The redshift of extragalactic nebulae
by **F. Zwicky.**
(16 II. 33)

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Synopsis. This work is a presentation of the main characteristics of extragalactic nebula, as well as the methods that have been used for research into them. In particular, the so-called redshift of extragalactic nebulae is discussed in detail. Various theories that have been advanced to explain this important phenomenon are briefly discussed. Finally it is indicated how redshift promises to be of importance for the study of penetrating radiation.

§ 1 **Introduction**.

It has been known for a long time that there are certain objects in space, which, if observed with small telescopes, appear as strongly blurred, luminous spots. These objects vary in structure. Often they are spheroid, often elliptical, and many of them have a spiral-like appearance, for which reason they are sometimes designated as spiral nebulae. Thanks to the enormous resolving power of modern giant telescopes, it was possible to determine that these nebulae lie outside the boundaries of our own Milky Way system. Images made with the hundred-inch telescope on Mount Wilson reveal that these nebulae are star systems similar to our own Milky Way system. The extragalactic nebulae are by and large uniform across the sky and, as has been shown, also uniformly distributed over space. They occur as single individuals or grouped in clusters. The following lines attempt a brief outline of the more important features and a description of the methods that have made it possible to establish these features.

§ 2 **Distances and general characteristics of extragalactic nebulae**.

As already mentioned, it is possible with the help of modern telescopes to resolve a number of nebulae wholly or in part into individual stars. In the great Andromeda nebula, for instance, a large number of individual stars have been observed.

Recently, globular star clusters have also been discovered in the nebula, similar to those which lie in areas of our own Milky Way system. The fortunate fact of the observability of individual stars in nebulae opens up two ways to determine their distances.

A) *Determining distance by means of the period-luminosity relation for Cepheids.*

Cepheids are stars whose brightness varies periodically with time. These periods are usually in the range of one to sixty days. The absolute magnitude is an unambiguous function of the period, which function has been determined for stars of our own system. For a known period it is thus possible to derive the absolute magnitude of Cepheids from this relationship. By determining the apparent magnitude and comparing this with the calculated absolute magnitude, we obtain directly the distance of the stars. A number of Cepheids have been observed in the Andromeda nebula. Its distance and diameter have been determined with their help at approximately 900,000 and 42,000 light-years respectively. For comparison, it should be recalled that our own system has a diameter whose upper limit is estimated at about 100,000 light-years. Similarly, the distances of eight other nebulae have been found. In nebulae whose distance is greater than a few mllion light years, individual Cepheids can no longer be resolved. To determine their distance other methods must therefore be devised.

B) *Statistics of the brightest stars of a nebula.*

This method rests on the assumption that in extragalactic star systems, the relative frequency of the absolute magnitudes of stars is the same as in our own system. Experience with previously investigated neighboring systems is in fact in agreement with this assumption. The absolute magnitude of the brightest stars in our own and in neighboring systems yields on average — 6.1 with a variation of less than half a large class. Similar determinations of the distances with the help of novas shall here only be noted.

C) *Determination of the distance of nebulae by means of their total apparent magnitude.*

Using the first two methods, the distances of about sixty extragalactic nebulae have so far been found. From the measured apparent magnitude and the known distance of the nebulae we can immediately infer their absolute magnitude. We thus obtained the following distribution curve (Fig. 1).
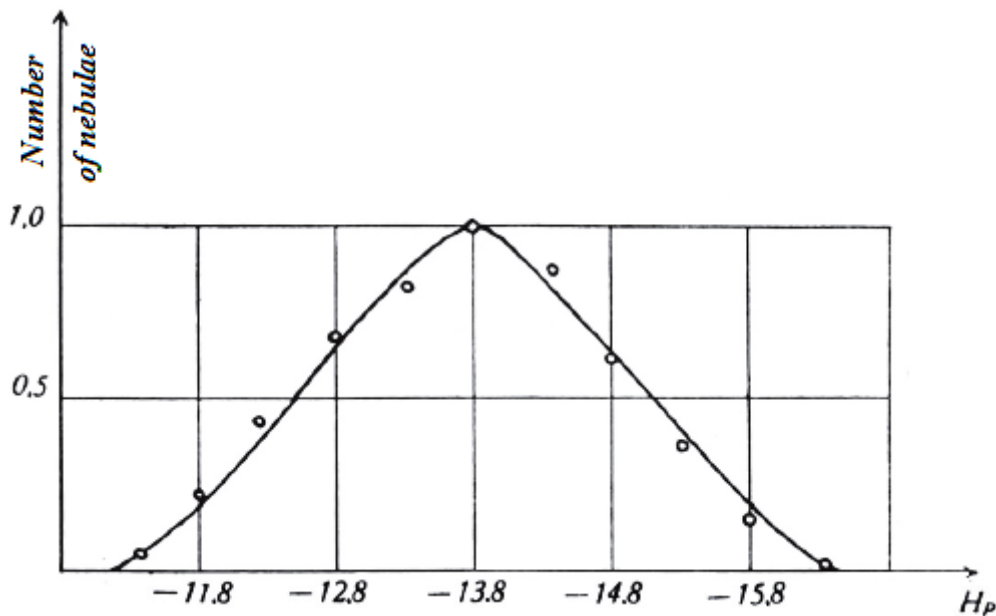

