23 May 1969, Volume 164, Number 3882 **SCIENCE**

Antimatter, Quasi-stellar Objects, and the Evolution of Galaxies

The "symmetric cosmology" leads to a theory of quasars and a basic understanding of the evolution of galaxies.

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The discussion about the possible existence of antimatter, which essentially was initiated by Klein's work, has indicated that there are very few physicists who explicitly claim that the universe is asymmetric in the sense that it contains koinomatter (that is, ordinary matter) but no antimatter. Most physicists seem to agree that there should be equal quantities of the two kinds. There are no decisive arguments for this view, which indeed is essentially based on philosophical or esthetic feelings. But to most people these seem to be more compelling, in the cosmological discussion, than ordinary physical arguments.

An interesting aspect of the antimatter problem is the following. The only known way of producing a number of koinonucleons (protons or neutrons) is by processes which generate the same number of antinucleons (antiprotons or antineutrons). Hence, a few of all the koinonucleons we know—those produced in accelerators—are generated in pairs with antinucleons. But how have the rest of the koinonucleons—those which constitute ordinary matter—been produced? We have three alternatives.

1) We can postulate that there exists another process by which they were "created," at the time of a "big bang" or on some other occasion. This means that we introduce a new law of nature.

2) We can assume that they are "eternal," which means that we place their "creation" at the time $-\infty$.

3) If we do not want to postulate any new laws of nature, we have to assume that all the common nucleons are produced in pairs with antinucleons, by essentially the same kinds of processes as those we know from accelerator experiments. This means that the particles which constitute our ordinary matter were produced at an early stage in the development of the universe (or of our part of the universe) under physical conditions very different from the present ones. This implies that there was a prematter state, where energy was available in such a form that pair production of koinonucleons and antinucleons could take place.

The "symmetric" approach to cosmology should be regarded as an attempt to see how far we can go without introducing any new laws of nature (*1, 2*). As we have seen, this means that we accept the assumption that all the koinonucleons we know were once produced in pairs with antinucleons. We accept a pre-matter state, but no new laws of nature. From this it follows that the start of the present matter state of the universe (or our part of it) must be a homogeneous mixture of koino- and antimatter. It does not make sense to start from a state in which all the antimatter is located in one (distant) part of space and all the koinomatter is located in our region, because —unless we introduce new laws of nature—we must then specify the processes by which the koinonucleons and antinucleons were separated after production of the pairs.

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The Big-Bang Theory

The symmetric approach seems irreconcilable with the "big-bang" theory, because a homogeneous mixture of matter and antimatter having the density required by the big-bang theory would result in immediate annihilation. The expanding universe should consist of rapidly decaying mesons, neutrinos, γ-photons, electrons, and positrons, but it should contain very few nucleons. Although the advocates of the big-bang theory have never explicitly stated it, their universe is necessarily asymmetric in the sense that it contains koinomatter but no antimatter. It is important to bring this issue into the cosmological discussion.

Antimatter in Our Galaxy

In principle the requirement of koinomatter-antimatter symmetry in the universe could be satisfied if all the antimatter were located in one (distant) part of the universe and all the koinomatter, in our part of the universe. This is the view most people adopt if, on the one hand, they do not deny the general symmetry in the universe but, on the other hand, they do not want considerations about antimatter complicating their problems. As a representative form of such views we could take the idea that every second galaxy —among them, for example, the Andromeda nebula—consists of antimatter, whereas every second galaxy, including our own, consists exclusively of koinomatter.

There are two alternative requirements for accepting this view.

1) We may introduce a new law of

nature according to which the Andromeda nebula was "created" out of antimatter whereas our own galaxy was "created" out of koinomatter. This alternative is irreconcilable with our general approach.

2) From an initially homogeneous mixture there has been a large-scale separation associated with a transportation of koinomatter to our galaxy. Our galaxy consists of this koinomatter, or of an excess of koinomatter that was left after a koinomatter-antimatter burnout. In a similar way antimatter was concentrated in the Andromeda nebula. Such a process would have had to take place before the galaxies formed, because it is difficult to believe that a large-scale exchange of matter between the galaxies could take place after they had formed. The required process would mean a systematic transport of koinomatter in one direction and of antimatter in the other over distances of the order of a million light-years. The driving force of the process would have had to be at work before the galaxies formed. Whereas small-scale separation is possible, it is indeed very difficult to believe that a large-scale process fulfilling these requirements could have taken place.

