4. Comparison with the Expanding Universe Theory

Like the expanding universe theory, Klein's theory accepts, of course, the interpretation that the galactic red-shift is a Doppler effect. The extrapolation to future times is somewhat similar in both theories. The extrapolation backwards is also similar for a certain interval of time, but whereas the expanding universe theory accepts an extrapolation to a very small radius (almost zero in our scale), this theory claims that there has been a turning produced by the radiation pressure. At the turning point the density was higher than the present average density, but only by a few orders of magnitude.

5. Calculation of the Average Density in the Metagalaxy

The maximum density of the sphere occurs a little before the minimum size is reached. The maximum particle density is $n_{\max}=\rho_{\max}/m_p$. From our equations we find

$$n_{\max}=A(\gamma m_p/c^2d^4)=A(\gamma m_p m_e^4 c^6/e^8)$$
$$=1.9\times10^{-2}A \text{ cm}^{-3} \quad \text{(III.20)}$$

where A is a constant which for Bonnevier's curves in Fig. 2 varies, between 0.5 and 1.6.

The present average density in the metagalaxy is estimated to be 0.3–3×10^{-30} g cm^{-3} [see McVittie (1961)] which means $n=0.2$–2×10^{-6} cm^{-3} which is four or five orders of magnitude less than the theoretical maximum. As according to the general picture we should have passed the turning point and be moving outwards we should expect the present average density to be considerably less than the maximum density.

6. Calculation of the Hubble Parameter

In a similar way we can calculate the Hubble parameter η_H. The value of η varies during the development of the system. At the turning point it is zero but shortly afterwards it reaches a maximum, later decreasing asymptotically to zero. We find for the maximum value

$$\eta_{\max}=B(\gamma m_p/cd^2)=B(\gamma m_p m_e^2 c^3/e^4)$$
$$=1.7\times10^{-9}B \text{ year}^{-1}, \quad \text{(III.21)}$$

where B is a constant, which in Bonnevier's curves varies between 0.9 and 1.9. When the maximum is passed, the value of η decreases rapidly. Since $\eta=v/R$ this depends in part on the deceleration of the outward velocity due to gravitation, but the major part is due to the increase in R.

The observational value of the Hubble parameter is of the order

$$\eta_H=10^{-10} \text{ year}^{-1}. \quad \text{(III.22)}$$

This value is smaller than the theoretical maximum by one power of ten, corresponding to a value which is reached some time after the maximum.

7. Correlation between the Average Density and the Hubble Parameter

Neglecting the change in outward velocity and the time difference between the turning and the maximum in η, we find the following relation between the present value η_H and the maximum value $\eta_{\max}$:

$$\eta_H=\eta_{\max}(R_0/R), \quad \text{(III.23)}$$

where R/R_0 is the ratio between the present size R of the metagalaxy and the size R_0 at the turning point. For the present density θ we obtain

$$\theta=\theta_{\max}(R_0/R)^3, \quad \text{(III.24)}$$

where $\theta_{\max}$ is the maximum density (at the turning). From (III.23) and (III.24) we obtain the following approximate relation between the θ and η_H:

$$\theta/\eta_H^3=\theta_{\max}/\eta_{\max}^3. \quad \text{(III.25)}$$

According to the theory of Secs. III.5 and III.6 the maximum value of η_H should be of the order of the inverse value of the time unit given by (III.12), and $\theta_{\max}$ of the order of the mass density unit given by (III.14). Hence we obtain from (III.12) and (III.14)

$$\theta/\eta_H^3=(\gamma m_p^2/c^2d^4)(cd^2/\gamma m_p)^3 \quad \text{(III.26)}$$

or

$$\theta/\eta_H^3=cd^2/\gamma^2 m_p=0.32\times10^{24} \text{ g sec}^3 \text{ cm}^{-3}.$$

The observational values are: $\theta=3$–30×10^{-31} g cm^{-3}, $\eta_H=100$–150 km/M parsec$=3.2$–4.8×10^{-18} sec^{-1}, giving

$$10^{22}<\theta/\eta_H^3<10^{23}$$

which is not very far from the theoretical value.