Fig. 1.

H_p = Photographic brightness.

The mean absolute visual brightness of the nebulae is found to be — 14.9 with a variation of approximately five classes and a full width at half maximum of the size distribution curve of about two size classes. This dispersion is unfortunately too large to allow an accurate determination of the distance of an *individual* nebula from its apparent magnitude and the distribution curve of the absolute magnitudes. How it is still possible to determine the distances of an isolated nebula with great accuracy, is discussed later. The following fact allows us, however, to find the distance of a large number of extremely faint nebulae. As already mentioned, nebulae often group in dense clusters which include a hundred to a thousand individuals. It is of course extremely likely that such an apparent cluster of nebulae also means a real cluster in space, and that, therefore, all these nebulae lie at about the same distance. It is relatively easy to determine the distribution curve of the apparent magnitudes of the nebulae of a cluster. This distribution curve

is virtually the same as the distribution curve of the absolute magnitudes of the sixty nebulae whose distances have been found under A) and B). This is proof that the apparent nebular cluster also corresponds to a genuine dense swarm in space. A comparison of the average apparent brightness of the nebulae in the cluster with the mean absolute value of —14.9 immediately provides the distance to the cluster. Distances of the following nebulae have been determined in this way.

Table I.

Nebular cluster	Distance in millions of light years
Coma-Virgo	6
Pegasus	23.6
Pisces	22.8
Cancer	29.3
Perseus	36
Coma	45
Ursa Major I	72
Leo	104
Gemini	135

The number of nebulae per unit volume in one of these dense swarms is at least a hundred times larger than the corresponding mean number of individual nebulae distributed in space.

It is of interest to interpolate here are some brief remarks concerning other features of nebulae which are accessible to investigation by means of the hundred-inch telescope.

In the first place, with respect to the structure of the universe it is of importance whether the distribution of nebulae over space is uniform or not. In the case of uniformity we expect for the number of nebulae in a spherical shell of radius r and thickness dr a constant number of nebulae proportional to r^2, provided that we are dealing with a Euclidean space. This expectation indeed corresponds very closely to reality, that is, for that part of the universe which is within the range of the hundred-inch telescope. This of course does not mean that space will not occasionally turn out to be a non-Euclidean space, should it manage one day to penetrate further into it.

We must not omit to mention that the above conclusions are only valid in the absence of absorption and scattering of light in space. However, the finding of a uniform distribution of nebulae up to the greatest attainable distances with a method that requires the virtual absence of absorption and scattering is, in itself almost a proof of the correctness of this assumption. In fact, an actually existing uniform distribution of nebulae would be falsifed through absorption because the number of nebulae weaker than r^2 in spherical shells of constant thickness would increase with distance and eventually even decrease. In view of the fact that gas and dust masses can be verified with certainty in the interstellar space of our system, it would however be of great importance to provide an independent proof of the transparency of intergalactic space and to show that a curvature of space, combined with absorption and scattering, does not simulate a uniform distribution of nebulae. A statistical study of the apparent diameter of nebulae would for instance be suitable for this.

Theoretically, the presence of intergalactic matter must correspond to the vapor pressure of the existing star systems. Assuming that the universe has reached a stationary state, this vapor pressure can be estimated[1]). It turns out to be extremely small, practically ruling out the discovery of intra-galactic matter.

