ON HIERARCHICAL COSMOLOGY

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(Received 26 July, 1982)

"There is a strong trend towards clear- cut, universally valid answers that exclude different approaches. Whenever one way of thinking is developed with great force and success, other ways are unduly neglected. It was aptly expressed by Marcus Fierz, the Swiss physicist-philosopher: 'The scientific insights of our age shed such glaring light on certain aspects of human experience that they leave the rest in even greater darkness'."

Victor F. Weisskopf, *Bulletin The American Academy of Arts and Sciences,* Vol. XXXV, November 1981, No. 2.

Abstract. Progress in laboratory studies of plasmas and in the methods of transferring the results to cosmic conditions, together with *in situ* measurements in the magnetospheres, are now causing a *'paradigm transition'* in cosmic plasma physics. This involves an introduction of *inhomogeneous models* with double layers, filaments, *'cell walls'*, etc.

Independently, it has been discovered that the mass distribution in the universe is highly inhomogeneous; indeed, *hierarchical.* According to de Vaucouleurs, the escape velocity of cosmic structures is 10^2–10^3 times below the Laplace–Schwarzschild limit, leaving a *void region* which is identified as a key problem in cosmology.

It is shown that a plasma instability in the dispersed medium of the structures may produce this void and, hence, explain the hierarchical structure. The energy which is necessary may derive either from gravitation or from annihilation caused by a breakdown of cell walls. The latter alternative is discussed in detail. It leads to a 'Fireworks Model' of the evolution of the metagalaxy.

It is questioned whether the homogeneous four-dimensional big bang model can survive in an universe which is inhomogeneous and three-dimensional.

1. Paradigm Transition in Cosmic Plasma Physics

During the 70's *in situ* measurements in the magnetospheres, including the solar wind region ('solar magnetosphere') have drastically changed our understanding of the properties of cosmic plasmas. Further, we have learned how to generalize results from plasma investigations in one region to other regions. This means that laboratory investigations of plasmas of the size of, say, 10 cm can be used to achieve better understanding of cosmic plasmas of magnetospheric dimensions, say 10^{10} cm. By another step of 10^9 we can transfer laboratory and magnetospheric results to galactic plasmas of, say, 10^{19} cm. A third jump of 10^9 brings us to the Hubble distance 10^{28} cm and hence to cosmological problems (see Figure 1).

All this has led or is leading to a revision of our concept of cosmic plasmas which in many respects is so drastic that it is appropriate to speak of a *change in paradigm.* Essential differences between the old and the new paradigm are given below.

Astrophysics and Space Science **89** (1983) 313–324. 0004–640X/83/0892–0313$01.80.

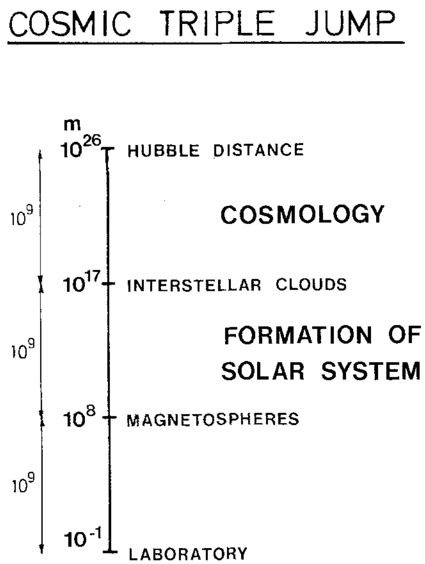

Fig. 1. *Cosmic Triple Jump.* Scaling up results of *laboratory* research by a factor of 10^9 makes them applicable to magnetospheric conditions. A new jump by 10^9, together with *in situ* measurements in the magnetospheres, makes them applicable to galactic conditions. A third jump by a factor of 10^9 brings us out to the Hubble distance. This means that the *new paradigm* which is now introduced in magnetospheric plasma physics will cause *drastic changes in astrophysics in general, including cosmology.* It will cause a confrontation between highly inhomogeneous three-dimensional models and the big bang model which is homogeneous and four-dimensional.

