AGE DISTRIBUTION OF GALAXIES

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1. Introduction

This paper is concerned with the two questions: how might the large scale study of the universe assist the study of the evolution of individual galaxies, and how might a knowledge of the evolution of individual galaxies assist the large scale study of the universe, particularly in regard to the choice between evolutionary and steady state cosmologies?

We first bring together certain simple general results concerning ages of galaxies in known cosmological models. We then briefly discuss the observational results for the actual universe. Finally, we return to the two questions just stated.

The reader need not be familiar with the mathematics of current cosmological theory. A few simple results are quoted here and their significance should be evident without a knowledge of their derivation. However, the derivation can readily be found in any published exposition of the theory.

2. Evolutionary cosmology

We consider first evolutionary cosmology or, as it is commonly called, relativistic cosmology. The most interesting cases under this heading are probably the so called "big bang" cosmologies.

We restrict attention to smoothed out, homogeneous isotropic cosmological models, and to observations by observers who share in the general motion of the material present. In any such model there must exist a parameter t that labels the stage of evolution as seen by any observer. If t is measured in units of the proper time of any observer, then t is known as *cosmic time*. If $t = 0$ is some singular state of the universe, then t is also the *age of the universe* in the neighborhood of the observer.

In any such model, the motion of the material relative to any observer must be radial and spherically symmetric. Therefore, there must exist a parameter T such that, in the neighborhood of the observer, to the first order in distance the motion must be of the form

(2.1) speed of recession = distance divided by T,

where T depends upon the cosmic epoch t at which the motion is observed. Since the motion of the whole system is the aggregate of the motions seen by all the local observers, who are all equivalent because the model is postulated to be homogeneous, we should expect to find that the model is characterized entirely by the function $T(t)$, which we call the Hubble time.

The theory of relativity is used in the first place to provide a definite treatment of space-time and of light propagation. When it is so used, the expectation just mentioned is fulfilled, apart from the circumstance that there are three categories of model specified in practice by a constant k that can take the values $-1, 0, +1$. For the purposes of this paper, we may largely forget about k.

The theory of relativity is used in the second place to relate the function T to the properties of the matter present, but we do not need to go into this.

It happens to be more convenient to use a function $R(t)$ rather than $T(t)$, where $R(t)$ satisfies the equation

$$\frac{1}{R}\frac{dR}{dt} = \frac{1}{T}, \tag{2.2}$$

together with the condition $R(t) > 0$ for all admissible values of t. Then we see that $dR/dt > 0$ implies expansion of the universe (rather than contraction).

If radiation of wavelength λ_e is emitted by an observer at $t = t_e$ and is received as radiation of wavelength λ_0, by an observer at $t = t_0$, then

$$Z \equiv \frac{\lambda_0}{\lambda_e} = \frac{R(t_0)}{R(t_e)}. \tag{2.3}$$

This is a general result of the relativistic treatment of light propagation in these models, and it holds good for all admissible t_e, t_0. The quantity $z = \Delta\lambda_e/\lambda_e$, where $\Delta\lambda_e = \lambda_0 - \lambda_e$, is the familiar *cosmical redshift*. However, the parameter $Z = 1 + z$, is more generally useful; it may be called the *reddening* parameter.

2.1. *Seeing into the past.* It is often remarked that if an observer looks at a part of the universe that is L light years distant in space, he sees that part as it was L years ago in time. Thus, he sees a part of the universe that is L years younger than his immediate cosmic vicinity. The relation (2.3) enables us to state this notion in more precise terms.

If at cosmic epoch t_0 an observer views a part of the universe for which the reddening is Z, then he sees that part as it was at cosmic epoch t_e where $R(t_e) = Z^{-1}R(t_0)$.

On account of the homogeneity of the model, the remote part at epoch t_e is similar to the observer's part at the same epoch. So the observer may be said to be looking into his own past.

The simplest model in the category is the case $R(t) \equiv t$. This is the case in which gravitational effects are treated as negligible, and so it may be called the *special relativity model.* It is also called the *Milne model.* In this case (2.3) becomes $t_e = Z^{-1}t_0$ (figure 1).