Another interesting question is associated with the spectral types of nebulae. Most extragalactic nebulae have absorption spectra similar to that of the sun with very prominent *H* and *K* lines of calcium and an intense *G*-band of Ti (4308 Å), Fe (4308 Å) and Ca (4308 Å). Therefore nebulae belong to spectral type *G*. The spectral type is independent of the distance, so far as the observations extend to date. A distance-dependent shift of the total spectrum will be discussed later. The width of the absorption lines usually amounts to several Ångstrom units, and is likewise independent of the distance.

A small percentage of the observed nebulae also exhibits emission lines (nebulium), which usually emanate from the core part of the nebula. Very little is unfortunately known yet of the physical conditions in such systems.

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[1]) F. Zwicky, Proc. of the Nat. Academy of Sci., Vol. 14, p. 592, 1928.

Third it is of importance to investigate the occurrence of the different forms of nebulae already mentioned. The statistical distribution is approximately 74% spirals, 23% spherical nebulae, and about 3% show an irregular appearance.

Fourth, I wish to mention the determination of the magnitude distribution within a single nebula. This study has been undertaken recently by E. HUBBLE at Mount Wilson. HUBBLE obtained the following preliminary result. Luminosity is represented as a universal function $L(r,z)$, where r is the distance from the center of the nebula, and z is a suitable parameter. By varying z, the magnitude distributions in all nebulae can be reduced with high accuracy (about 1%) to the same function, up to values of r for which the brightness has dropped to 1/1000 that of the center. It is also of importance with respect to the virtual absence of absorption and scattering in intergalactic space that the distribution function of z's in the different nebulae is independent of the distance. Casually it should be mentioned that L coincides with that function, which corresponds to the brightness distribution in an isothermal Emden gas sphere.

Fifth, it is of enormous importance that the nebulae at great distance exhibit red-shifted spectra in which the shift increases with distance. The discussion of this so-called redshift is the main topic of this work.

§ 3 The redshift of extragalactic nebula.
Relationship between distance and redshift.

V.M. SLIPHER at the observatory in Flagstaff, Arizona was the first to observe that certain nebulae display shifts of their spectra corresponding to a Doppler effect of up to 1800 km/sec. Against this, no relationship has as yet been established by SLIPHER between redshift and distance. Such a relationship was first conjectured by G. STRÖMBERG[1]) on the occasion of his investigation upon the velocity of the sun relative to more and more distant objects. He found that the mean velocity of the sun relative to the system of our neighboring nebulae is very large, i.e. of the order of magnitude of 500 km/sec, and that the group of nebulae used has an expansion which seems to depend on the distance of the individual nebulae.

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[1]) G. STRÖMBERG, Astrophys. Journal 61, 353-388 (1925).

Since at the time of Stromberg's investigation there was still no known reliable estimate of the distances of the nebulae, K. LUNDMARK tried to bring the observed large velocities into context with the "compactness" of photographic images of nebulae. This later proved to be an attempt in the right direction. The test was positive but without success, because it turned out that the apparent diameters of nebulae at the same distance display large variations.

E. HUBBLE at Mount Wilson worked in the same direction. He also first tried to connect the red-shift to the apparent concentration of the nebulae. He started from the idea that the redshift correlated with the famous Einstein effect. It appeared, however, that it was not possible in this way to uncover rational relationships.

E. HUBBLE then tried to correlate the redshift with the distance of different nebulae. This experiment has, as is well known, since then been crowned by great success. The nebulae which were initially available for such an investigation had distances from one to six million light-years. The discussion of all the data showed a linear relationship between redshift and distance, with the result that the shift of an apparent escape velocity of 500 km/sec corresponded to a million parsecs (1 parsec equals about 3.26 light-years). The range, however, was at the same time relatively large, e.g. our next-door Andromeda nebula has a *violet* shift of about 200 km/sec, i.e. it moves either apparently or really toward us. Nevertheless it later emerged that the shift of the spectra first calculated here was an extraordinarily good one. The best proof of the amazing rigor of Hubble's method is probably that he could already in any case predict the redshifts to an accuracy of within a few per cent on the basis of the above relationship, and indeed for distances which have grown to up to thirty times those first used.