Page numbers refer to the recent monograph *Cosmic Plasma* (Alfvén, 1981a):

(1) *Electric double layers*, which did not attract very much interest until five or ten years ago, are now known to accelerate charged particles to kilovolt energies in the terrestrial magnetosphere. They may also exist elsewhere and accelerate particles to even much higher energies (p. 29).

(2) The transfer of energy in magnetized cosmic plasmas can usually not be described by local 'merging' or 'reconnection' of magnetic fields. A global *electric current description* is required. This leads to the necessity of drawing the *circuits* in which the current flows (pp. 16, 29, 42).

(3) In the magnetospheres, plasma exists in an *active* and a *passive* state. This is probably true for all cosmic plasmas (p. 37).

(4) Cosmic plasmas are often not homogeneous, but exhibit *filamentary structures* which are likely to be associated with currents parallel to the magnetic field. It is likely that filamentary structures in interstellar clouds as well as further out are also produced by filamentary currents (p. 16).

(5) In the magnetospheres there are thin, rather stable *current layers* which separate regions of different magnetization, density, temperature, etc. (p. 39).

(6) It is necessary that similar phenomena exist also in more distant regions. This is bound to give space a general *cellular structure* (or more correctly, a cell wall structure (pp. 40, 126).

(7) In the treatment of the evolution of dispersed media, the *pinch effect* term is usually neglected. If this mathematical mistake is corrected, the conventional treatment of, for example, the formation and evolution of interstellar clouds and the double radio sources must be revised (pp. 94, 97).

(8) It is doubtful whether large-scale *turbulence* in the proper sense is important in cosmic plasmas (p. 84).

(9) In case a current flows in a partially ionized plasma, a chemical separation may take place. Due to this and other effects, space plasmas have a general tendency to be *separated* into regions of different *chemical composition.*

(10) In 'dusty plasmas' the action of electromagnetic and gravitational effects may combine to produce '*gravito-electrodynamic effects*' (Mendis *et al.*, 1982).

(11) The *critical velocity* discovered from the band structure of the solar system may be important to many other problems of interaction between a neutral gas and a magnetized plasma (pp. 91, 110).

(12) The 2/3 fall-down and the *cosmogonic shadow effect*, which is the signature of the transition from a plasma to a planetesimal state, is likely to be decisive for the *evolutionary history of the solar system* (pp. 52–53 in Alfvén, 1981b).

(13) The arguments for the non-existence of antimatter in the cosmos are not valid (Rogers and Thompson, 1980). On the other hand, there are sound arguments for the existence of antimatter, which means that *annihilation* should be considered an important source of energy. In fact, annihilation seems to be the only reasonable energy source for those celestial objects which emit very large amounts of energy (e.g., quasars) (pp. 98, 131).

(14) Radio, X-ray, and γ-ray emissions and cosmic ray acceleration are largely due to plasma processes. Theories of, for example, double radio sources (p. 56), the formation of stars and planetary systems from interstellar clouds (p. 110), energy release in quasars (p. 137) and acceleration of cosmic radiation up to 10^{19} eV (p. 58) must be based on plasma physics. Hence the paradigm transition implies a revision of considerable parts of radio, X-ray and γ-ray astronomy, the theory of cosmic rays, and also of cosmology. These sciences must ultimately be based on the observed properties of laboratory and magnetosphere plasmas.

2. A New Approach to Cosmology

The purpose of this paper is to investigate to what extent the new paradigm applies to cosmology. This has already been discussed in the monograph *Cosmic Plasma* (Alfvén, 1981a; in the following referred to as CP), Chapter VI, but it seems appropriate to reconsider some of the arguments given there in light of new results.