In this particular model in order to see a part of the universe that is, say, one tenth the age of our own neighborhood, we should have to observe at reddening $Z = 10$. Now the largest value of Z yet observed for a normal galaxy is about 1.5; the largest value for a quasistellar object is about 3. Thus, in order to see far into the past in this model, an observer would have to be able to observe at reddenings much greater than any yet attained in practice. Although this particular model is somewhat extreme, in a qualitative way we can say quite generally: *in order to see far into the past, an observer must be able to observe drastically reddened radiation.*

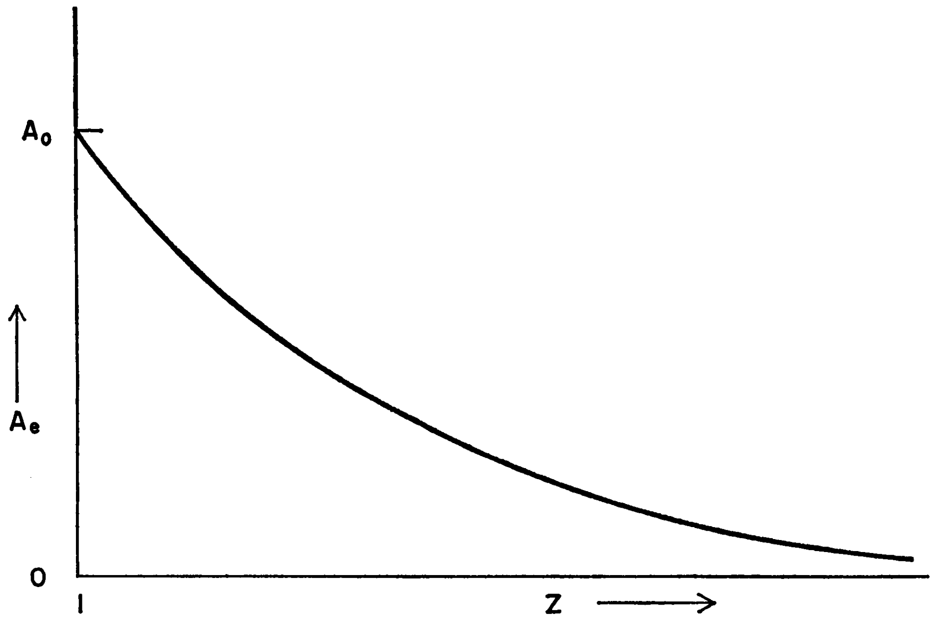

FIGURE 1

In evolutionary cosmology, radiation of wavelength λ_e emitted at cosmic epoch t_e has wavelength $\lambda_0 = Z\lambda_e$ when observed at cosmic epoch t_0. The figure shows qualitatively the relation between t_e, Z for fixed t_0.

2.2. *Ages of galaxies.* Suppose that, in the evolution of a model universe, effectively all galaxies are formed between cosmic epochs t_f and t_f^*. Then at any given Z value, an observer sees galaxies with ages between $t_e - t_f^*$ and $t_e - t_f$. The situation is shown qualitatively in figure 2. Two possibilities have to be contemplated.

(a) *Age spread small compared with local age.* This is the case of a fairly well-defined *age-distance relation;* see figure 2a. However, if it is necessary to see galaxies very much younger than the observer's in order to detect the relation, then once again *the observer would have to observe at large reddening.*

(b) *Age spread comparable with local age.* Here, there is a large age spread at most Z values; see figure 2b. *There is not a well-defined age-distance relation;* there is, of course, a relation between maximum age and Z, but this may not be of much value for observational tests.

We cannot say much more without using some theory of the formation of galaxies. In evolutionary cosmology, there is no well-formulated theory of galaxy formation in general. But there is one possibility that may apply to the