The difficulty of photographing the spectra of very distant nebulae lies in the necessity of exceptionally long exposure times. In fact it was necessary to expose plates up to fifty hours and more, and it seemed hardly possible to penetrate much further into space with this investigation. In recent times much progress has been made with this,

using a spectrograph whose camera lens has an aperture ratio of F/0.6. Dispersion however was thus greatly sacrificed, and the spectra obtained are only about two millimeters long. The exposure times could however be reduced to a few hours. Nevertheless, it does not seem to be possible to penetrate more than about 200 million light-years into space. The reason for this lies partly in the location of the hundred-inch telescope near the great city of Los Angeles, because the illumination of the night sky and the associated strong light scattering in the telescope unfortunately sets the astronomical observations on Mount Wilson a limit which still lies below the actual performance of the telescope. For the 200-inch telescope which is currently under construction in the California Institute of Technology, a more favorable location will therefore have to be selected.

The redshifts of the different nebulae, expressed as apparent Doppler escape velocities are summarized in the following Table II.

Table II [1]).

Nebular clusters	Number of nebulae in the cluster	Apparent diameter	Distance in 10^6 light years	Average velocity
				km / sec
Virgo	(500)	12°	6	890
Pegasus	100	1°	23.6	3810
Pisces	20	0.5	22.8	4630
Cancer	150	1.5	29.3	4820
Perseus	500	2.0	36	5230
Coma	800	1.7	45	7500
Ursa Major I	300	0.7	72	11800
Leo	400	0.6	104	19600
Gemini	(300)	—	135	23500

These results are shown graphically in Fig. 2.

From this compilation it follows that the extra-galactic nebulae have velocities which are proportional to the distance. The specific velocity per million parsecs is,

$$v_s = 558 \text{ km/sec.} \tag{1}$$

The mean redshift of each individual nebula is derived from the shifts in the means of at least three spectral lines.

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[1]) See E. HUBBLE and ML HUMASON, Astrophys. Journal LXXIV, 1931 In this work can be found the most important references.

These are typically the *H*- and the *K*-lines, the *G*-band (λ = 4303 Å) and, occasionally, one of the lines H_δ (4101 Å), H_γ (4340 Å), Fe (4384 Å) and H_β (4861 Å). The uncertainty in the redshift of the nebular cluster in Leo is for instance obtained in this way as
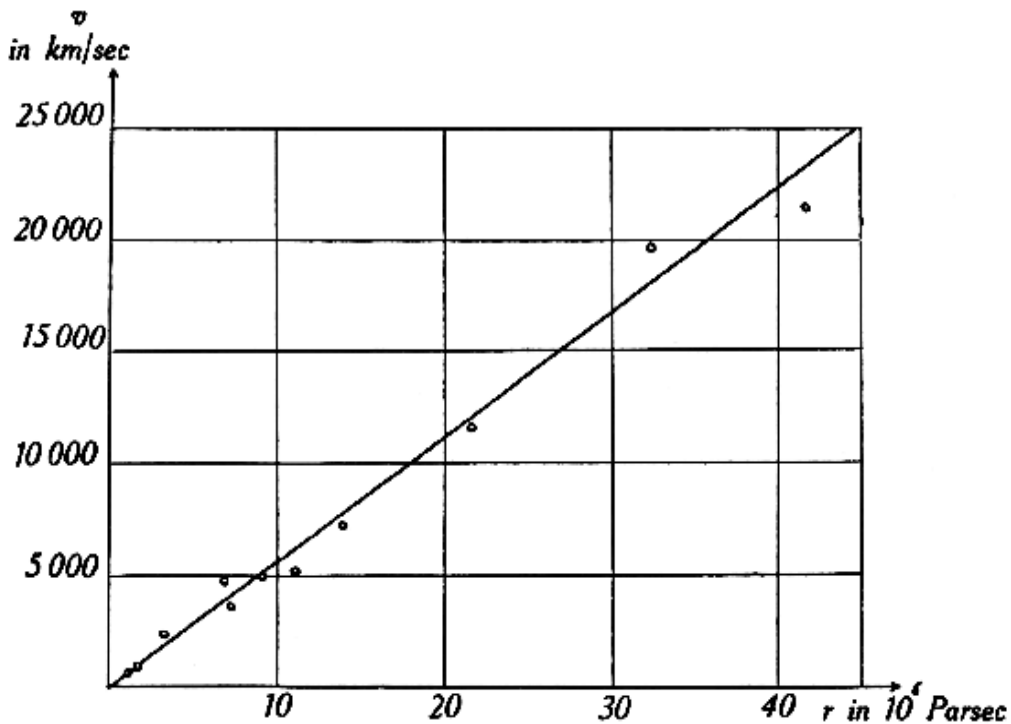
$$v = 19621 \pm 300 \text{ km/sec.}$$

Fig. 2.

