Published in Helvetica Physica Acta, Vol. 6, p. 110-127, 1933.
https://arxiv.org/abs/1612.00805

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THE REDSHIFT OF EXTRAGALACTIC NEBULAE

(Die Rotverschiebung von extragalaktischen Nebeln)

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(Translated by H. Andernach (heavily editing a raw translation from https://tradukka.com/translate)

Abstract: This gives a description of the most essential characteristics of extragalactic nebulae, as well as of the methods used to investigate these. In particular, the so-called redshift of extragalactic nebulae is discussed in detail. Various theories which have been proposed to explain this important phenomenon, are briefly discussed. Finally, it will be indicated to what extent the redshift promises to become of importance for the study of cosmic rays.

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Special terms were interpreted as follows:

- Nebel = nebula (not galaxy, to preserve the original flavor of the text)

- Fluchtgeschwindigkeit = recession velocity (not escape velocity, as there is no escape here...)

- Perioden-Helligkeits-Beziehung = Period-Brightness Relationship (not period-luminosity, to preserve the original word "Helligkeit")

- penetrating radiation = cosmic rays

1. INTRODUCTION

It has been known for a long time that there are certain objects in space, which appear, when observed with small telescopes, as very blurry, self-luminous patches. These objects possess structures of different types. Often they are spherical in shape, often elliptical, and many of them have a spiral-like appearance, which is why they are occasionally called spiral nebulae. Thanks to the enormous angular resolution of modern giant telescopes, it was possible to determine that these nebulae lie outside the bounds of our own Milky Way. Images taken with the 100-inch telescope on Mt. Wilson reveal that these nebulae are stellar systems similar to that of our own Milky Way. By and large, the extragalactic nebulae are distributed uniformly over the sky and, as has been demonstrated, are also distributed uniformly in space. They occur as single individuals or group themselves to clusters. The following lines intend a brief summary of the more important characteristics and a description of the methods that made it possible to establish these characteristics.

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 partially, into single stars. In the great Nebula in Andromeda, for example, a great number of individual stars have been observed. Recently also globular star clusters have been discovered in this nebula, similar to those which lie within our own Milky Way. The fortuitious fact of the observability of individual stars in nebulae opens two ways to determine their distances.

A) Distance Determination with the help of the Period-Brightness Relationship for Cepheids.

Cepheids are stars the brightness of which varies periodically with time. Periods are usually in the range of one up to sixty days. The absolute magnitude is a unique function of period, a function which has been determined for the stars of our own system [Milky Way]. If the period is known, it is therefore possible to derive the absolute magnitude of these cepheids from this relationship. If, in addition to that, one determines the apparent magnitude, and compares it with the absolute magnitude, one immediately obtains the distance of the stars. Several of cepheids have been observed in the Andromeda nebula. Based on these, the distance and diameter of Andromeda was determined to be 900,000 and 42,000 light-years, respectively. For comparison, it is important to remember that our own system has a diameter the upper limit of which is estimated to be about 100,000 light years. The distances of eight other nebulae have been found in the same way. In nebulae more distant than a few million light years, individual cepheids cannot be resolved. To determine their distance other methods must therefore be devised.

B) Statistics of the brightest stars of a nebula

This method is based on the assumption that in the extragalactic stellar systems the relative frequency of the absolute magnitude of stars is the same as in our own system. The experience with the previously examined neighboring systems are in fact in accordance with this assumption. The absolute magnitude of brightest stars in our own and neighboring systems turns out to be -6.1 on average, with a dispersion of less than a half a magnitude. We just note that similar distance determinations were obtained with the help of novae.

C) Distance determination of nebulae using their total apparent magnitude.

With the help of the first two methods, the distances of about sixty extragalactic nebulae have been found. From the measured apparent brightness and the known distance of these nebulae we can immediately infer their absolute brightness. In this way we obtain the following distribution curve (Fig. 1).