As neither of the alternatives is acceptable, we must draw the following conclusions.

The symmetric approach to cosmology—without the assumption of any ad hoc laws of nature—leads necessarily to the conclusion that there should be antimatter in our galaxy as well as in all galaxies. Presumably one half of the mass of a galaxy should consist of koinomatter and the other half, of antimatter.

A Theory of Galactic Evolution

The annihilation of even a small fraction of the koinomatter-antimatter in a galaxy releases very large energies. Hence it is obvious that the presence of both kinds of matter in a galaxy will be of fundamental importance to the evolution and structure of the galaxy.

One may think that we know so much about the structure of our own galaxy that we can immediately exclude the presence of antimatter inside it. The result of the last few years' discussion seems to be that the antimatter idea perhaps comes in conflict with various current speculations, but not with any well-established theories, still less with any observational facts. On the other hand no decisive argument for the existence of antimatter exists. However, the need for very large energy sources is obvious. For example, the ejection of matter from galactic nuclei, as studied by Ambarcumjan (*3*) and others, may require such large energies that only annihilation suffices.

Here we propose a theory about the role of antimatter in the evolution of galaxies. The essence of the theory is as follows.

1) A galaxy is formed as a body consisting of "ambiplasma," by which we mean a mixture of koinomatter and antimatter. In the section entitled "Model of a Protogalaxy" we show that such a body is subject to two limitations: (i) it must have enough mass to allow gravitation to keep it together; (ii) condensation must start at a density low enough to prevent rapid annihilation of the ambiplasma.

We show that, in order to satisfy these requirements simultaneously, an ambiplasma body must have a linear dimension and a mass which, in order of magnitude, are equal to or larger than the average linear size and mass of a galaxy. Because of irregularities in the shape and density of the ambiplasma cloud as it starts to condense from the surrounding medium, clouds of too large dimensions will probably fragment into a number of bodies each of which has a mass of the same order of magnitude as a large galaxy. Hence we identify such an ambiplasma body with a protogalaxy.

2) For the formation and first stages of evolution of a protogalaxy, the following processes should be of importance. (i) A small-scale separation of koinomatter and antimatter is produced by processes, for example, of the kind discussed elsewhere by Alfvén [see (*1*) and (*2*)]. The small-scale regions later coalesce into larger regions. (ii) An essential part of the ambiplasma becomes separated and the koinomatter and antimatter are collected in, probably, a large number of cells, each containing only one kind of matter. The cells are separated by reasonably stable "Leidenfrost" layers (*4*). In the separated regions, stars form. (iii) Nonseparated parts of the ambiplasma annihilate. Newly formed stars of opposite kinds of matter may collide, and such collisions will release large quantities of energy. The proton-antiproton annihilation produces neutrinos, γ-rays, and 100-Mev electrons and positrons. Annihilation is the main source of energy for the observed activity in the newly formed galaxies. (iv) The protogalaxy has a general magnetic field. The electron-positron gas, which is very little affected by gravitation, moves out in two opposite directions, given by the magnetic field (which itself will be modified by the outstreaming ambiplasma). The spiraling of the relativistic particles, of which the gas consists, produces radio emission. In this way a double radio source is produced. The two components contain equal amounts of electrons and positrons.

3) After some billions of years the nonseparated parts are burned out and the separated parts have become stabilized. The energy release—the "activity" of the galaxy—decreases and is mainly located in the nucleus, where collisions still occur. In this way the protogalaxy develops by way of quasi-stellar objects, N-type galaxies, Seyfert galaxies, and ordinary radio galaxies into our normal galaxies.

During certain stages of the evolution from a protogalaxy into a normal galaxy the release of energy will give rise to phenomena of the kind observed in typical quasi-stellar objects. Hence we identify a quasi-stellar object with a protogalaxy in a certain stage of evolution.

We discuss below a protogalaxy model which we proposed some years ago, and then we compare its properties with the observed properties of quasi-stellar objects. We then follow the evolution of the protogalaxy in more detail.

Model of a Protogalaxy

As stated above, the assumption of a symmetric universe seems inevitably to lead to the conclusion that all galaxies should contain essentially the same amount of koinomatter and antimatter and that separation of the two sorts of matter is to some extent connected with condensation of the initial ambiplasma to galaxies. This makes it seem likely that the formation of "protogalaxies" should be governed by the properties of the ambiplasma out of which they are generated. We show next that a condensing ambiplasma is likely to form bodies of the size and mass of the usual galaxies.