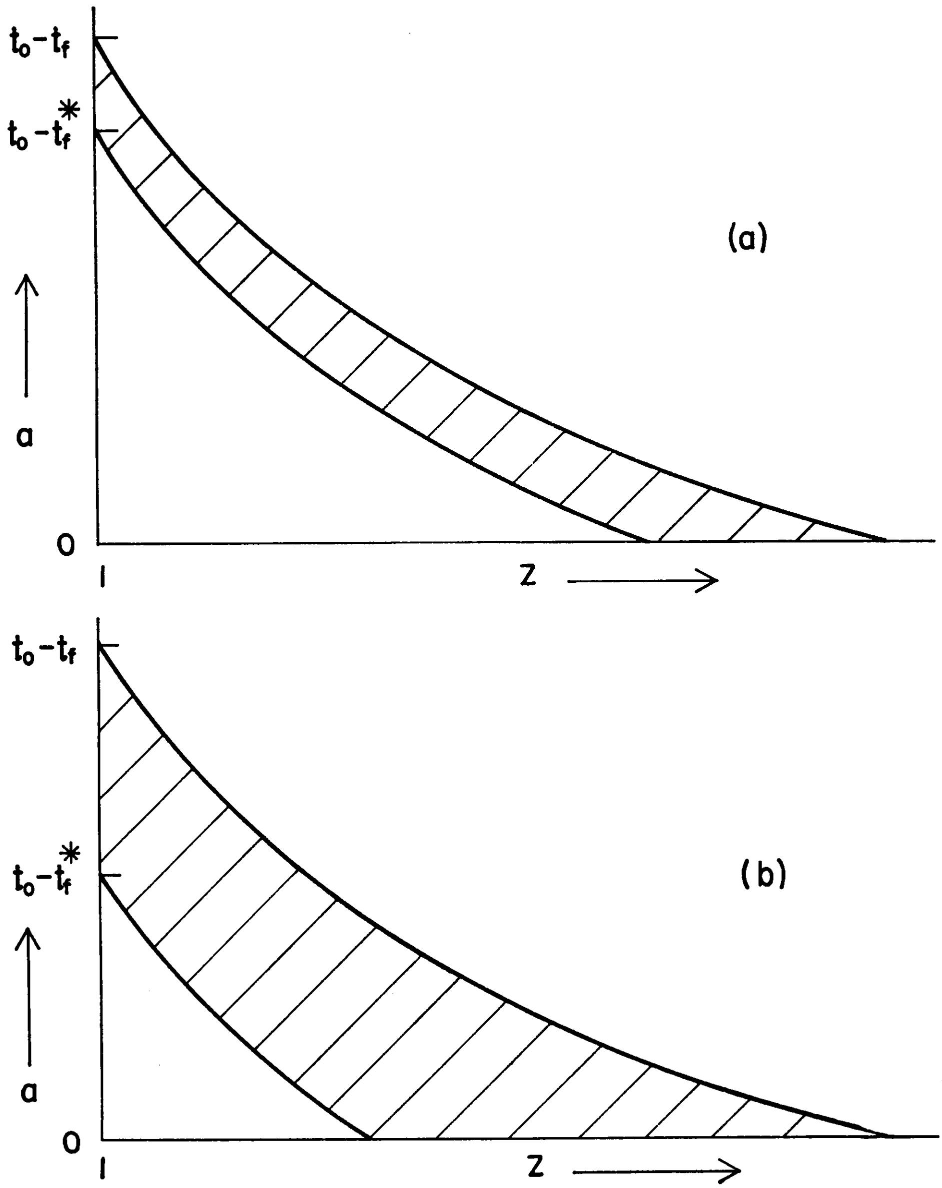

FIGURE 2

In evolutionary cosmology, if galaxies are formed between cosmic epochs t_f, t_f^*, then galaxies showing a given value of Z have age a where $t_e - t_f > a > t_e - t_f^*$ and t_e, Z are shown in figure 1. The figure shows qualitatively the relation between a, Z for fixed t_0 when

(a) the age spread is small compared with the local age,

(b) the age spread is comparable with the local age.

formation of certain other objects; in particular, it is of interest in regard to a recent suggestion by E. Teller concerning the origin of quasistellar objects (see below). We proceed to discuss this possibility.

2.3. *Collisional effects.* If there is any observable effect of interactions between galaxies, this may be expected to show a marked dependence upon cosmic epoch in an evolving model. Since the simple discussion about to be given applies only to a smoothed out model, the results may be expected to apply to encounters between field galaxies, or galaxies belonging to different clusters, but not to encounters within one and the same cluster.

In cosmological models of the sort considered, we have the theorem: *if the world line of a body of proper mass m_0 is a geodesic, then its energy as measured by the local observer is*

$$m_0 c^2 (1 + K^2/R^2)^{1/2}, \tag{2.4}$$

where K is a constant throughout the motion, so that K depends only on the initial motion of the body. Energy here refers to rest energy and translational energy.

I recently gave a particular case of this theorem in a lecture and P. G. Goodstein immediately generalized it. In passing, it is interesting to note that the reddening formula (2.3) is the limiting case of (2.4) where $m_0 \to 0$, $K \to \infty$, and $m_0 K$ tends to a finite limit.