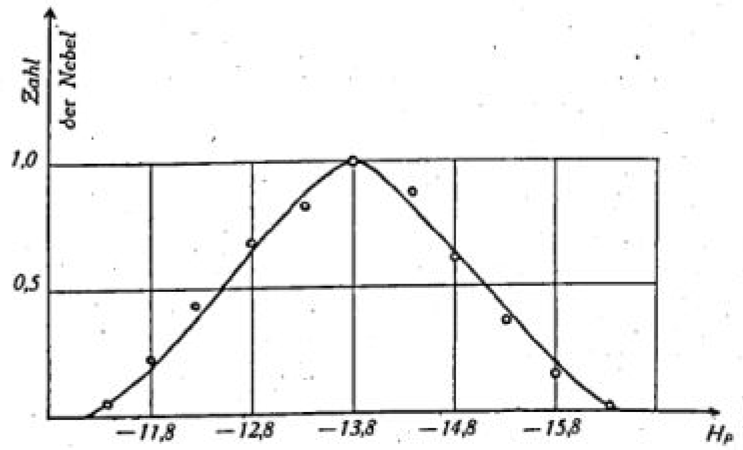

Figure 1. H_P = absolute photographic magnitude (Y axis: number of nebulae).

The average absolute visual magnitude of the nebulae is -14.9 with a dispersion of about five magnitudes and a half-width of the distribution curve of about two magnitudes. This dispersion is unfortunately too big to allow an exact determination of the distance to an individual nebula from its apparent brightness and and the distribution curve of absolute magnitudes. We shall discuss later how it is still possible to determine the distance to certain individual nebulae with great accuracy. However, the following fact allows us to find the distance of a large number of extremely faint nebulae. As already mentioned, nebulae often group themselves in dense clusters, which contain from 100 to 1000 individuals. It is of course extremely likely that such an apparent accumulation of nebulae is also a real accumulation in space, and that therefore all these nebulae are located at approximately the same distance. It is relatively easy to determine the distribution curve of 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 proves that the apparent accumulation of nebulae [on the sky] corresponds to a real dense swarm in outer space. A comparison of mean apparent brightness of the nebulae in the cluster with the mean absolute magnitude of -14.9 immediately yields the distance of the cluster. The distances of the following clusters of nebulae were determined in this way.

Table 1. Distance in millions of light years of various galaxy clusters

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 greater than the corresponding average number of individual nebulae dispersed in space.

It is of interest to include here some brief comments regarding other features of nebulae which are accessible to research with the help of the 100-inch telescope.

With regard to the structure of the Universe, first and foremost is the question whether the distribution of nebulae over space is uniform or not. In the case of uniformity we expect the number of nebulae in a spherical shell of radius r and constant thickness dr to be proportional to r^2, provided that we are dealing with a Euclidean space. This expectation actually corresponds very accurately to reality, i.e. for that part of the Universe within reach of the 100-inch telescope. This does not mean, of course, that space will not eventually turn out as non-euclidian, once we are able to penetrate farther in space.

We must not fail to mention that the above conclusions are only valid in case that absorption and scattering of light in space may be ignored. The finding of a uniform distribution of nebulae to the largest achievable distances with a method that assumes the practical lack of absorption and scattering, is in fact by itself almost a proof for the correctness of this assumption. Indeed, an actually existing uniform distribution of nebulae would be biased by absorption, in such a way that the number of nebulae in spherical shells of constant thickness would increase more weakly with distance than r^2, and eventually even decrease. In view of the fact that gases and clumps of dust can be proven to exist in interstellar space of our system [Milky Way], it would nevertheless be of great importance to have an independent proof of the transparency of intergalactic space, and to show that it is not the curvature of space, combined with absorption and scattering, that would feign a uniform distribution of the nebulae. A statistical study of the apparent diameters of nebulae would, for example, serve this purpose.

Theoretically, the presence of *intergalactic* matter should correspond to the vapor pressure of the extant star systems. Assuming that the Universe has reached a steady state, it is possible to estimate this pressure (F. Zwicky, Proc. of the Nat. Academy of Sci., vol. 14, p. 592, 1928). It turns out to be extremely small and would practically exclude the detection of *intragalactic* matter.

Another interesting question is related to the spectral types of nebulae. Most extragalactic nebulae possess absorption spectra similar to that of the Sun with strong salient H and K lines of calcium and an intense G-band of Ti (4308 A), Fe (4308 A) and Ca (4308 A). Therefore, nebulae belong to the spectral type G. The spectral type is independent of the distance, as far as the observations reach out so far. A distance-dependent displacement of the total spectrum will be discussed later. The width of the absorption lines is usually several Angstroms and is also independent of the distance.

A small percentage of the observed nebulae also show emission lines (Nebulium), usually originating in the core region of the nebulae. Unfortunately very little is known as yet about the physical conditions in such systems.