Like all gas clouds of cosmic dimensions, the primeval ambiplasma is gravitationally unstable and will condense to a number of bodies. In each of these bodies the ambiplasma is acted upon by gravitation. We assume that the body which is formed has a general magnetic field. We do not discuss the processes by which such a field is produced, but simply point to the fact that all celestial bodies which are large enough (large planets, stars, galaxies) seem to be magnetized.

The presence of gravitation and magnetization contributes to the separation of koinomatter and antimatter which may have started much earlier. Models of this process have been suggested (*2, 5*). A condensing protogalaxy will consist of regions of four different kinds: (i) regions of koinomatter in which star formation may have started; (ii) regions of antimatter (also with stars); (iii) regions of heavy ambiplasma (that is, protons plus antiprotons); in these regions there is a constant production of light ambiplasma (electrons and positrons); (iv) regions of light ambiplasma.

Gravitation acts strongly on regions i, ii, and iii. Such regions will be the main constituents of the condensing protogalaxy itself. Component iv has a very low mass. At the same time it is the hottest of all the components, because it is produced with energies in the 100-Mev range. Gravitation will not be able to prevent such a gas from expanding and leaving the protogalaxy. Hence a protogalaxy, which, in regions of type iii (heavy ambiplasma), constantly produces light ambiplasma, will emit light ambiplasma to its environment. The emission will be guided by the general magnetic field of the protogalaxy.

The development of a galaxy is governed by the constant decrease in component iii, which in the final state is close to zero. The decrease takes place in two ways.

1) Part of the ambiplasma is separated, which means that components i and ii increase toward a limit which is not far from the present mass of a quiet galaxy.

2) The rest of the ambiplasma is annihilated. Light ambiplasma is produced, which escapes to the environment of the galaxy. Energy is released which is radiated—usually after complicated processes of degradation.

Our present knowledge of the processes is too rudimentary to allow us to calculate what fractions of the initial ambiplasma will be separated or annihilated. Qualitative arguments of various kinds seem to indicate that the probabilities of occurrence of the different processes should be of similar orders of magnitude. Hence we shall assume roughly that something between 10 and 90 percent of the initial mass will be separated, and that the rest will be annihilated. This implies that the total energy release during the development of a galaxy is 0.1 to 10 $M_p c^2$, where M_p is the present mass of a galaxy and c is the velocity of light.

In the primeval ambiplasma, random density fluctuations may lead to concentrations which will, however, be dissolved again unless they are massive enough to be kept together by their self-gravitation. Only rather large clouds can be kept together long enough to form a galaxy. The dimensions necessary for the formation of a protogalaxy may be estimated by means of the virial theorem

$$2E + \Omega + \ldots = 0 \quad (1)$$

where E is the kinetic energy and Ω is the gravitational energy. We shall assume here that other forms of energy are negligible—for example, the magnetic energy. (This does not exclude the possibility that in small volumes there are reasonably strong fields.) Also, the coupling between the high-energy electron plasma and the heavy plasma is assumed to be weak. Confining ourselves to order-of-magnitude estimates, we see from Eq. 1

$$\frac{GM^2}{R} \geq \frac{3\ kTM}{m_p} \quad (2)$$

where G is the gravitational constant, k is the Boltzmann constant, m_p is the proton mass, and R and M are the radius and the total mass, respectively, of the protogalaxy when it is formed. In our approximation it is assumed that neither the density nor the temperature varies very much within the sphere. If n_p is the average number of protons or antiprotons per cubic centimeter, we have

$$M = \frac{4}{3}\pi R^3 n_p m_p = 7 \times 10^{-24} n_p R^3 \quad (3)$$

(in centimeter-gram-second units).

Thus

$$R \geq 2 \times 10^{19}\left(\frac{T}{n_p}\right)^{1/2} \quad (4)$$

The mass and radius computed from Eqs. 3 and 4 are lower limits because we have neglected other forms of energy. On the other hand, when a protogalaxy is formed, the temperature can rise somewhat before the body evaporates. In Fig. 1 the lines $M/R = kT/Gm_p$ are plotted for different values of T. Unless a protogalaxy lies definitely above the line corresponding to its temperature, it will evaporate very rapidly.

Figure 1 also shows lines n_p = a constant, which gives the time of annihilation τ according to the formula [see (*2*)]

$$\tau = 4 \times 10^6/n_p$$

where τ is given in years and n_p, in number of particles per cubic centimeter.