If v is the local speed of the body, and if v is appreciably less than light-speed c, then (2.4) shows that

$$v \propto R^{-1}. \tag{2.5}$$

Applied to the random motion of the galaxies, this shows that *in the expansion of the universe the mean random motion $\bar{v}$, say, dies out like R^{-1}.* This effect may be described as the *adiabatic cooling of the expanding universe.*

Suppose now that at any epoch t, subsequent to the formation of the galaxies, there are $n(t)$ galaxies per unit volume. Then the definition of R means that

$$n = NR^{-3}, \tag{2.6}$$

where N is a constant.

We now postulate that some "product" results from some kind of encounter between a pair of galaxies, and that such a product remains in existence for a fixed proper time interval after it has been formed. Then the number of effective collisions suffered by each galaxy per unit volume per unit time is proportional to $n\bar{v}$ and, from the properties of n, $\bar{v}$ just quoted, this is proportional to R^{-4}. Thus the ratio of the number of product systems to the number of galaxies per unit volume is proportional to R^{-4}, so long as this ratio is fairly small. Also, this ratio is a local property, but a remote observer viewing the same locality naturally sees the same ratio. Therefore, since $Z \propto R^{-1}$, in any small interval of Z,

$$\frac{\text{number of product systems}}{\text{number of galaxies}} \propto Z^4. \tag{2.7}$$

3. Steady-state cosmology

The consideration of steady-state cosmology analogous to the consideration of evolutionary cosmology just given leads to a unique cosmological model. It is usually interpreted as implying that matter is continually created uniformly throughout the model at just the rate required to replenish the effect of the expansion of the universe; the newly created matter is considered to be mostly protons and electrons in equal numbers; this matter must then continually condense to form new galaxies.

In its simple form, the model may actually be got by taking the particular case of the foregoing work in which any observable property is independent of t. Of course, t then loses its significance as cosmic time, which clearly can have no meaning in a steady state model, but t retains its significance as an observer's proper time. In the model, T is a constant and $R = e^{t/T}$.

It can readily be shown that, for any well-defined ingredient whatever, we have

(3.1) fraction of objects with ages a to $a + da = \frac{3}{T} e^{-3a/T} \, da,$

(3.2) fraction with ages exceeding $a = e^{-3a/T},$

(3.3) mean age $= \frac{T}{3}.$

This simple result is of wide application. For instance, if galaxies in the model are formed by gravitational contraction of appropriate masses of the created matter the process must require a time of the order of T itself. That is to say, the galaxies must be composed of atoms of age greater than about T. But in any region of space, according to the result quoted, only a fraction of about $e^{-3} \doteqdot 1/20$ of the matter satisfies this condition. So we see that, in the model as envisaged, only a small fraction of all the matter is contained in the galaxies. This is the frequently quoted inference that *a steady-state universe contains a large amount of intergalactic matter.*

If galaxies are formed in the manner suggested, then any suitable stage in the formation of a condensation may be labeled zero age for a galaxy. Then the distribution of ages measured from this zero is again the distribution described, again with the same value of T. This distribution is always and everywhere the same in the model. As is well known, *a simple steady-state model exhibits no age-distance relation.*

Once again, although the application is different, not much more can be said without some theory of the formation of galaxies, and one possibility in this regard will now be considered.

3.1. *Galaxy formation in a steady-state universe.* Various interesting suggestions regarding the process of formation of galaxies from diffuse created matter have been advanced but none has come to be generally accepted.

I recently put forward a different suggestion, depending upon a different concept of continual creation. The concept in the steady-state theory, as hitherto considered, made the creation process into a continual succession on the atomic scale of uncaused events each conceptually like the unique uncaused event (the "big bang") of evolutionary cosmology. I ventured to suggest that a preferable hypothesis might relate the appearance of new matter to the presence of existing matter. One would then suppose that in certain physical conditions matter can "breed" new matter. In particular, it is known that galaxies experience "violent events" in the course of which matter is ejected with great speeds; the suggestion is that occasionally a portion of ejected matter becomes the embryo for the growth of a new galaxy according to the postulated process. This growth would stop at some critical stage, and in due course the process would be repeated. On the average, each existing galaxy would have to produce the embryo of a new galaxy once in $T/3$ years in order to maintain a steady state. However, I should wish not to contemplate more than a roughly steady state [2].