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

Fourthly, I would like to mention the determination of the brightness distribution within a single nebula. This investigation has been undertaken recently by E. Hubble at Mt. Wilson. Hubble obtains the following preliminary result. The brightness can be expressed as a universal function $L(r, \alpha)$, where r is the distance from the center of the nebula, and α is an appropriate parameter. By varying α, one can reduce the brightness distributions in all nebulae with great accuracy (approximately 1%) to the same function, in fact up to values of r, for which the brightness has fallen to 1/1000 of that of the centre. It is also of importance with respect to the practical lack of absorption and scattering in intergalactic space, that the distribution function of the α's of the different nebulae is independent of distance. Incidentally, we mention that L coincides with the function that corresponds to the brightness distribution in an isothermal Emden gas sphere.

Fifth, it is of enormous importance that the nebulae at a great distance show redshifted spectra, where the shift increases with distance. The discussion of the so-called redshift is the main topic of the present 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 some nebulae show shifts of their spectra, which correspond to a Doppler effect of up to 1800 km/s. However, Slipher did not establish any relationship between redshift and distance. Such a relationship was first suspected by G. Stroemberg (1925, ApJ 61, 353-388) upon his study of the speed of the Sun relative to more and more distant objects. He found that the mean velocity of the Sun, relative to the system of neighboring nebulae, is large, of the order of 500 km/s, and that the group of the nebulae used shows an expansion which seems to depend on the distance of the individual nebula.

Since at the time of Stroemberg's research no reliable distance determination of the nebula was known, K. Lundmark attempted to relate the observed high velocities with the compactness of the photographic images of the nebula. This proved later as an attempt in the right direction. Nevertheless, the attempt remained unsuccessful, as it turned out that the apparent diameter of nebulae at the same distance exhibit large variations.

E. Hubble worked at Mt. Wilson in the same direction. First he also tried to relate the redshift to the apparent concentration of the nebula. Herein he set out from the idea that the redshift would correspond to the well-known Einstein effect. However, it turned out that it was not possible to uncover sensible relationships in this way.

Consequently, E. Hubble tried to relate the redshift with the distance of the different nebulae. This attempt, as is well known, has since been of great success. The nebulae which were available initially for such an investigation, had distances from one up to six million light years. The discussion of all data showed a linear relationship between redshift and the distance, with the result that the redshift correspondeds to an apparent recession velocity of 500 km/s per one million parsec (1 parsec equal to approximately 3.26 light years). The dispersion was however relatively large, as for example the neighboring Andromeda Galaxy has a violet shift of approx. 200 km/s, i.e. is either seemingly or really moving towards us. Despite this, it was found later that this spectral shift, calculated for the first time, was an extremely good one. The best proof of the amazing care of Hubble's method of work is perhaps, that on the basis of the above relationship up to now he could predict the redshifts in each case to within a few percent, and in fact for distances up to thirty times higher that those of the initially used [sample of nebulae].

The difficulty in photographing the spectra of very distant nebulae lies in the need of extremely long exposure times. Indeed it was necessary to expose plates up to fifty hours and more, and it seemed hardly possible to penetrate further into space with this method. In more recent times great progress has been made by using a spectrograph, the camera lens of which has a focal ratio of f/0.6. However, with this one had to sacrifice a lot in the dispersion, and the spectra obtained are only about 2 millimeters long. However, the exposure times could be shortened down to a few hours. Nevertheless, it does not seem possible to penetrate farther into space than about 200 million light years. The reason for this lies partly in the location of the 100-inch telescope in the vicinity of the large city of Los Angeles, since the illumination of the night sky and the associated strong light scattering into the telescope unfortunately limits the astronomical observations on Mt. Wilson, to a level below the actual performance of the telescope. For the 200-inch telescope, currently under construction for the California Institute of Technology, a more suitable location will therefore have to be selected.

The redshifts of various clusters of nebulae, expressed as apparent Doppler recession velocities, are put together in the following Table 2.

Table 2.

Cluster of nebulae	Number of nebulae in the cluster	Apparent diameter, in degrees	Distance in 10^6 light years	Average velocity, in km/s
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	2.5	36	5230
Coma	800	1.7	45	7500
Ursa Major	300	0.7	72	11800

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Leo	400	0.6	104	19600
Gemini	(300)		135	23500

These results are graphed in Fig. 2.