IV. ON THE EXISTENCE OF ANTIMATTER

1. Antimatter Stars and Antimatter Galaxies

As we have seen in Sec. III the theory leads to values of the average density and of the Hubble constant which are in reasonable agreement with the observational values. In Sec. II it was shown that there is no observational evidence which excludes the existence of antimatter. In this section we discuss the existence of antimatter more in detail.

First it should be pointed out that even if it could be proved that there is no antimatter in the metagalaxy, essential parts of our model may still be correct. If we assume that the initial plasma contains for example 60% matter and 40% antimatter, then the development of the metagalaxy should occur in approximately the same way as described above. At the maximum density near the turning point most of the antimatter would be annihilated together with an equal quantity of matter, and the rest—if any—would disappear in a similar way when later condensations into galaxies took place. Hence we would be left with a metagalaxy containing only matter and with a total mass of $60-40=20\%$ of its original mass. A theory along these lines would compete favorably with other cosmologies, but it does not satisfy our postulate about the complete symmetry between matter and antimatter. We shall not discuss it further.

There is obviously no antimatter on the Earth. We also know that the Moon does not consist of antimatter because the space vehicles which have landed on it have not produced very conspicuous phenomena. The Sun emits plasma which reaches the Earth during magnetic storms and aurora, and since no conspicuous annihilation phenomena occur, we can also be sure that the sun consists of ordinary matter. The same is very likely the case for all bodies in the solar system.

Hence if the solar system has originated during the development of the kind we have studied, there must have been a separation of matter and antimatter so that we should expect to find the antimatter somewhere else in the metagalaxy.

The question whether the stars we observe consist of matter or antimatter cannot be decided with certainty. There is a general belief that they consist of matter, but no proof exists. As discussed already in Sec. I.2, an analysis of the light emitted from a star cannot decide whether a certain star consists of matter or antimatter. Comets or meteoric matter approaching us from very long distances are moving in elliptic or parabolic orbits, and not a single case of hyperbolic orbit is known with certainty.

No definite conclusion can be drawn from an analysis of cosmic radiation as shall be shown in Sec. 3.

Thus if we claim that every second star we observe in the night sky consists of antimatter, it is at present impossible to prove it, but it is equally impossible to disprove it. The claim would be in agreement with our postulated matter antimatter symmetry, but it is no necessary consequence to it, because there is a possibility that every galaxy contains either matter or antimatter. In this case our galaxy may consist exclusively of matter, but we cannot avoid the conclusion that every second of the galaxies we observe consists of antimatter.

2. On the Possiblity of Detecting Antimatter

As already mentioned in the first section it is impossible to decide by spectroscopic analysis whether a celestial object consists of matter or antimatter. An ambiplasma manifests itself primarily by the emission of radio waves, but it does not necessarily emit any detectable γ rays. Hence all radio stars may in principle derive their energy from annihilation. However, as shown in Table II, the emission should preferably occur at rather low frequencies unless the magnetic fields are extremely strong. Since high-energy electrons can be produced also in other ways, the radio stars are no certain indications of the existence of antimatter.

Some celestial objects, e.g., the quasars seem to emit such enormous quantities of energy that it is unlikely that nuclear reactions suffice for its generation. In some cases total annihilation of matter and antimatter may be the only possible energy source.

The very sudden release of an enormous amount of energy in a supernova has not yet been explained in a satisfactory way. If antimatter stars exist a collision between an antimatter and a matter star may be the cause of a supernova.

3. Cosmic Radiation and Antimatter

Cosmic radiation is usually supposed to be accelerated by electromagnetic processes in space. If part of the cosmic radiation we receive is generated in an antimatter region, this part should consist of antiprotons.

The low-energy part of cosmic radiation contains definitely no antiprotons. According to Peters (private communication) this holds up to 10^{12} eV. It is impossible to decide at present whether the primaries exceeding 10^{12} eV contain any antiprotons or not.