The different absorption lines suffer the same relative shift, just like the Doppler effect. It is thus for a particular nebula

$$\Delta\lambda/\lambda = \text{constant} = K = v/c \vdots = xr \tag{2}$$

independent of wavelength λ, and the displacement can, as we have done, be conveniently expressed in velocity measures. Therefore, the same value of *K* also applies to the shift of the maximum of the continuous emission spectrum.

It must not be left out of consideration that we have plotted in Fig. 1 the mean Doppler velocity of the nebular swarms. This speed is the average of the values of several individual nebulae (2-9) in each cluster. It is of great importance for the theory of the effects discussed here, that the velocities of the individual members of a cluster can be very different from the mean. In the Coma system, for example, which has been the most studied to date, the following individual values have been measured.

Apparent velocities in the Coma cluster.

$v = 8500$ km/sec   6900 km/sec
            7900   6700
            7600   6600
            7000   5100 (?)

It is possible that the last value of 5100 km/sec corresponds to a so-called field nebula which does not belong to the Coma system, but rather only projects into it. The probability for this assumption is not very large (1/16). Even if we omit this nebula, the variations in the Coma system still remain very large. It is in this context of interest to recall that the average density in the Coma cluster is the greatest observed until now.

Now that the relationship between distance and redshift is known. we can conversely derive the distances of individual nebulae, if their redshifts are measured spectroscopically. Furthermore, we can again independently check the reliability of the methods discussed earlier for determining the distance. For this we in fact need only to determine the distribution curve of the magnitudes of all individual nebulae of the same redshift. This new distribution curve must match that of Fig. 1 if our original distance determination is correct. This is, in fact, very nearly the case.

As already mentioned, the light shift means a shift of the entire emission spectrum of the nebula. In addition to reduction of apparent photographic brightness in geometric function to the distance, there is also a reduction due to the redshift. The problem of spatial distribution of nebulae at large distances is not only the curvature and absorption of space, but is also closely related to the redshift, which greatly complicates the whole situation.

In conclusion, we must mention some results of VAN MAANEN, which appear to be in contradiction with Hubble's estimate of distance. VAN MAANEN has measured the apparent motions (in angular measure) of nebulae over the celestial sphere over a period of about twenty years. Since the corresponding angular velocities of the nearest nebula are only about 0.01 seconds of arc per year, this study can use only nebulae with well-defined, star-like "cores",

otherwise the determination of the coordinates of the nebula is greatly complicated by the blurring of its photographic image. Combining the Van Maanen angular velocities with the Hubble distances, we obtain extremely high speeds. For N.G. 4051, which according to HUBBLE lies at a distance of 4,000,000 light years and has the apparent radial velocity 650 km/sec, VAN MAANEN measures an angular velocity of 0.015" per year, from which results a real velocity of 94,000 km/sec. Therein lies a big problem. A trivial solution seems not to be precluded a priori in which perhaps the movement observed by VAN MAANEN could be attributed to not the nebula, but the star background used as a reference system. It must be emphasized, however, that VAN MAANEN has found similar discrepancies for 13 nebulae. From this still emerged the result that all these nebulae appear to move away from the pole of the Milky Way, which is difficult to explain by the assumption of a movement of the reference system.

Of equal importance is Van Maanen's determination of the intrinsic rotation of extragalactic spiral nebulae. In Messier 33, according to HUBBLE 900,000 light-years distant, VAN MAANEN observed, superimposed over the above-mentioned transverse motion, a rotation of the entire nebula whose components for individual objects in the nebula are of the order of 0.012" to 0.024" per year. At the above distance rotation speeds result of the order of 33,000 km/sec, whereas for example F. G. PEASE measured an intrinsic rotation of only 800 km/sec for N.G.C. 4594 from the Doppler effect at both ends of its diameter [1]).