The changes in concept which are most important to cosmology are those identified as (4), (5), (6), (13), and (14) in Section 1 above. The big bang model is a basically homogeneous model. Such models have been generally relied upon in larger parts of cosmic plasma physics. However, observations very often have demonstrated that they are misleading and not useful even as first approximation. They have to be replaced by strongly inhomogeneous models. It seems legitimate to ask whether the big bang model should be revised in the same way as so many other homogeneous models.

Independent of this, a change towards inhomogeneous models of a 'clumpy' universe has already occurred in part. Out to some percent of the Hubble distance there is now strong support for a *hierarchical model* of the mass distribution. However, the big bang model is still claimed to be valid close to the Hubble distance. Also, there is a region which is largely unknown observationally one or two orders of magnitude inside the Hubble distance in which the application of inhomogeneous models is controversial. Investigations relating to this region have recently led to the unexpected discovery of large *void regions* (for a survey, see *Physics Today* **35**, 17, 1982) which perhaps are difficult to reconcile with the postulated homogeneity of these regions.

3. The Hierarchical Model

Inspired by Fournier-d'Albe (1907), Charlier (1908, 1922, 1924) demonstrated that it is possible to avoid the Olbers and Seeliger objections to a Euclidean infinite universe, by assuming that the universe is 'clumpy', with a hierarchical matter distribution. This means that stars should be organized in galaxies G_1, a large number of these galaxies form a larger 'galaxy of type G_2' – we would today prefer to speak of a 'cluster' – a large number of these a still larger structure G_3, and so on to infinity. Charlier showed that the mean density of a structure of size R must obey the relation

$$\rho \sim R^{-\alpha} \tag{1}$$

with $\alpha > 2$. This leads to an infinite universe with infinite mass but with average density zero.

The Charlier school speculated whether our metagalaxy (a synonym for what in the big bang formalism is considered as the whole 'universe') may have sisters which together form a still larger structure (a 'teragalaxy'), thus continuing one step further in the hierarchy. (This is, of course, against the big-bang view.)

With the arrival of the big-bang cosmology, the Charlier model was considered to be of historical interest only. However, in a classical paper de Vaucouleurs (1970) revived that model by demonstrating that within wide limits the maximum *observed density distribution* satisfies (1), but with $\alpha = 1.7$.

In his theoretical interpretation of the observations de Vaucouleurs must take into account the Hubble expansion, which means that his hierarchical model is not identical with Charlier's. Furthermore, he accepts the big bang model, which is homogeneous and four-dimensional, and considers the hierarchical structure to be valid only on a 'small' scale; i.e., out to a few percent of the Hubble distance. The reasons why he does not consider still larger structures is that few reliable observations exist further out.

Peebles and collaborators have treated the observational data with advanced statistical methods, and have essentially confirmed the de Vaucouleurs hierarchical model (Peebles, 1980). (See survey article by Groth *et al.*, 1977). However, they find a value of α which is somewhat higher: $\alpha = 1.77$. Like de Vaucouleurs, Peebles accepts a compromise with the big bang model, even if sometimes he seems not quite happy with this.

Neither Charlier nor anyone else seems to have given any reason *why* matter has this structure and is distributed in this way. Only by implication do they claim that there must be *some law of physics* which produces a hierarchical structure; if not we will run into conflict with the Olbers and Seeliger paradoxes. Peebles (1980) believes that the hierarchical structure can be explained as a result of instabilities in the big bang model. However, very much work is required to give convincing arguments for this, and it may be allowed to look for alternatives, as we shall do in this paper.

4. Evolution of a Cosmic Structure

We shall here discuss the general evolution of cosmic structures ('clouds') with mass M and radius R, especially as to how the escape velocity of a cloud changes with time. There are two effects which make the escape velocity

$$v_{\text{esc}} = \left(2G \times \frac{M}{R}\right)^{1/2} \tag{2}$$

increase in a systematic way:

(1) The cloud accretes matter from the surroundings so that M increases.