Plausible values for a protogalaxy are $M = 5 \times 10^{44}$ grams, $R = 2 \times 10^{23}$ centimeters, $n = 10^{-2}$ particle per cubic centimeter, and $T = 10^6$°K. As we see, both the size and the mass of the body are of the same order of magnitude as those for galaxies.

Concerning the further properties of the protogalaxy, it is important to note that no mechanism has been proposed which could produce an efficient separation on a galactic scale, but there are several small-scale processes which might be efficient. Hence the separation is likely to be connected with a small-scale structure of the metagalaxy. This is not surprising. Most cosmic plasmas which we have been able to study more closely exhibit small-scale structures. Examples are the granulation of the photosphere and the filamentary structure of the chromosphere and corona. In many gaseous nebulae, also, filamentary structures are observed. The small-scale structure seems to be produced either by hydromagnetic waves, by turbulence, or by filamentary currents. Quite generally, the time for homogeneous models in cosmical electrodynamics seems to be approaching its end. In many fields it is obvious that essential properties of cosmic plasmas can be understood only from models which take into account strongly inhomogeneous small-scale structures (*6*).

With this as a general background, it seems reasonable to conclude that the separation could proceed as a small-scale process. Hydromagnetic waves and filamentary currents with a linear dimension of, say, 10^{16} to 10^{18} centimeters may produce a large number of small cells of separated matter and antimatter.

The cells will move around in the ambiplasma and will frequently come into contact with other cells. If two cells in contact with each other contain different kinds of matter, an intense development of energy (a Leidenfrost phenomenon) at the interface may push them apart again. If cells containing the same kind of matter come into contact, they will merge into one larger cell. In this way the cells rapidly grow.

It is thought that they are cooled by radiation, and therefore compressed by the surrounding hot ambiplasma.

It is possible that star formation starts very early. As the conditions for star formation are not very well understood (7), it is difficult to decide at what time the condensation to stars begins.

Theory of Quasi-stellar Objects

The protogalaxy model we have discussed and its evolution toward normal galaxies has essential properties which make identification of the evolving protogalaxy with the quasi-stellar object seem reasonable. The different properties of the quasi-stellar objects have recently been reviewed by E. M. Burbidge (*8*) and by Sandage (*9*). The main properties may be summarized and explained in the following way.

1) Red shift. The spectra of quasi-stellar objects are generally characterized by very large red shifts, as was first found by M. Schmidt (*10*). Although other views have been advanced, it seems likely that the red shifts are due to the expansion of the metagalaxy and that the objects are at cosmological distances (*11*).

2) Emitted energy. The emitted energies are then found to 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 quasi-stellar objects one could estimate the emitted energies to be of the order of $10^{46.5 \pm 1.0}$ erg/sec.

As has been suggested by Teller (*12*) and others, it seems reasonable to suppose that the energy in these objects derives from the annihilation of the koinomatter and antimatter. In fact, there seems to be no other source which is able to deliver the enormous energies required. Discussion of a great number of more or less improbable models which have been suggested supports this conclusion.

If the unobservable energy going into neutrinos is not included in the calculation, we find that the annihilation of one solar mass per year will release, on the average, 3×10^{46} erg/sec. Thus in many cases the annihilation of only a small fraction of a solar mass per year would suffice to account for the energy production, whereas, in the most energetic objects, annihilation of as much as 10 solar masses per year would be required.

The mass of a typical galaxy equals 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 annihilating more than 10 percent of its mass. Hence there is enough energy to allow a galaxy to spend an essential part of its lifetime as a quasi-stellar object. The energy release that would have been necessary to make the metagalaxy turn its initial contraction into an expansion 10^{10} years ago has been estimated at 4×10^{59} erg/sec (*2*). If we divide this figure by the number of galaxies in the metagalaxy, which is of the order of 10^{10}, we find the average value for the energy release, per galaxy, caused by the radiation explosions that turned the initial contraction into an expansion to be 4×10^{49} erg/sec; this is a hundred times the output of an energetic quasi-stellar object. Hence the quasi-stellar objects as we observe them today should emit much less energy per unit mass than the metagalaxy emitted at the time its contraction turned to expansion.

3) General structure. A quasi-stellar object is supposed to contain about equal amounts of koinomatter and antimatter, which have already been separated into a large number of regions, each containing mainly one kind of matter. A typical region will contain interstellar gas, in part condensing to stars.