(see E. Hubble and M. L. Humason, ApJ 74, 43, 1931. In this work, also the most essential bibliography may be found.)

It follows from this compilation that extragalactic nebulae have velocities which are proportional to their distance. The specific velocity, per million parsec, is

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

The redshift of each individual nebula is on average based on the mean shifts of at least three spectral lines. These are usually the H- and K-lines, the G-band (λ = 4303 A), and occasionally one of the lines Hδ (4101 A), Hγ (4340 A), Fe (4384 A) and Hβ (4861 A). The uncertainty in the redshift of the cluster of nebulae in Leo results in this way for example, as

$$v = 19621 \pm 300 \text{ km/s.}$$

The various absorption lines suffer the same relative shift, just as expected for the Doppler effect. Thus we have for a certain nebula:

$$\Delta\lambda/\lambda = \text{constant} = K = v/c = \kappa r \tag{2}$$

regardless of the wavelength, λ, and conveniently the shift may be expressed, as we have done, in velocity units. The same value of K therefore also applies to the shift of the maximum of the continuous emission spectrum.

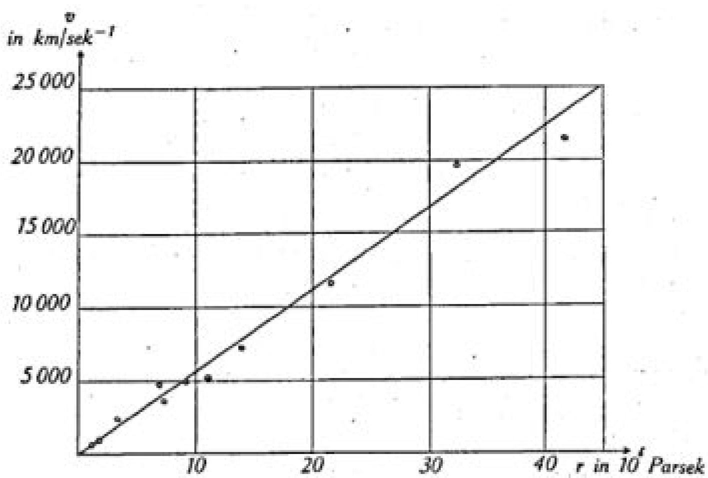

Figure 2.

It must be borne in mind that Fig. 1 lists the mean Doppler velocity of clusters of nebulae. This speed is the average of the values of several individual Nebula (from 2 to 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 deviate from the mean. In the Coma cluster, for example, which until now is the best investigated, the following individual values have been measured.

Apparent velocities in the Coma cluster	
v = 8500 km/s	6000 km/s
7900	6700

7600	6600
7000	5100(?)

It is possible that the last value of 5100 km/s corresponds to a field nebula which does not belong to the Coma system, but is only projected on to it. The probability of this assumption is however not very large (1/16). Even if we omit the nebula, the variations in the Coma system still remain very large. In this context it is of interest, to remind the reader that the average density in the Coma cluster is the largest so far observed.

Now, since the relationship between the distance and the redshift is known, we can use the relation to infer the distances of individual nebulae, if their redshifts are spectroscopically measured. Also, we can use it as an independent check of the reliability of the above-mentioned methods of distance determination. To do this, in fact we only need the brightness distribution of all individual nebulae of the same redshift. This new distribution curve must agree with that of Fig. 1, if our original distance determination were correct. This is in fact very approximatly the case.

As mentioned above, the redshift means a shift of the entire emission spectrum of the nebula. In addition to the diminution of the apparent photographic magnitude in geometric dependence on the distance, there is still another faintening effect caused by the redshift. The problem of the spatial distribution of the nebulae at large distances is thus not just closely linked with the curvature and absorption of space, but also with the redshift which complicates the whole situation very much.