The new hypothesis is speculative, but it is less speculative than the hypotheses about creation that underly both evolutionary cosmology and the usual form of steady-state cosmology. For it regards the appearance of new matter as an ordinary physical process in the interaction of existing matter with existing matter, and not as an uncaused process. In fact, it avoids the necessity of having to say anything at all about the creation of the universe.

I have pointed out that the observable consequences of the hypothesis would be different according as the time required for a galaxy to attain the supposed critical mass, at which further mass increase would effectively cease, is much less than T or is about T or more. In the first case it would be rare to observe a galaxy of less than critical mass; in the second case, most galaxies observed would not yet have attained this mass.

Another important feature is that *this version of steady-state cosmology does not demand the existence of intergalactic matter.* At any rate, the existence of such matter is no longer a prerequisite for the formation of new galaxies.

4. Observational results

We have been using the term galaxy for convenience but we are interested in any class of object that can be observed out to what may be termed "cosmological distances." In age studies, we are, of course, specially interested in any features of such objects, either as individuals or in relation to other objects, that vary with time in a discoverable fashion. We consider the following categories.

4.1. *Galaxies.* Astronomers have for a long time had a system of classification of what they regard as "normal" galaxies. More recently a great deal of work has been done upon the morphology of these galaxies and also of peculiar galaxies, upon their internal motions, and to some extent upon the details of their composition in terms of stars, dust and gas. It has to be admitted, however, that as yet there is no agreement about anything concerning the evolution of a galaxy as a whole. And here it must be made clear that we are considering the evolution of a galaxy as an individual system assuming that such evolution is not appreciably affected by the behavior of the rest of the universe. Thus, if A, B are two different galaxies, there is no known case where we can claim with assurance that A was once like B or even that A is older than B. About all that can be said in regard to ages is that our own galaxy must have been composed largely of stars for between about 7×10^9 and 15×10^9 years and that roughly the same figures apply to all generally similar galaxies.

The situation is summarized more fully in the contribution to the Symposium by Dr. E. Margaret Burbidge and Dr. G. Burbidge [1]. In the discussion, Professor J. Neyman mentioned a conjecture that among binary systems of galaxies, those systems in which the two members are of markedly different types are in general older than those in which the members are of closely similar types. This conjecture may provide a vital clue to the ordering of galaxies in age sequence.

4.2. *Radio galaxies.* "Strong" radio galaxies are inferred to be galaxies that are undergoing some disturbance that causes them to emit strongly in radio frequencies over a (cosmically) short interval in their lives. The mere fact of being a strong radio emitter is therefore a time dependent feature of the galaxy concerned, and so this ought to render the feature particularly useful in age studies.

There has been some indication that this has proved to be the case. For the counts of radio sources, chiefly those made in Cambridge, England, have appeared to be most readily interpreted as showing that radio galaxies occurred more frequently at an earlier cosmic epoch than our own. However, as will be mentioned in section 5, it now appears that the interpretation is less simple.

4.3. *Clusters of galaxies.* Clusters of galaxies potentially provide a means of studying the universe to greater distances than can be done by using only individual galaxies. At present, unfortunately, even less is known about the evolution of clusters than about that of individual galaxies; hitherto they have not, therefore, assisted much with age studies. It should, however, be remarked that the relation of a galaxy to a cluster to which it belongs may supply additional information about that galaxy; for instance, there is some indication that the brightest galaxy in a cluster is a more standard object than any other cluster member.

4.4. *Quasistellar objects.* The so called "quasars" show greater redshifts than any hitherto measured for galaxies. If these redshifts are cosmological, it follows that quasars are the most remote objects yet observed. It then follows that they emit energy at one hundred or more times the rate at which the greatest normal galaxies are observed to radiate. Every theory of such objects then shows that they must be short lived on a cosmic scale; most estimates of the proper life of an object as an observable quasar vary from about 10^3 years to about 10^6 years.

Accepting this interpretation, in the usual terminology we should say that we observe quasars out to all distances up to 10^{10} light years or more. Since 10^{10}

years is very large compared with the estimates of the lifetimes just quoted, it follows that quasars as such must appear and disappear at all distances out to more than 10^{10} light years. If the universe is evolving, we could then say that they can appear and disappear at any cosmic epoch over an interval of at least 10^{10} years, that is, over most of the past history of the universe.

If a quasar is the same sort of object whenever one makes its appearance, then it might seem that nature has provided the astronomer with a most unexpected standardized facility for the exploration of the universe. However, we still cannot finally exclude the possibility that quasars are not at the distance corresponding to a cosmological interpretation of their redshifts.