In some parts of the system there will be boundary layers in the gas, with Leidenfrost phenomena between different kinds of matter. The rate of annihilation and the radiation from these parts will be small or moderate. In other parts, mostly in the nucleus of the system, the density as well as the rela-

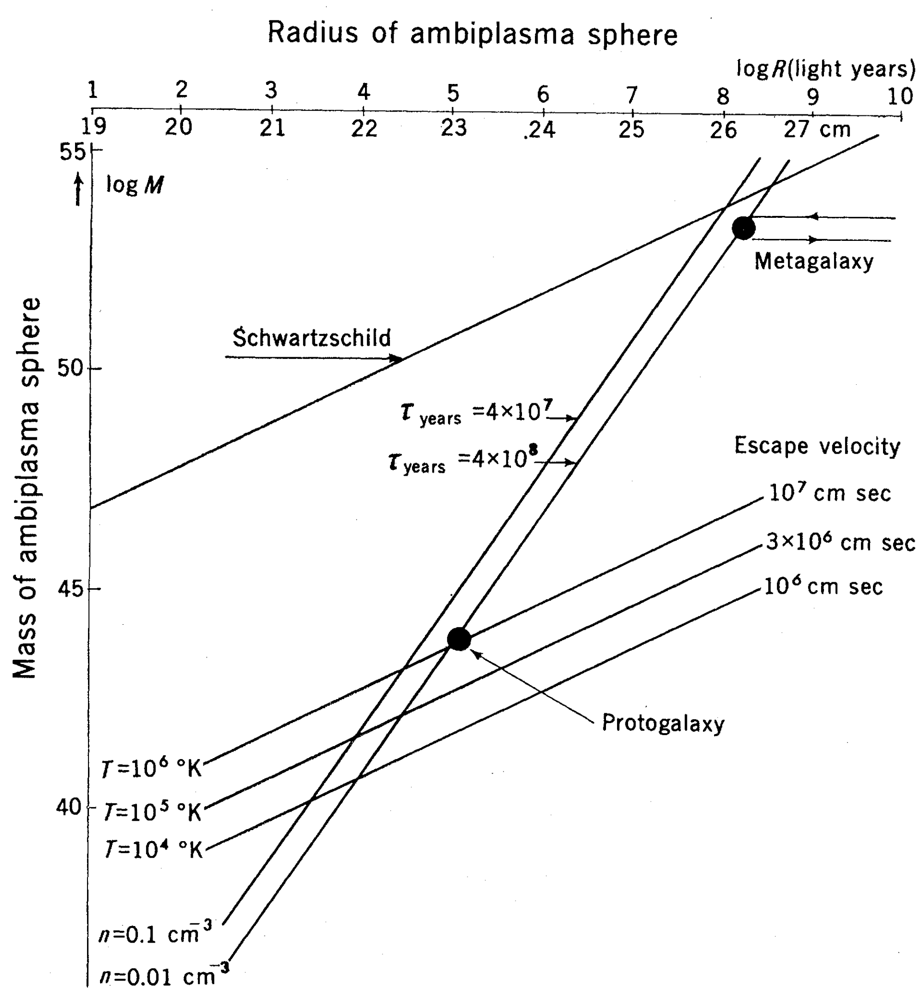

Fig. 1. Properties of a celestial body consisting of ambiplasma. The Schwartzchild limit is given by $R = 2GM/c^2$ (see text). The black dot at the right marks the position of the metagalaxy when its contraction is reversed into expansion. At this event its density is of the order 10^{-2} particle per cubic centimeter, corresponding to an ambiplasma lifetime of the order 4×10^8 years. At the reversal, the metagalaxy is divided into a number of protogalaxies (lower black dot). Their mass must be large enough to prevent them from dissipating—a requirement which gives the limiting lines for different temperatures. With a given mass the radius must not be too small; otherwise annihilation would occur before the separation of matter and antimatter had taken place.

tive velocities will greatly exceed the average for the system. Therefore it seems plausible that collisions between stars will not be rare. If such collisions take place between stars composed of opposite kinds of matter, there will be a sudden release of annihilation energy.

4) Size of the energy source and variations in the intensity of the radiation. Observation shows that, in a typical quasi-stellar object, much of the energy is released mainly within a very small volume, probably in the nucleus of a more extensive system. Within this small region it is sometimes possible to distinguish even smaller components emitting most of the energy. Thus in the center of 3C 273 a radio component smaller than 0.0006 second of arc, or 5×10^{18} centimeters, has been found, together with other components about 3 and 30 times larger (*13*).