It is usually assumed that the interstellar magnetic field is of the order 10^{-6}–10^{-5} G. In a field of, say, 3×10^{-6} G, a 10^{12}-eV proton has a Larmor radius of 10^{15} cm $=10^{-3}$ light-year. If we denote by L the distance to the closest antimatter region in which cosmic rays are generated, we can be sure that $L>10^{15}$ cm, but this does not tell us very much because this distance is of the order of the planetary system and we have no reason to suppose that it should contain any antimatter. Taking into account that the cosmic rays diffuse in interstellar space we can certainly increase the value of L by some orders of magnitude, but it is a matter of controversy by how many. It is possible that the diffusion length carries us to the closest stars

($L \approx 4\times10^{18}$ cm) in which case we may conclude that these do not consist of antimatter—but this is not at all certain.

In any case there is no reason for assuming that the low-energy cosmic rays ($<10^{12}$ eV) originate outside our galaxy, so cosmic-ray evidence does not exclude that other galaxies contain antimatter or consist of it.

4. Matter–Antimatter Separation and the Formation of Galaxies

During the development of the metagalaxy the formation of galaxies should occur. This process may be a result of a gravitational instability in the metagalactic medium. As the instability of the medium increases with increasing density, galaxies should be formed especially when the medium has a maximum density which occurs somewhat before the time of the turning.

It is possible that the galaxies are formed after the separation of matter and antimatter. In this case each galaxy may contain either matter or antimatter. However, as shown in Sec. II.5, there is some difficulty in finding a large-scale process, whereas small-scale processes are more easy to imagine. Hence we would expect that the conditions for separation should be more favorable in condensations like galaxies than in the more homogeneous state before the galaxy formation has started. This means that if the process of Sec. II.5 is the main separation process we should rather expect every galaxy to contain both matter and antimatter. This is not in conflict with any observations.

There are different ways in which the matter and antimatter may be distributed if they coexist within a galaxy. One possibility is that the distribution is at random, so that in every part of the galaxy every second star consists of antimatter. If this is true, the separation should be a rather late process, taking place when the general structure of the galaxy is already given.

Another possibility is that the separation of matter and antimatter is connected with the general structure of galaxies. Suppose that the ambiplasma which is forming a galaxy contains an excess of, for example, matter. According to Sec. II.4 (see Fig. 2), we should expect that under the action of gravitation such an ambiplasma separates into three regions: a central region containing heavy ambiplasma, which we may identify with the nucleus of a galaxy; an intermediate region containing matter alone which we may identify with the region in which we live; and the outermost region containing light ambiplasma (electrons and positrons) which we may identify with the galactic halo emitting radio waves. In the nucleus, a separation of matter and antimatter takes place later so that it is saved from complete annihilation.

An alternative is that the initial plasma forming the galaxy contains equal parts of matter and antimatter, but that at an early time matter is enriched in one half of the galaxy and antimatter in the other half. Again the nucleus should consist of heavy ambiplasma. Of the two spiral arms of galaxies one should consist of matter and the other of antimatter. The galaxy should be surrounded by two clouds of light ambiplasma in some cases manifesting themselves as two radio stars, a configuration which is common.

Finally it should be remembered that the turning from contraction to expansion of the metagalaxy should be produced by the pressure of the annihilation radiations. At the turning point the metagalaxy was essentially opaque to the radiation. This is of course not the case at present because the density has decreased by about four powers of ten. Hence most of the radiations have escaped from the metagalaxy. The annihilation within the metagalaxy has decreased very rapidly due to the expansion and also because of the separation of matter and antimatter. We should expect to see synchrotron radiation from the distant parts of the metagalaxy, because we observe there what happened at an early time.

V. ARE THERE FOREIGN METAGALAXIES?

According to Klein there may be other metagalaxies in the universe. Our metagalaxy is supposed to have originated because of gravitational instability of a homogeneous ambiplasma filling a volume many orders of magnitude larger than our metagalaxy. In this medium there may be other regions in which metagalaxies are formed. The large scale geometry may be essentially Euclidean and the universe infinite both in space and time. However, during the development of a metagalaxy the gravitational potential may be so large that the geometry locally becomes strongly non-Euclidean. This occurs especially at the turning point where the gravitational red-shift may become very large, which means that we approach the Schwarzschild limit.