In the end we must mention some results of van Maanen, which appear to be in contrast with Hubble's determination of distances. Over a period of about twenty years, van Maanen has measured apparent movements (in angular units) of nebulae on the celestial sphere. Since the corresponding angular velocities of the nearest nebulae amount to only about 0.01 arcseconds per year, only nebulae with well-defined, star-like "nuclei" are useful for this purpose, as otherwise the definition of coordinates of the nebula is more difficult due to the blurryness of its photographic image. If one combines van Maanen's angular velocities with Hubble's distances, one obtains extremely high velocities. For NGC 4051, which according to Hubble is located at a distance of 4 million light years, and has an apparent radial velocity of 650 km/s, van Maanen measures an angular velocity of 0.015" per year, which results in a real velocity of 94,000 km/s. This constitutes a big problem. A trivial solution which does not appear impossible from the outset, may be that van Maanen's observed motions do not originate in the nebula, but may be attributed to the reference system used for the stellar background. It must be emphasized however that van Maanen has found similar discrepancies for 13 nebulae. Another result was that all these nebulae appear to move away from the pole of the Milky Way, which seems hard to explain with a movement of the reference system.

Equally important is van Maanen's determination of the rotation of extragalactic spiral nebulae. For Messier 33, according to Hubble at a distance of 900,000 light years, van Maanen observed, superimposed on the above mentioned transversal movement, a rotation of the entire nebula, the components of which for individual objects range from 0.012" up to 0.024" per year. With the mentioned distance, rotation speeds of about 33,000 km/sec result, while e.g. F.G. Pease measured for NGC 4594 from the Doppler effect at both ends of its diameter a rotation of only 800 km/s. [For Messier 33 itself the observations are not yet completed. However, the rotational velocities are only about 50 km/s.]

If one does not ascribe van Maanen's results to observational errors, but takes these as characteristic of the nebula itself, and one is not ready to drop Hubble's distance determinations, one is facing a serious problem.

4. SPECULATIONS CONCERNING THE REDSHIFT.

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

1. The redshift is analogous to a Doppler effect, i.e. $\Delta\lambda / \lambda$ for a given nebula is a constant.

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

3. There is no noticeable absorption and scattering of light in space, which may be associated with the redshift.

4. The definition of the optical images of nebulae is as good as is expected from the resolving power of the instruments. The distance of the objects apparently plays the role expected from geometric considerations.

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

6. The great dispersion of the single values of the radial velocities of the nebulae of dense clusters must be explained in the context of the redshift.

7. The speed of light, on its long way from the nebula to us, is practically the same as the speed of light known to us from terrestrial measurements. This was found from aberration measurements on nebulae by Stroemberg and van Biesbroeck.

8. A theory of the redshift, which at the same time does not provide an explanation of van Maanen's results, is at least unsatisfactory.

The facts stated above reflect the observational material up to a distance of about 150 million light years. For their explanation there are presently two general suggestions. The first includes all theories of cosmological character, which are based on the theory of relativity. The second one assumes an interaction of light with matter in the Universe.

A) Cosmological theories.

In recent years a large number of attempts were made to explain the redshift on the basis of the theory of relativity. Some essential thoughts in this respect are the following.

The general theory of relativity has led to two views regarding the structure of space. The first one is represented by Einstein's quasi-spherical world, while de Sitter has derived the possibility of a hyperbolic space for the case of vanishingly small mass density.

While the geometry of Einstein's space does not lead directly to a redshift, it is necessarily linked with de Sitter's world. However, R. C. Tolman has shown that for the latter case $\Delta\lambda / \lambda$ not only depends on the distance of the nebula, but also on its proper speed. It follows then that apart from the redshift one also has to expect blueshifts which would on average be smaller, but nevertheless of the same order of magnitude as the redshifts, which contradicts the observations. Therefore it was not possible to relate the redshift directly to the curvature of space.

A further important suggestion comes from Friedmann, Tolman, Lemaitre and Eddington, whose work suggests that a static space, according to the theory of relativity, is dynamically unstable, and therefore starts to contract or expand. This result was then interpreted by him [the author does not specify WHO] that the redshift would correspond to an actual expansion of the Universe. This proposal has since been discussed by many researchers. The easiest formulation was recently put forward by Einstein and de Sitter (A. Einstein and W. de Sitter, Proc. of the Nat. Acad. Sci., Vol. 18, p. 213, 1932). These two researchers have temporarily given up the existence of an overall curvature of space. The curvature of space was essentially a consequence of the introduction of a so-called cosmological constant Λ in Einstein's field equations, which is equivalent to postulate a repulsive force which compensates Newton's attraction for very large distances. This postulate was historically necessary to understand the existence of a non-vanishing mean density which would otherwise lead to infinite gravitational potentials in the limiting case of an infinite static space. This latter difficulty however disappears automatically, if all matter in space moves away from, or approaches each other. Omitting the cosmological constant Λ and the mean curvature, the expansion of matter can then be related directly to the average density. An expansion of 500 km/s per million parsecs, according to Einstein and de Sitter, corresponds to a mean density $\rho \sim 10^{-28}$ g/cm^3. Based on observations of self-luminous matter, Hubble estimates $\rho \sim 10^{-31}$ 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 $\rho \sim 10^{-28}$ g/cm^3 does not therefore appear unreasonable. Einstein's theory further yields the following more precise relationship for the redshift