Soon after the first quasi-stellar objects were identified it became evident that considerable variation in the optical magnitudes and variation in the radio flux densities are common properties of the observed objects (*14, 15*). Both long-term variations and sudden "flashes" have been observed (*16*). Although in a few cases the possibility of a periodicity in the variations has been pointed out, the variations seem, in the main, to occur at random.

Such variations are reconcilable with our model if we accept the possibility that star formation started very early. Collisions between stars of opposite kinds of matter should produce sudden and violent energy outbursts. The stars need not necessarily be of the same size. Typically we will have a small star, or even a body of substellar size, falling into a bigger star. When it collides with the big star, annihilation will start immediately, but in order that the velocity of the falling body may be reversed, a large quantity of matter must be annihilated. This requires thorough mixing of antimatter and koinomatter. As such a mixing is a relatively slow process, the smaller body will penetrate the star well below its surface, before most of the annihilation takes place. The γ-radiation emitted in the annihilation process will be absorbed in the stellar gas, causing strong heating and shock waves. The consequence will probably be a supernova-like explosion with a sudden release of very large energies. Whereas the annihilation of nonseparated ambiplasma may produce at least part of the slowly varying emission from the quasi-stellar object, collisions involving large condensed masses will lead to the sudden outbursts observed from time to time. The emitter will be very small in this case, more or less of stellar dimensions.

5) Light emission. The optical spectra of quasi-stellar objects are generally characterized by very broad emission lines of the same sort that are observed in gaseous nebulae, although the width of the lines differs from one object to another (*17*). The optical continuum of the quasi-stellar objects studied so far shows a very strong excess in the ultraviolet, and the excess is usually also very strong in the infrared spectral region (*14, 18*).

In our model the released annihilation energy will be degraded by a number of complex processes. Intense local heating may give rise to the ultraviolet continuum. Expansion of somewhat cooler regions will be accompanied by emission of broad spectral lines. Further, if—as suggested by Low (*19*)—the source is surrounded by a layer of dust, a large fraction of the energy may finally be emitted as infrared radiation.

6) Polarization of light. Variable polarization of light has been observed in several quasi-stellar objects (*16, 20*). When a smaller body penetrates the outer parts of a star and is annihilated, the explosion will produce a massive jet of hot plasma, ejected radially from the star. Electron scattering as well as optical synchrotron radiation may give highly polarized radiation from such a jet. Each new explosion would result in a new more-or-less polarized component of radiation. Thus, sudden changes in the degree of polarization as well as in the position angle could accompany major increases in the intensity of the optical radiation.

7) Radio emission. Some quasi-stellar objects are among the strongest radio sources so far known. On the other hand, many quasi-stellar objects have been found for which no radio radiation has been recorded. The flux density of the radio radiation from quasi-stellar objects seems to vary considerably, even over short periods of time, as mentioned above. A radio outburst seems to start at the shortest wavelengths and later to occur at longer wavelengths up to 40 centimeters. The successive shifting of the maximum flux density of an outburst from shorter to longer wavelengths has been demonstrated most beautifully by Paulin-Toth and Kellermann (*21*) for the compact radio galaxy 3C 120, which in many respects is similar to a quasi-stellar object.

In the annihilation process considered in our model, a large fraction (17 percent) of the energy goes into relativistic (100 Mev) electrons and positrons. Although some of these particles will be annihilated immediately, the rest will form a cloud of light ambiplasma rising like a bubble through the stellar atmosphere, or ejected in the explosion. This cloud will later continue to expand, moving away from the star where it was formed. Possible stellar magnetic fields may be dragged out in this motion, and the particles will probably, in a later stage, spiral around the lines of force in a larger-scale galactic field, emitting synchrotron radiation at radio wavelengths. Radio frequencies are probably high in the early stages after the cloud forms, and the energy maximum will shift toward longer wavelengths as the cloud expands and moves away from the active region.

Soon after the explosion the relativistic particles of the light ambiplasma will spiral in a magnetic field related to the exploding star. Such a field may be considerably stronger than the general field of the young galaxy. On the other hand it has a fairly small volume. Thus it seems possible to account for the emission of rather energetic synchrotron radiation without assuming impossibly large energies stored in the magnetic field of the object.