5. Comparison of theory and observation: fundamental questions

In this discussion we deal only with considerations regarding age effects of one sort or another.

Suppose we wish to begin by testing the hypothesis that the universe is in a steady state. We can first notice that if any intrinsic property of galaxies, or of any of the other objects considered, shows any statistical dependence upon redshift then this would contradict the hypothesis. The dependence would have to be interpreted as an age-distance effect. Actually, no contradiction of this sort has been established. But the discussion in section 2 shows that this could be because astronomers have not yet been able to see far enough into the past in order to detect an age effect, or because such effects are masked by the spread of ages at all observable distances.

Secondly, we ask if any statistical result of counts of galaxies (or other objects) contradicts the predictions of steady-state cosmology. If there is such a contradiction, it could arise directly from the use of a wrong model; or it could arise from an age-distance effect in regard to the frequency of occurrence of the objects concerned; or it could arise as an age-distance effect in regard to a statistical dependence of intrinsic properties of the objects upon epoch, this effect not being otherwise detectable because redshifts are unobtainable for these objects. As already mentioned, it has long been claimed that the Cambridge counts of radio sources do supply a clear contradiction of this sort, and this is usually interpreted as evidence of an age-distance effect of one sort or another.

At present, however, the whole matter is once again in a state of doubt. P. Véron [4] has announced the remarkable discovery that the feature of the counts upon which the alleged contradiction mainly depends is produced by those radio sources that have the general character of quasars. If only radio galaxies are counted, there is not a clear contradiction of the steady state, or so it seems to the writer. As he sees it, the situation is: if the quasars are at cosmological distances, then they may provide a contradiction of steady-state cosmology even more definite than do any other available observations; on the other hand, if there is some other explanation of the quasar phenomenon, no clear contradiction of steady-state cosmology may yet be claimed.

5.1. *Age sequence of galaxies.* In order to test the steady-state hypothesis, we do not need to know in advance how a galaxy changes with age. Were we to find a dependence of any local property upon redshift, we should conclude that the universe is evolving (that is, not in a steady state). We should then further conclude that the age of the galaxies decreases statistically with increasing redshift. In this way *the study of the universe on a large scale may enable astronomers to place an age sequence upon the observed forms of galaxies and perhaps to assign actual ages.* This possibility has not yet been realized.

On the other hand, if we find no contradiction with the steady state, the situation becomes simpler, but more difficult. It is simpler because in this case, a study of ages is not complicated by any age-distance effect; it is more difficult because there is no age-distance effect that could enable us to recognize an age sequence. In this case, the study of the universe on a large scale is likely to be less helpful in the study of ages of galaxies for their own sakes. On the other hand, any inference from other evidence about ages must now be compatible with the general result of (3.1), and this should prove to be a useful check.

5.2. *Quasistellar sources.* Teller [3] has considered the hypothesis, which has been discussed by others as well, that the quasar phenomenon is produced by encounters between pairs of galaxies, one composed of matter and the other of antimatter. According to Teller's picture, the energy release would result from collisions between stars belonging to such galaxies.

Were such processes to occur in an evolving universe, our result (2.7) shows that the proportion of quasars to galaxies would increase very steeply with increasing redshift. Available observations do not show this effect. On the other hand, were the processes to occur in a steady-state universe then the proportion of quasars to galaxies would, of course, be everywhere the same. While Véron's statistics would not quite agree with this result, they would disagree with it less than with the result (2.7) for evolving models. If quasars do arise from encounters between other systems, their properties would therefore on the whole rather strongly favor steady-state cosmology. However, such an origin of quasars is by no means yet established.

In any case, if quasars are "cosmological" and at the same time short lived, it is on general grounds rather difficult to see why they should keep on occurring in an evolving universe. In a steady-state universe, they would have to keep on occurring. So the mere existence of quasars, if "cosmological," appears to support the view that the universe is in something like a steady state.

6. Conclusion

This brief survey of the subject probably appears disappointing as regards information about ages of any systems of cosmological significance. Perhaps the most important feature of the discussion is that Véron's analysis of the statistics of radio sources, and the present writer's suggestions about the process of continual creation, seem to have weakened some of the evidence against steady-state cosmology. Further, there is some indication that the existence of quasars may provide positive evidence for such cosmology.

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