$$\Delta\lambda/\lambda = \kappa r[1 + 7\Delta\lambda/(4\lambda)]. \qquad (3)$$

This means that for large distances the redshift should increase stronger than linearly with the distance. On the basis of the previous observational material it is unfortunately not possible as yet to prove this important conclusion. The most recent observed values of $\Delta\lambda / \lambda \sim 1/7$ for the largest distances are however large enough to expect considerable deviations (25%) from the linear relationship.

Theory also leads to certain conclusions regarding the distribution of brightness levels, number of nebulae, diameter, etc., as function of distance, which however have not yet been proven.

Up to now none of the cosmological theories has dealt with the problem of the large velocity dispersion in dense clusters, such as the Coma system.

B) Direct influence of existing matter in space on the frequency of light.

Several years ago I already attempted to consider various physical effects such as the Compton effect on stationary or moving electrons in outer space, the Raman effect, etc., to explain the redshift (F. Zwicky, Proc. Nat. Acad. Sci., Vol. 15, p. 773, 1929). It turned out that none of these can play an important role. When considering effects, which have their origin in an immediate spatial interaction between light and matter, it proves impossible to explain the transparency of intergalactic space.

However, I had then suggested another possible effect, which however will be barely observable on Earth, but for the existence of which some theoretical reasons can be put forward. According to relativity theory, each photon, or light quantum, of frequency ν can be assigned an inertial as well as gravitational of $h\nu / c^2$. Thus, 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, respectively, with identical gravitational potentials, then, on the way from P_1 to P_2, the photon will lose a certain amount of linear momentum and will release it to matter. That photon becomes redder. This effect could be described as gravitational friction, and is caused essentially by the finite velocity of propagation of gravitational effects. Its strength depends on the mean density of matter, as well as on its distribution. In this case the redshift $\Delta\lambda / \lambda$ not only depends on distance, but also on the the distribution of matter. Studies to prove these conclusions are in progress.

In conclusion it has to be said that none of the currently proposed theories is satisfactory. All have been developed on extremely hypothetical foundations, and none of these has allowed to uncover any new physical relationships.

5. COMMENTS ON THE VELOCITY DISPERSION IN THE COMA CLUSTER OF NEBULAE

As we have seen in sect. 3, there exist in the Coma cluster apparent differences in velocity of at least 1500 to 2000 km/s. In relation with this enormous velocity dispersion one can make the following considerations.

1. If one assumes that the Coma system has reached a mechanically stationary state, it follows from the Virial theorem

$$\bar{\varepsilon}_{\rm k} = -\frac{1}{2}\,\bar{\varepsilon}_{\rm p} \qquad (4)$$

where $\bar{\varepsilon}_{\rm k}$ and $\bar{\varepsilon}_{\rm p}$ denote the mean kinetic and potential energies, e.g. per unit mass in the system. For the purpose of estimation, we assume that matter is distributed uniformly in the cluster. The cluster has a radius R of approximately one million light years (equal to 10^{24} cm) and contains 800 individual nebulae each of a mass of 10^9 solar masses. The total mass M of the system is therefore

$$M \sim 800 \times 10^9 \times 2 \times 10^{33} = 1.6 \times 10^{45}\ {\rm g}. \qquad (5)$$

From this we have for the total potential energy Ω:

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

where Γ = gravitational constant

or

$$\bar{\varepsilon}_{\rm p} = \Omega/M \sim -64 \times 10^{12}\ {\rm cm}^2/{\rm s}^2 \qquad (7)$$

and furthermore

$$\begin{aligned} \varepsilon_{\rm k} = \overline{v^2}/2 = -\varepsilon_{\rm p}/2 = 32 \times 10^{12}\ {\rm cm}^2/{\rm s}^2 \\ (\overline{v^2})^{1/2} = 80\ {\rm km/s}. \end{aligned} \qquad (8)$$

In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s 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 observations of luminous matter [This would be in approximate accordance with the opinion of Einstein and de Sitter as discussed in Sect. 4.]. If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.