Thus if one does not attribute the van Maanen results to errors of observation but rather accepts them as characteristic of the nebula itself, and does not want to drop the Hubble distance estimates, one faces a serious problem.

§ 4. Speculation concerning the redshift.

A complete theory of redshift must lead to results which satisfy the following requirements.

l. Redshift is a Doppler effect analogue, i.e. $\Delta\lambda/\lambda$ is a constant for a given nebula.

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[1]) The observations of Messier 33 itself are not yet complete. The rotational velocities amount to only about 50 km/sec.

2. The apparent Doppler velocity is proportional to the distance r and is 558 km per second and million parsecs.

3. There is no appreciable absorption and scattering of light in space which might be associated with the red shift.

4. The precision of the optical images of the nebula is as good as one can expect from the resolution of the instruments. The distance of the objects seems to play the role expected from geometrical considerations.

5. The spectral types of nebulae are essentially independent of the distance.

6. The large range of individual values of velocities of densely-clustered nebulae must be explained in connection with the redshift.

7. The speed of light on the long way from the nebula to us is practically the same as the speed of light known from terrestrial measurements. This was ascertained by aberration measurements of for nebulae by STRÖMBERG and also of BIESBROEK.

8. A theory of redshift which does not simultaneously provide an explanation of the van Maanen results is at least unsatisfactory.

The facts cited represent the observational material up to a distance of about 150 million light years. Before us so far lie two general proposals for their clarification. The first includes all the theories of a cosmological character which are based on the theory of relativity. The second is based on an interaction of light with the matter in space.

A) Cosmological theories.

A large number of attempts have in recent years been made to explain the redshift on the basis of the theory of relativity. Some key ideas are the following.

The general theory of relativity has led to two views concerning the structure of space. One is represented by the Einstein quasi-spherical world, while DE SITTER has derived for the case of vanishingly small mass density the possibility of a hyperbolic space.

While the geometry of Einstein's space does not directly lead to a redshift, such a thing is necessarily linked with the de Sitter world. R. C. TOLMAN has shown, however, that with this $\Delta\lambda/\lambda$ depends not only on the distance, but also on the intrinsic speed of the nebula. It follows that one would expect in addition to the redshift also blueshifts which, though smaller on average, are on the whole of the same order of magnitude as the redshifts, which contradicts the observations. The redshift could therefore not be directly associated with the curvature of space.

Another important proposal comes from FRIEDMANN, TOLMAN, LEMAITRE and EDDINGTON, from whose work it emerges that a static space according to the theory of relativity is dynamically unstable and will therefore begin to contract or expand. This result was interpreted by them as meaning that the redshift corresponds to an actual expansion of the universe. This proposal has since been discussed in detail by many researchers. The simplest formulation has recently been given by EINSTEIN and DE SITTER[1]). These two researchers provisionally propose an overall curvature of space in its entirety. The curvature of space was in essence a consequence of the introduction of a so-called cosmological constant Λ in the Einstein field equations, corresponding to the postulate of a repulsive force, which for very large distances compensates for Newtonian attraction. This postulate was historically necessary to understand the existence of a non-vanishing average mass density, which would otherwise lead in the limiting case of an infinite static space to infinite gravitational potentials. However, this latter difficulty falls away automatically if all masses in the universe move apart or together. The expansion of the material can then be brought in the absence of Λ and under the average curvature into direct correspondence with the mean density. An expansion of 500 km/sec per million parsecs corresponds according to EINSTEIN and DE SITTER to an average density $\varrho \backsimeq 10^{-28}$ g/cm^3. From the observations of self-luminous matter HUBBLE estimates $\varrho \sim 10^{-31}$ g/cm^3. It is of course possible that luminous plus dark (cold) matter taken together result in a significantly higher density, and the value of $\varrho \sim 10^{-28}$ g/cm^3 therefore does not appear

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[1]) A. EINSTEIN and W. DE SITTER, Proc. of the Nat. Acad. Sci. Vol. 18, s. 213, 1932.

unreasonable. According to EINSTEIN the following more accurate equation further arises for the redshift

$$\Delta\lambda/\lambda = xr \left[1 + 7 \, \Delta\lambda/4\lambda\right]. \tag{3}$$

This means that for large distances the redshift should increase more than linearly with distance. On the basis of the observational data to date, it is unfortunately not yet possible to confirm this important conclusion. Values of $\Delta\lambda/\lambda \sim 1/7$ recently observed for the greatest distances are nevertheless large enough to enable us to expect considerable differences (25%) from the linear relationship.