(2) The cloud radiates energy to the surroundings. This energy release may make its temperature decrease. It may also be furnished by macroscopic internal motion, which first is transformed to temperature. Both the decrease in temperature and in internal motion produce a contraction so that R decreases. This means that gravitational energy is released which slows down the contraction.

The systematic increase in v_{esc} is counteracted by two forces:

(a) Matter falling in from the surroundings may increase the energy of the cloud and hence prevent an increase in v_{esc}. If the surroundings can deliver only a finite quantity of energy, the halt in the increase will be only temporary.

(b) Release of internal energy. In small clouds of the size of stars, nuclear energy will be released, which can go on for a very long time, during which the star burns. However, nuclear energy release is not likely to be very important in the large clouds (galaxies–metagalaxy) we consider here.

Furthermore, periodic radial oscillations may make v_{esc} change periodically.

5. The de Vaucouleurs Diagram

Figure 2 is based on Table I (p. 1208) in the already quoted paper by de Vaucouleurs (1970). (More recent results seem not to change his figures very much.)

From the diagram we may conclude that the evolution we have sketched above actually applies to *stars*. The diagram shows how protostars evolve to ordinary stars and eventually to white dwarfs and neutron stars through an essentially leftward displace-

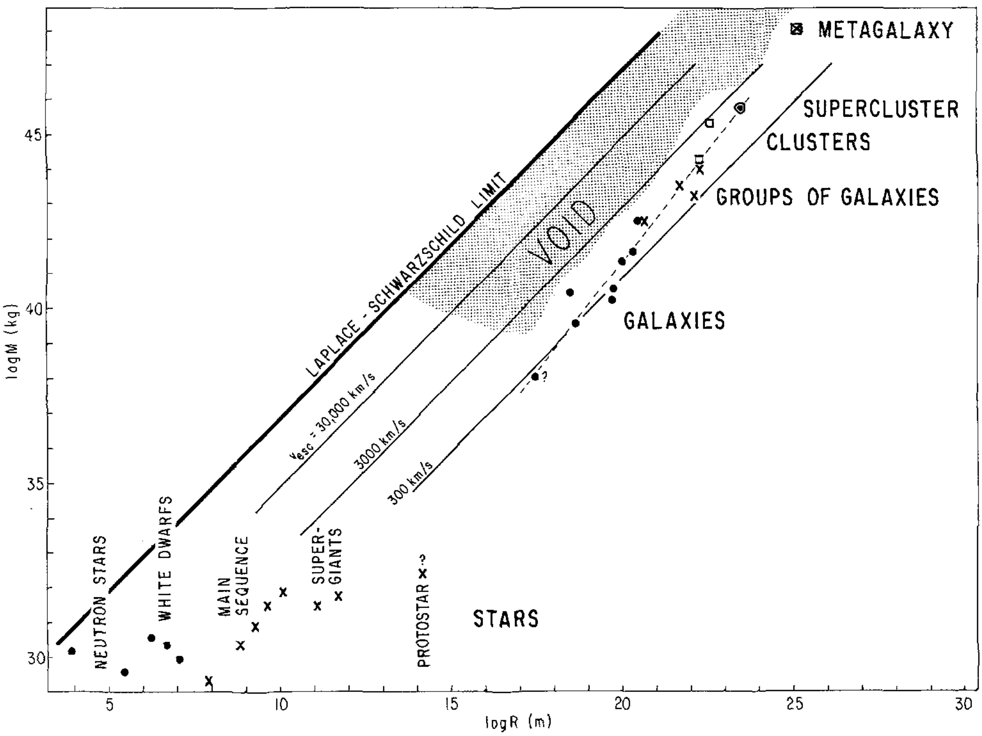

Fig. 2. *Mass and radius of typical stars, galaxies and galactic clusters according to de Vaucouleurs (1970).* Values for the metagalaxy are taken from Alfvén (1981a), p. 137. Mass accretion causes an upward displacement; energy loss (e.g., by radiation), a displacement – toward the left. Stellar evolution is seen to displace the stars towards the Laplace–Schwarzschild limit. However, an expected similar displacement of very large objects is stopped two or three orders of magnitude from this limit, leaving a large void region between $v_{esc}/c \approx 0.003$ and $v_{esc}/c = 1$. *The explanation of this void is a key cosmological problem.*

ment in the diagram. This means that they move towards the Laplace–Schwarzschild limit. Whether they finally reach this limit (i.e., become black holes) is of course an open question. We shall not discuss this here.