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

$$\varepsilon_{\rm k} = -\varepsilon_{\rm p} \qquad (9)$$

One may thus save only a factor of 2 compared to the assumption 1, and the need for an enormous density of dark matter remains.

3. Let the average density in the Coma cluster be determined purely by luminous matter (*M* as mentioned above). Then the large speeds cannot be explained on the basis of considerations of type 1 or 2 above. If the observed speeds are real anyway, the Coma system should fly apart in the course of time. The end result of this expansion would be 800 single nebulae (field nebulae), which would have proper speeds, as shown in 2., of the order of the original ones (1000 to 2000 km/s). In analogy, one would have to expect that single nebulae with such large proper speeds can also be observed in the present evolutionary state of the Universe. This conclusion hardly matches the experimental facts, as the spread of proper speeds of individually occurring nebulae does not exceed 200 km/s.

4. One may also attempt to consider the speeds as apparent ones, interpreting them as caused by Einstein's redshift. Assuming the above mass *M* one would have for the relative change of the wavelength

$$\Delta\lambda/\lambda \sim -\varepsilon_{\rm p}/c^2 \sim 3.5 \times 10^{-8}\ , \qquad (10)$$

which is equivalent to a speed of only 10 m/s. Thus, in order to arrive to an explanation of the large velocity dispersion, one would have to permit a much greater density of dark matter than under assupmtions 1 or 2.

These considerations indicate that the large velocity dispersion in the Coma system (and other dense clusters of nebulae) holds an unsolved problem.

6. COSMIC RAYS AND REDSHIFTS

Comparing the intensity of visible light from our Milky Way ($L_{\rm m}$) with the intensity of light ($L_{\rm w}$), that comes to us from the rest of the Universe, one obtains

$$L_{\mathrm{m}}/L_{\mathrm{w}} \gg 1 \; . \tag{11}$$

Under the assumption that cosmic rays are not of local nature, one obtains for these the ratio of intensities, *S*, analogous to that in (11)

$$S_{\mathrm{m}}/S_{\mathrm{w}} < 0.01 \; . \tag{12}$$

This follows from the practical absence of cosmic ray variations with sidereal time. As I discussed elsewhere (F. Zwicky, Phys. Rev., January 1933) the inequality (12) is difficult to understand because cosmic rays that originate at very large distance, would arrive at Earth with very reduced energy as a result of the redshift. If for example the redshift were consistently proportional to distance, then light quanta from a distance greater than 2000 million light years would reach us with zero energy. (This consideration implies by the way, that even in the presence of an infinite number of stars in the Universe, the light intensity would have a finite, well defined value everywhere.) Under reasonable assumptions about the type of reaction which produces cosmic rays, the inequality (11) is very hard to understand, and the main difficulty lies, as indicated, in the existence of the redshift (F. Zwicky, Phys. Rev., January 1933).

Finally I would like to point out, that the coexistence of the two inequalities (11) and (12) will pose great difficulties for certain recent opinions about the origin of cosmic rays. For example, G. Lemaitre has proposed that one may consider cosmic rays as remnants of certain super-radioactive processes that happened a long time ago. However, at the same time a correspondingly huge amount of visible and ultraviolet light must have been emitted. Since interstellar gases (as well as our atmosphere) absorb cosmic rays more than visible light, the coexistence of inequalities (11) and (12) is incomprehensible.

It is also important, in this context, to point out the following interesting fact. A belt of irregularly shaped boundaries which runs along the Milky Way and stretches from about -10° to about +10° Galactic latitude, completely blocks our view of extragalactic space, i.e. no extragalactic nebula can be observed in this belt. It is known that part of this absorption can be ascribed to very large, dense masses of dust. If cosmic rays were of extragalactic origin, one would actually expect them also to be absorbed along the Milky Way, i.e. one should observe on Earth a variation of cosmic ray intensity with sidereal time. Since such variation is not found, one is tempted to conclude that cosmic rays can not be of extragalactic origin. However, the density and extent of interstellar matter in the Milky Way must be examined more thoroughly.

The present work has emerged from numerous discussions with staff researchers at Mt. Wilson Observatory working in this area. I am particularly indebted to Dr. W. Baade for plenty of valuable advice.

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