Our model predicts young radio emitters that are extremely small as compared to typical radio sources. Since, we believe, the collisions and explosions take place mainly in the nucleus of the young galaxy, the angular separation of young radio source components should also be quite small, even when the components are due to independent explosions within the same galaxy.

Evolution of Quasi-stellar Objects toward Normal Galaxies

We have interpreted the quasi-stellar objects as being very young galaxies that represent an early phase in the evolution from the protogalaxy into various types of radio galaxies and, finally, normal galaxies. The quasi-stellar-object phenomena may become evident when the protogalaxy has reached a stage in its contraction when a dense nucleus is formed. At this early time the separation of matter and antimatter into different cells is far less complete than in our galaxy; this means that the cells are mostly small, so that collisions between bodies of different kinds of matter are much more frequent than they are now. This is especially the case in the nucleus, where the density is much higher than it is in other parts of the system. During this period, therefore, many events of the kind described in our model will take place in the nucleus of the young galaxy, with consequences observed as typical properties of quasi-stellar objects. During this active period the annihilation of matter is of the order of a few solar masses per year, with large variations in the number of events per year and in the average energy release, because of the statistical nature of the collisions.

The annihilation is especially effective in regions where collisions between bodies composed of different kinds of matter are frequent. Therefore, as time goes on, the galaxy evolves into a more stable state. Although the galaxy still contains approximately equal amounts of matter and antimatter, this is separated into cells that are much larger and probably more stable configurations than those of the early stages. All unstable configurations are annihilated. In the evolution from a protogalaxy to a normal galaxy, a considerable fraction of the original mass will be lost by annihilation.

As the evolving galaxy becomes more stable, the number of collisions and explosions will decrease with time. The quasi-stellar object will be transformed into an N-type galaxy, a Seyfert galaxy, or some other kind of radio galaxy. The end product will, supposedly, be normal galaxies. We do not believe that the evolution always follows exactly the same path. The details will depend on many parameters, among them the total mass of the system and the angular momentum in the rotation of the galaxy. The presence of magnetic fields of galactic dimensions may also strongly influence the course of the evolution.

It should perhaps also be pointed out that, in the later stages of evolution, when the galaxy is rather quiet and normal over long periods, there may be sudden interruptions of this quiet evolution by collisions of the type described above. Although the probability of such collisions becomes increasingly smaller, it is never exactly zero. Thus a certain activity may be observed in otherwise normal galaxies, mainly in the nucleus.

Strong radio galaxies are characterized by the presence of magnetic fields and relativistic electrons. In our model the electrons and positrons (in equal numbers) are produced in the annihilation process. When spiraling in the magnetic field they emit synchrotron radiation, mainly in the radio region of the spectrum. As shown by Ekspong, Yamdagni, and Bonnevier (*22*), the spectrum emitted from an ambiplasma is reconcilable with the observed spectra. In many cases the magnetic field required is as strong as 10^{-2} gauss. It should be observed, however, that, if the field is inhomogeneous, most of the radiation comes from the regions with the strongest field (because the emission is proportional to H^2). Hence the average field may very well be weaker by several orders of magnitude.

The clouds of relativistic electrons and positrons which comprise the light ambiplasma will drift along the magnetic lines of force. It is possible that in many galaxies a dipole-like magnetic field of large dimensions may exist, along which the light ambiplasma may drift in two opposite directions (each cloud containing both electrons and positrons). In this way the double radio sources which are so often observed may be formed. Immediately following a period of strong activity in the nucleus the radio source will be concentrated in the nucleus. As time goes on, the two main components of the source become more separated and also become expanded.

Some radio sources show both a set of old, well-separated components and another set of younger, little-separated components close to the nucleus (a well-known example is the strong radio galaxy Centaurus A, connected with the peculiar galaxy NGC 5128). This indicates that at least two major explosions have taken place in this galaxy. The time interval between these two explosions seems to be of the order of 10^7 years.

Origin of Elements

The problem of how the elements were synthesized constitutes a challenge to all cosmologies, and so far none has been able to provide a very satisfactory explanation. If quasi-stellar objects are considered to be protogalaxies, the theory of element production at the time of thermonuclear reactions in stars runs into difficulties because the quasar absorption spectra show the presence of heavy elements. This means that these elements must have been produced no later than the time of formation of the quasi-stellar objects. We seem to have three alternatives.

1) The elements were produced at a very early time—for example, at the time of the universe's transition from the prematter state to the matter state. This means that when koinonucleons and antinucleons were produced, the heavy elements were generated at the same time.