6. A Key Cosmological Problem

For large structures, the evolution apparently does *not* proceed in the same way. In fact, there are no observed objects above what we shall call the de Vaucouleurs (dV) limit, which is located two or three orders of magnitude from the Laplace–Schwarzschild (LS) limit. It seems unlikely that this is due to observational difficulties, because very concentrated galactic clusters should not be very difficult to observe.

We shall discuss here possibilities of explaining this void region. It turns out that *the void region between the dV and LS limits should be identified as a key problem in cosmology.*

When looking for an explanation of the de Vaucouleurs limit to large structures (10^{18}–10^{24} m), it is natural to conclude that it represents an instability limit. In fact, there seems to be no other possibility because we cannot stop the left-upward displacements in the diagram. The instability cannot be due to a release of nuclear energy – as in stars – because for the large structures we consider this to be insufficient. Hence, if we do not want to introduce new laws of nature, there are only two energy sources available: *gravitation* and *annihilation.*

7. Explosion of a Cosmic Structure

Without discussing now which of these is preferable, we shall demonstrate that the hierarchical structure can be derived from the *assumption* that a developing structure *explodes as soon as it has reached the dV limit*, which means as soon as $u_{esc} > \chi c$ with $\chi \approx 0.003$.

What has been said implies that a cosmic cloud has three evolutionary states, i.e.,

(a) *Pre-explosion state.* The cloud is gravitationally bound and contracts slowly because of 'viscosity' and radiative energy losses. The 'viscosity' effects include not only ordinary hydrodynamic viscosity of the dispersed medium but also 'electromagnetic viscosity' resulting from dynamo effects producing a network of electric currents. Some examples of such effects are discussed in CP, Chapters III.4.4, V.3.2, V.4, and V.6.

(b) *Explosive state.* The 'explosion' is not necessarily a sudden event but may be a state of energy release during a considerable time, resulting in an increase in internal energy so that the cloud is no longer gravitationally bound. Large parts of the cloud are ejected. Perhaps the whole cloud is broken up into fragments. Observationally the explosive state should be characterized by a high 'activity'; i.e., an abnormally high generation of X-rays, γ-rays, and radio waves.

(c) *Post-explosive state.* The result of the explosion will be that fragments of the cloud are emitted (see Section 9).

A naive identification of celestial objects in these three states would put strongly gravitationally bound clusters with rather low activity into (a), very active objects into (b) and clusters with large quantities of 'missing mass' into (c). See also Sections 8 and 10. However, much detailed work is needed before a credible identification can be achieved.

8. Extrapolation of the Range of Validity of the Observational Hierarchical Model

For reasons presented in detail in CP, Chapter VI, it seems legitimate to extrapolate the observed range of the hierarchical structure to include also the *metagalaxy. This is represented in Figures* 2 *and* 3.

9. Post-Explosion Evolution. The Fireworks Model

When an explosion is triggered off there must be a considerable energy release, so that a large number of fragments of widely different masses are thrown out in different directions.