Hence in some respect we are facing a revival of the type of universe considered by Charlier (1908 and 1921). According to him the universe may be infinite in space and time and also the total mass may be infinite, but still the average density zero. As Charlier has shown, this is possible if there is an infinite series of systems of increasing magnitude.

It is interesting to discuss whether foreign metagalaxies could be observed and, if so, how they would look when seen from outside.

When a metagalaxy is in the early state of contraction it consists of an enormous mass of ambiplasma. At the annihilation, γ rays and synchrotron radiation are emitted. If both kinds of radiation reach us without absorption, the latter would be by far the more easily detected. The frequency is determined by the magnetic field, about which we know very little. It is possible that the maximum energy is emitted at rather low frequencies (e.g., with an order of magnitude of much less than one megacycle).

When the metagalaxy approaches its state of maximum density the emitted energy increases, and if the magnetic field becomes stronger—as is likely—the frequency also increases. At the same time, the formation of galaxies is likely to start and also the formation of stars in the galaxies. This process results in optical emission, which grows until the metagalaxy reaches about the present state of our metagalaxy. The last phase consists in a general dispersion of the galaxies when the whole metagalactic system expands.

Near the turning point, the rate of energy P developed by annihilation is of the order

$$P=Mc^2/\tau=8\times10^{54}(3\times10^{10})^2/2\times10^{16}$$
$$=4\times10^{59}\text{ erg/sec}=10^{26}P_{\odot},$$

where the unit values of Sec. III.1, have been introduced for the metagalactic mass and time scale. $P_{\odot}$ means the energy/sec radiated from our sun.

As a comparison, we receive from a strong radio source an energy flux of 10^{-11} erg cm^{-2} sec^{-1}, which would correspond to a source emitting 10^{59} erg/sec at a distance of 10^{35} cm$=10^{17}$ light years.

However, a very large fraction of the released energy will be absorbed in the metagalaxy itself. In fact, the turning is supposed to be because of the radiation pressure. Further, a metagalaxy near the turning is more or less separated from the external world by relativistic effects, so that only a very small fraction of the released energy will leak out.

Moreover, especially during the early time of development, the main part of the synchrotron radiation may be emitted at so low frequencies that it does not pass the ionosphere. Hence it can be observed only from spacecraft. However, even the interstellar medium may absorb, or completely cut out, the radiation. In fact, an interstellar density of 1 electron cm^{-3} corresponds to a plasma frequency of 10^4 sec^{-1}, and no radiation of lower frequency can pass.

If we observe a foreign metagalaxy in the same state of development as our own, its surface brightbess should be about the same as the average night sky light λ_0 we receive from our own metagalaxy outside our galaxy, i.e., the surface brightness of the sky, if we smear out all the extragalactic objects. It would be difficult to observe such an object. At the turning point the mass density of a metagalaxy is about 10^3 or 10^4 of the present density in our metagalaxy. Supposing that the total star-light emission is the same, the surface brightness would be $10^2\lambda_0$ or $10^3\lambda_0$. If the metagalaxy contains 10^{10} galaxies, it would look like a galaxy if its distance were 10^5 times larger than the distance to the galaxy. This means that a metagalaxy would be observable optically if its distance is less than 10^{14} light years. However, very close to the turning even the optical light would not leak out.

From what has been said it is evident that there are certain difficulties in observing a foreign metagalaxy. At an early state of development it would emit mainly radio waves of a very low frequency which may be cut off by the interstellar plasma near us. At a late state of development, its surface brightness would not exceed the surface brightness of our own metagalaxy, and hence be difficult to observe. The enormous release of annihilation energy near the turning point should be detectable if the metagalaxy is not too far away, but relativistic effects cut off the metagalaxy during part of this period.

The Doppler shift Δ of a spectral line emitted from a star in a foreign metagalaxy consists of four parts:

$$\Delta=\Delta_c+\Delta_g+\Delta_r-\Delta_g^0,$$

where Δ_c is the shift resulting from the contraction or expansion of the metagalaxy, Δ_g is the gravitational red shift due to the gravitational potential in the foreign metagalaxy, Δ_r derives from the relative motion between the center of gravity of the foreign metagalaxy and our sun, and finally Δ_g^0 corresponds to the gravitational potential of our sun due to its position inside our own metagalaxy.