The theory also leads to certain conclusions relating to the distribution of magnitudes, number of nebulae, diameter, etc., depending on the distance, but which are also not confirmed.

None of the cosmological theories has until now addressed the problem of the large range of velocities in dense nebular clusters such as the Coma system.

B) Direct influence of the frequency of the light by matter present in space.

An attempt to use various physical effects such as the Compton effect on resting or moving electrons in space, Raman effect, etc., to explain the redshift was made by me a few years ago [1]. It was found that none of these can play a significant role. That is to say, by drawing on effects which have their origin in a direct spatial interaction between light and matter, it appears impossible to explain the transparency of intergalactic space.

In answer to this, I suggested at that time another possible effect which can hardly be observed on earth, but for whose existence certain theoretical foundations can be put forward. A photon or quantum of light of frequency v corresponds according to the theory of relativity to a sluggish as well as heavy mass hv/c^2. So there is an interaction (attraction) between light and matter. If the photon is emitted and absorbed at two different points P_1 and P_2 whose gravitational potentials are *the same*, so it loses on the way from P_1 to P_2 a certain momentum and releases this as matter. The photon becomes redder. This

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[1] F. ZWICKY, Proc. of the Nat. Acad. Sci, Vol. 15, p 773, 1929.

effect, which might be called gravitational friction, is essentially caused by the finite speed of propagation of gravitational effects. Its size depends on the mean density of matter, as well as its distribution. The redshift of $\Delta\lambda/\lambda$ in this case depends not only on the distance but also on the distribution of matter. Studies are under way to test this conclusion.

Finally, it is well to say that none of the hitherto proposed theories can satisfy. All are developed on an extremely hypothetical basis, and none of them has succeeded in practice in uncovering any new physical connections.

§ 5 Remarks on the spread of velocities in the Coma nebulae.

As can be seen from the compilation in § 3 there exist in the Coma cluster apparent differences in speed of at least 1500 to 2000 km/sec. In connection with this huge spread of velocities one can present the following considerations.

1. If it is assumed that the Coma system has mechanically reached a stationary state, it follows from the virial theorem

$$\bar{\varepsilon}_k = -\tfrac{1}{2}\,\bar{\varepsilon}_p, \tag{4}$$

where $\bar{\varepsilon}_k$ and $\bar{\varepsilon}_p$ represent the mean kinetic and potential energies, for example of the unit of mass in the system. For purposes of estimation, we assume that the matter is distributed in the cluster uniformly throughout the space. The cluster has a radius R of about a million light-years (equal to 10^{24} cm) and contains 800 individual nebulae each of a mass corresponding to 10^9 solar masses. The total mass M of the system is therefore

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45} \text{ g.} \tag{5}$$

It follows for the total potential energy Ω:

$$\Omega = -\frac{3}{5}\,\Gamma\,\frac{M^2}{R} \tag{6}$$

Γ = gravitational constant

or

$$\bar{\varepsilon}_p = \Omega/M \sim -64 \times 10^{12} \text{ cm}^2 \text{ sec}^{-2} \tag{7}$$

and further

$$\bar{\varepsilon}_k = \overline{v^2}/2 = -\varepsilon_p/2 = 32 \times 10^{12} \text{ cm}^2 \text{ sec}^{-2}$$
$$(\overline{v^2})^{\frac{1}{2}} = 80 \text{ km/sec .} \tag{8}$$

As observed, to obtain an average Doppler effect of 1000 km/sec or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observation of luminous matter [1]. If this should prove true, the surprising result would emerge that dark matter is present in very much greater density than luminous matter.

2 One can also assume that the Coma system is not in stationary equilibrium, but that the entire available potential energy appears as kinetic energy. It would then be

$$\varepsilon_k = -\varepsilon_p \tag{9}$$

Through this assumption one can save only by a factor of 2 compared to 1., and the need for an enormous great density of dark matter remains in place.