These clouds or cloudlets will all develop in the same way as the original cloud: they will accrete mass M, e.g., from coalescing with other clouds or cloudlets which were thrown out and/or other pre-existing clouds or cloudlets. They will radiate energy so that their size R has a tendency to decrease. Hence, their escape velocity, which immediately after the explosion of the primary cloud is likely to be far below the de Vaucouleurs limit, will increase until it eventually reaches the limit. The result is that the *secondary cloud* (emitted at the explosion of the first cloud) *also will explode*, emitting

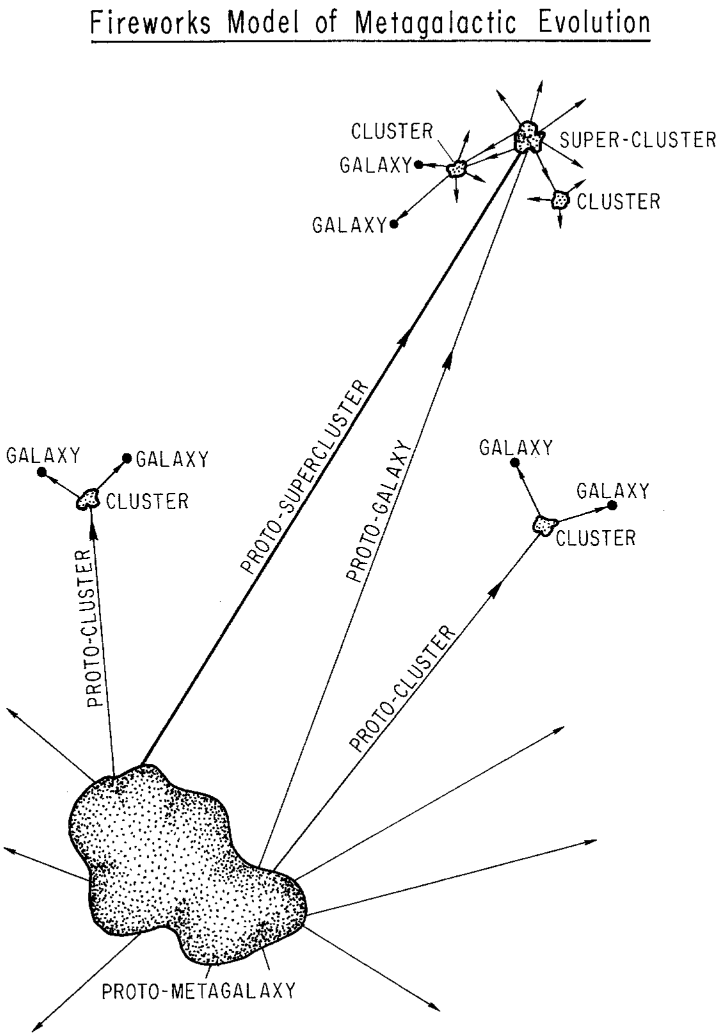

Fig. 3. *Fireworks Model.* When a structure, e.g., the proto-metagalaxy, explodes, it emits fragments, like proto-superclusters, proto-clusters and proto-galaxies, in all directions. These will capture mass (some of which may be other emitted fragments) and lose energy, until they also reach the limit of explosion. Secondary explosions (illustrated by the explosion of a super-cluster and a cluster) will occur. A similar evolution of the fragments will give rise to tertiary explosions, etc. The whole process, which is similar to certain fireworks, explains the hierarchical structure and the void region in Figure 2.

tertiary clouds in all directions. They may undergo a similar post-explosion development. The process is illustrated in Figure 3. The explosion of the proto-metagalaxy (CP, Chapter VI.5) is represented as the first step in a hierarchical series of explosions.

In some respects, this is similar to fireworks. The primary combustible device ejects a number of small combustible devices, which after some time explode and produce a hierarchy of miniature fireworks over a large region of space.

10. Properties of the Fireworks Model

We identify the primary cloud with the *proto-metagalaxy.* Its explosion causes a metagalactic expansion, which we identified with the Hubble expansion (see CP, Chapter VI.1.4).

The biggest fragments of the metagalactic explosion are identified with *proto-superclusters.* When these have developed so that their escape velocity reaches the de Vaucouleurs limit they explode emitting *proto-clusters* in all directions.

As a third step, the proto-clusters develop in a similar way and explode, emitting *galaxies* in all directions.