Since a foreign metagalaxy is observable only close to its turning point, it is likely that Δ_c is rather small. Further Δ_g must be much larger than Δ_g^0 because our metagalaxy is already rather far from its turning. Hence the Doppler shift is approximately

$$\Delta=\Delta_g+\Delta_r.$$

We know nothing about Δ_r. The value of Δ_g depends on the time distance from the turning point. Close to the turning point there would be a very strong gravitational red shift.

SUMMARY

The complete symmetry between elementary particles and antiparticles suggests that the universe contains equal quantities of matter and antimatter.

There is no observational evidence that all celestial bodies consist of matter, and every second object may well consist of antimatter. Very thin layers in which matter and antimatter mix may separate matter and antimatter regions.

The properties of an "ambiplasma" (containing ionized matter and antimatter) are analyzed. It is shown that a magnetized ambiplasma should emit *synchrotron radiation but no detectable γ radiation.* It is possible that some—or perhaps all—radio stars contain ambiplasma and that their energy derives from annihilation.

Under the combined action of gravitation and electromagnetic forces an ambiplasma may be separated into matter and antimatter.

Note added in proof. An interesting method of detecting an ambiplasma has recently been suggested by N. A. Vlasov (1965).

The radio spectrum emitted from an annihilating magnetized ambiplasma has recently been calculated by Bonnevier, Ekspong, and Yamdagni. The spectrum seems to agree reasonably well with some common types of spectra from radio stars (private communication).

ACKNOWLEDGMENTS

I wish to thank Professor Klein for introducing me to his cosmological theories and for drawing my attention to the importance of studying the properties of an ambiplasma.

Dr. B. Bonnevier and I have collaborated and he has kindly helped me with many calculations. Mrs. Gun Giuli has assisted in preparing the manuscript.

REFERENCES

Alfvén, H. and C-G. Fälthammar, 1963, *Cosmical Electrodynamics* (Oxford University Press, Oxford), 2nd ed.

——, and O. Klein, 1962, "Matter–Antimatter Annihilation and Cosmology," Arkiv Fysik **23**, 187–194.

Alpher, R. A. and R. Herman, 1958, "On Nucleon–Antinucleon Symmetry in Cosmology," Science **128**, 904.

Bonnevier, B., 1964, "On the Early Development of the Metagalactic System," Arkiv Fysik **27**, 310.

Charlier, C. V. L., 1908, "Wie eine unendliche Welt aufgebaut sein kann," Arkiv f. Matematik, Astronomi och Fysik **4**, 24.

——, 1921, "How an Infinite World May Be Built Up," Arkiv f. Matematik, Astronomi och Fysik **16**, 22.

Goldhaber, M., 1956, "Speculations on Cosmogony," Science **124**, 218.

Klein, O., 1953, *Les processus nucléaires dans les astres* (Société royale des sciences de Liège), pp. 42–51.

——, 1958, *La structure et l'évolution de l'univers* (Institut international de physique Solvay, Bruxelles), pp. 33–51.

——, 1961, "Einige Probleme der allgemeinen Relativitätstheorie," in *Werner Heisenberg und die Physik unserer Zeit* (Braunschweig), pp. 58–72.

——, 1962, "Mach's Principle and Cosmology in Their Relation to General Relativity, in *Recent Developments in General Relativity* (Pergamon Press Ltd., Oxford, and Polish Scientific Publishers, Warsaw), pp. 293–302.

Kraushaar, W., G. W. Clark, G. Garmire, H. Helmken, P. Higbie, and M. Agogino, 1965, Astrophys. J. **141**, 845.

McVittie, G. C., 1961, Fact and Theory in Cosmology, London.

——, 1961, Problems of Extragalactic Research, *IAU Symposium* 15, p. 441.

Ryle, M., 1963, *Development in Radio Source Work Since 1960*, Intern. lecture Commission V, URSI, Tokyo.

Vlasov, N. A., 1965, "Optical Search for Antimatter in the Universe," Astron. Zh. **41**, 893 (1964) (English transl.: Soviet Astron.—AJ **8**, 715).