3. The average density in the Coma cluster is entirely determined by the occurrence of luminous matter (the above mass M). The great velocities cannot then be explained on the basis of considerations of type 1. or 2. If the observed velocities are nonetheless real, then the Coma system would fly apart with time. The result of this expansion would at the end be 800 single nebulae (field nebulae), which would, as is apparent from 2., have individual velocities of the original order of magnitude (1000 to 2000 km/sec). By analogy one should thus expect that single nebulae with such large individual velocities could also be observed at the present stage of development of the universe. However, this conclusion hardly accords with the empirical facts, according to which the range of individual velocities of singly occurring nebulae does not exceed 200 km/sec.

4. One can also try to conceive of the velocities as apparent, by interpreting them as being caused by the Einstein redshift. Assuming the above mass M one has for the relative change of the wavelength λ

$$\Delta\lambda/\lambda \sim -\varepsilon_p/c^2 \sim 3.5 \times 10^{-8} \tag{10}$$

which corresponds to a speed of only 10 m/sec. To arrive in this way at an explanation for the large rates of variation, one would need a much greater density of dark matter than allowed under 1. or 2.

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[1] This would be the order of magnitude in accordance with the view of EINSTEIN and DE SITTER discussed in §4.

From these considerations it appears that the large range of velocities in the Coma system (and in other dense nebulae) contains an as yet unresolved problem.

§ 6. Penetrating radiation and redshift.

Comparing the intensity of visible light from our Milky Way (L_m) with the intensity of the light (L_w) coming to us from the rest of the universe, we obtain

$$L_m/L_w >> 1 \qquad (11)$$

Assuming that the penetrating radiation is not local in character gives the ratio of the intensities of S analogous to those at (11) as

$$S_m/S_w < 0.01. \qquad (12)$$

This follows from the practical absence of sidereal variations of the penetrating radiation. As I have explained elsewhere [1]), the inequality (12) is therefore difficult to understand, because cosmic rays produced at very great distance reach Earth with greatly reduced energy owing to redshift. If for instance redshift were proportional throughout the distance, light quanta which come from distances greater than 2000 million light years would reach us with zero energy. (From this consideration it follows in passing that even in the presence of infinitely many stars in the universe, the light intensity nevertheless everywhere has a finite, well-defined value.) Under plausible assumptions about the type of reaction which produces cosmic rays, it is very difficult to understand the inequality (11), and here indeed lies, as indicated, the main difficulty in the existence of the redshift [1]).

Finally, I would like to point out that the coexistence of the two inequalities (11) and (12) will cause very great difficulties for certain recent views on the origin of the penetrating radiation. B. G. LEMAITRE has for instance proposed that one can consider the cosmic rays as a remnant of some super-radioactive processes that went away a long time before. Now, however, a correspondingly huge amount of

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1) F. ZWICKY, Phys. Review January 1933

visible and ultraviolet light must be emitted simultaneously. Since interstellar gases (as well as our atmosphere) absorb penetrating radiation more strongly than visible light, the coexistence of the inequalities (11) and (12) is incomprehensible.

It is also important in this context to point out the following interesting fact. An irregularly bounded girdle, which runs along the Milky Way and extends from about $-10\,°$ to $+10\,°$ galactic latitude, blocks completely our view into extragalactic space, i.e. no extra-galactic nebulae can be observed in this belt. It is known that a part of the absorption is due to very broad, dense masses of dust. If the penetrating rays are of extragalactic origin, one should actually expect that they would be absorbed along the Milky Way, i.e. one would observe on Earth a sidereal variation of the intensity of cosmic rays. Since such a variation is not found, one is tempted to conclude that the penetrating radiation cannot be of extragalactic origin. It must however be examined in more detail, at what density and to what extent interstellar matter occurs in the Milky Way.

The present work emerged from numerous discussions with researchers working in this field at Mount Wilson Observatory. I especially owe Dr. W. BAADE a great debt of gratitude for much valuable advice.

California Institute of Technology, Pasadena.

Translator's note: The contemporary usage has been retained, notably in the use of "nebula" (*Nebel*) for what are today recognised as galaxies. The author's "penetrating radiation" (*durchdringende Strahlung*) similarly represents what we would now term cosmic rays.