The evolutionary pattern may in reality be more complicated than indicated above. The explosion of the proto-metagalaxy will also emit smaller fragments, like proto-clusters and proto-galaxies, in all directions. An essential factor in the development of a proto-supercluster may be that it is hit by proto-clusters and by proto-galaxies, which contribute to increasing its mass considerably. It is also possible that such an impact may trigger the super-cluster explosion. The same holds for the evolution of the proto-clusters.

Concerning possible extrapolation of the hierarchy to still larger objects, see CP, Chapter VI.6.

11. The Case for Gravity as the Energy Source

Our next problem is to decide whether the explosion is caused by a release of gravitational or annihilation energy.

In the case of novae or supernovae we understand the explosion mechanism fairly well; before the explosion, gravity is balanced by the thermal energy supplied by nuclear energy together with the gravitational heating due to contraction. When nuclear energy is insufficient, gravity must take over the whole energy release, and – as a detailed analysis shows – this leads to an explosive collapse.

In principle, a similar energy release could take place in larger structures also. The result would be the explosion of the large clouds we need for explaining the hierarchical structure. If the energy source for the explosion is gravity, a large part of the structure either should find a new equilibrium with a much smaller radius, or be transformed into a black hole.

In, for example, a cluster of galaxies, such a process should consist of one or several large masses being formed just when v_{esc} of the whole cloud has reached a certain value. It is difficult to imagine what type of process this should be.

Attempts to find a process of release of gravitational energy should be encouraged. However, if such a process cannot be found, the only way to explain the hierarchical structure seems to be to assume that the energy source is *annihilation.*

12. The Case for Annihilation as the Energy Source

According to O. Klein's cosmology, the Universe contains equal amounts of matter and antimatter. He considers a very large sphere (much larger than the present size of the metagalaxy) which consists of a homogeneous mixture of koinomatter and antimatter. It contracts under the action of its own gravity. When its density increases, annihilation starts, which stops the inward motion and substitutes for this an outward motion identified with the Hubble expansion.

Like all homogeneous models, Klein's model has to be developed into a model which obeys the requirements of the new paradigm. However, the *symmetry* is one of its features which seems to be of permanent value, because, as has been shown in CP, there are now strong arguments for the existence of antimatter.

If we accept that the universe is symmetric with regard to koinomatter and antimatter, we have different alternatives to interpret this.

(1) Our galaxy may consist exclusively of koinomatter and other galaxies, e.g., the Andromeda galaxy, exclusively of antimatter. As the interaction between two galaxies is not very conspicuous, such a version of the symmetric approach would not be easy to refute.

(b) However, at the same time it would be more difficult to invoke annihilation as the energy source for a number of phenomena which seem very difficult to explain otherwise. Hence, we chose the latter alternative (see CP, IV.9, IV.10.1.3, VI.2.3).

In fact, as shown in CP:

(1) The arguments *against* the existence of antimatter are invalid in the new paradigm (see especially Rogers and Thompson (1980)). Indeed, there still does not exist any irrefutable argument for the view that α Centauri, our closest star, consists of koinomatter and not antimatter!

(2) There are several arguments *in favor* of the existence of antimatter. One of the most direct arguments is that the enormous amounts of energy released in quasars and similar objects can derive only from annihilation (unless we want to invoke new laws of nature).

(3) Measurements of cosmic radiation have shown that it contains some antiprotons. Some authors, like Stecker *et al.* (1981), interpret this as proof of the existence of antimatter. However, such conclusions are as model dependent as the arguments against antimatter (see also CP VI.2.4, p. 134). Only if it can be convincingly shown that cosmic radiation contains negative particles of larger mass than hydrogen do we have an irrefutable proof of antimatter in the cosmos.

13. Stability of an Ambicloud

Accepting annihilation as the energy source implies that we shall try to make a cosmological model which is a synthesis of the Charlier–de Vaucouleurs hierarchical model and the Klein symmetric model.