2) Production of the elements took place in the ambiplasma long before contraction of the metagalaxy turned to expansion and long before the protogalaxies formed.

3) The quasar activity also produces elements.

It is not very clear how element production could have taken place under alternatives 1 and 2. It seems that some ad hoc assumptions are inevitable. On the other hand it may be possible to work out a theory consonant with alternative 3 without making any ad hoc assumptions.

We have already seen that the violent fluctuations in quasi-stellar-object emissions require that stars or starlike bodies of one kind of matter are hit by bodies of the opposite kind of matter. Especially if the hitting bodies are not too big, they will penetrate a star to some depth and cause an explosion at the time of annihilation. A great release of energy will greatly heat a large part of the star and cause a number of shock waves. It is conceivable that heavy elements are produced under such conditions by processes which, in some respects, are similar to those thought to take place in the interior of normal stars. The gases ejected from the explosion should then contain newly produced heavy elements. It is likely that the absorption lines in quasars are produced by these ejected gases when they have cooled down at some distance from the source.

Summary

Astronomical observations indicate that there is a continuous developmental sequence from quasi-stellar objects, by way of N-galaxies, Seyfert galaxies, and radio galaxies, to ordinary galaxies. We interpret the sequence as an evolutionary pathway. If we accept this view we find that the total energy released during the lifetime of a galaxy is so great that the most likely source is annihilation.

The demand for symmetry in the

universe between koinomatter and antimatter indicates that there must be equal quantities of the two kinds of matter in every galaxy. From this it seems likely that a galaxy is born as an ambiplasma body, which releases a great deal of energy by annihilation. Separation of the ambiplasma into koinomatter and antimatter in reasonably stable configurations, and the burning out of the nonseparated ambiplasma, should be the main processes which govern the evolution from protogalaxies and quasi-stellar objects to ordinary galaxies.

References and Notes

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Organization of the Visual Pathways

Evidence is discussed concerning parallel pathways from the eye to the brain.

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Light rays which arise from objects and impinge upon the eye of a mammal are refracted by the cornea and lens to form a fairly accurate spatial representation of the visual world on the retina. The process of image formation is similar to that in a camera; the image is small and inverted, and both eye and camera can typically focus between infinity and some specific near point. However, the transformation from patterns of light and shadow on the retina into neural messages is more complex and subtle than a photographic process. Eyes operate over a far greater range of light intensities than a photographic film does, and the central pathways do not transmit a simple pictorial representation to the brain.

In this article I review the spatial organization of the retina and central visual structures in terms of certain questions. If the optics of the eye form a single, spatially ordered image on the retina, to what extent are the spatial organization and uniqueness of the visual image maintained along the route from receptors to visual centers in the brain? There is a functional corollary to this question: If the visual fields are represented in the brain more than once and in parallel, is some aspect of visual function being segregated by the independent maps? Earlier answers to these questions appear to have oversimplified the problem. Here I discuss some aspects of the comparative anatomy of the mammalian visual system and consider a few recent anatomical and behavioral experiments which may point the way to a more satisfactory view of structure and function in vision.

Review of Retinal Structures

The retina of mammals is a complex structure in which receptors, neurons, and their processes are arranged in orderly layers. One example of the mammalian retina is illustrated in Fig. 1, a low-power photomicrograph of the cat retina near the area centralis. The darkly stained area at the top of Fig. 1 is the choroid (*ch*), a highly vascular, deeply pigmented region which, although not a part of the retina proper, carries blood vessels supplying the receptors. Below the choroid, staining orange, is the tapetum lucidum (*t*), a reflective layer found in the eye of many nocturnal mammals; by reflecting light which has not been absorbed by receptors, the tapetum serves to increase overall sensitivity of the retina and is also the anatomical basis for the reflected shine often seen when eyes are illuminated at night. Below the tapetum lucidum is a single line of pigment epithelium cells (*pe*), which, in the cat retina, do not contain the large amount of melanin pigment seen in more strongly diurnal mammals. The areas below the pigment epithelium, stained pale blue and bright blue, are the densely packed outer segment (*os*) and inner segment (*is*) of the rods and cones; at the low magnification shown here, individual receptors are not resolved. It is the outer segments of the rods and cones that contain the photosensitive pigments responsible for transduction of light into neural activity and hence initiate the sequence of steps which results in vision. Note, incidentally, that the retina seems to be facing backward; that is, light must traverse all of the layers of the retina below the recep-

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