Consider a cosmic cloud (especially of a size between a galaxy and the metagalaxy) which contains matter of both kinds, separated from each other by a system of Leidenfrost layers.

Suppose that in a Leidenfrost layer (CP, p. 138) the density of the annihilation electrons is n_l and their temperature V_l. In the slabs of matter and antimatter which it separates, the corresponding values are n_s and V_s. A stationary equilibrium requires that

$$\frac{n_l}{n_s} = \frac{V_s}{V_l} .$$

If V_s/V_l is very large, the density in the Leidenfrost layer is very low and an efficient separation of koinomatter and antimatter is achieved.

However, if V_s gets so large that V_s and V_l become comparable, we cannot expect the Leidenfrost layer to be able to separate the two different kinds of matter in an efficient way. A general annihilation may take place, resulting in an explosion. Hence an ambicloud is intrinsically explosive.

If the escape velocity of a structure is increased, the kinetic energy of cloudlets falling in from infinity will increase. Collisions between such in-falling cloudlets and the cloudlets of which the structure consists will be increasingly violent. Also, the internal motions in the structure will increase. There should be an upper limit to the perturbations of this kind which the Leidenfrost layers could stand before a breakdown takes place, which may initiate a conflagration. This means that v_{esc} should have a critical value, above which the structure becomes unstable.

Because the theory of Leidenfrost layers is not yet sufficiently well developed, it is not yet possible to give a detailed theory which gives the critical value of the escape velocity.

14. Final Remarks

During the ages there seems to be an oscillation between two different types of cosmologies: during some periods it was believed that the structure of the universe can be understood through religious–philosophical–theoretical speculations, during others it is claimed that an empirical-observational approach is preferable.

Every major advance in our observational technique favours a transition from a speculative to an observational approach. It was Tycho Brahe's unprecedented observational accuracy and Galilei's introduction of the telescope, which caused the change from the theoretically based paradigm of Pythagoras–Aristoteles–Ptolemaios to the observationally-based paradigm of Kepler and Newton.

During the last decades the *in situ* measurements in space have given us a jump in the observational sophistication, which in some respects may be similar to what happened 400 yr ago. It seems legitimate to ask whether this implies that the theoretical approach which this time is based on the Lemaître and Friedmann speculative models (or on the Eddington, Milne–Dirac models) should be replaced by an observationally based paradigm – for example, a model of the kind summarized here.

Acknowledgments

I want to thank Drs H. E. Smith, L. Peterson, and R. Harms for discussions, Mrs Jane Chamberlin for the editing, and Mrs Pat Gifford for preparing the figures.

References

Alfvén, H.: 1981a, *Cosmic Plasma*, D. Reidel Publ. Co., Dordrecht, Holland.
Alfvén, H.: 1981b, *Astrophys. Space Sci.* **79**, 491.
Charlier, C. V. L.: 1908, *Astronomi och Fysik* **4**, 1.
Charlier, C. V. L.: 1922, *Astronomi och Fysik* **16**, 1.
Charlier, C. V. L.: 1924, *Publ. Astron. Soc. Pacific* **37**, 177.
de Vaucouleurs, G.: 1970, *Science* **167**, 1203.
Fournier-d'Albe, E. E.: 1907, *Two New Worlds*, Longman and Co., London.
Groth, E. J., Peebles, P. J. E., Seldner, M., and Soneira, R. M.: 1977, *Sci. Am.* **76**, 00.
Mendis, D. A., Houpis, H. L. F., and Hill, J. R.: 1982, *J. Geophys. Res.* (in press).
Peebles, P. J. E.: 1980, *The Large-Scale Structure of the Universe*, Princeton University Press, Princeton, N.J.
Rogers, S. and Thompson, W. B.: 1980, *Astrophys. Space Sci.* **71**, 257.
Stecker, F. W., Protheroe, R. J., and Kazanas, D.: 1981, NASA Tech. Memo. 82118, Goddard Space Flight Center, Md., U.S.A.