EXPERIENTIA

Vol. VI - Fasc. 12 Pag. 441–480 15. XII. 1950

Intergalactic Matter

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(1) *Definition and Problem*

Matter in the form of stars, dust and gases is heavily concentrated in a great number of extragalactic nebulæ or galaxies which vary much in size, shape and material content. At first sight the vast spaces between the galaxies, that is the intergalactic regions, appear to be empty.

The question thus arises first, if there exists any intergalactic matter at all and second, what is its physico-chemical composition and its spatial distribution? These questions may seem to be somewhat indefinite in view of the fact that the boundaries of the galaxies themselves are ill defined from both the theoretical and the observational viewpoint. In order to formulate our question as precisely as possible we shall start from two definitions.

The first definition states that the "gravitational half-way points and multiple way points" between the galaxies and the immediate regions surrounding them constitute the true *geometrical* representatives of intergalactic space. These points and regions may be mathematically strictly defined as saddle points (maximinima) of the gravitational potential, which, as is well known, cannot possess either any true maxima or minima.

The second definition states that all stars, groups of stars, dust and gas clouds are potential representatives of the *material content of intergalactic space* provided that their average kinetic energy per unit mass is greater than the difference in gravitational potential between their location and the nearest saddle-point. According to this definition some stars or other objects of very high velocity (relative to any inertia system) must thus be looked upon as true members of the population of intergalactic space, although they may, geometrically speaking, appear to be members of a galaxy.

Our precise question consequently is first, whether there exists any matter in all of the space between the galaxies, including in particular the regions near the saddle points of the gravitational potential and second, whether there exists any matter anywhere in space with velocities high enough to reach the aforementioned saddle points.

[1] California Institute of Technology and Mt. Wilson and Palomar Observatories.

Elaborating on the problems just stated we shall be most interested in the equal density contours of the intergalactic population of stars, of small solid bodies, of dust, of gas and of elementary corpuscles. We cannot, of course, give a definite answer to all of these questions at the present time. We shall, however, produce enough observational evidence to demonstrate clearly that intergalactic matter actually does exist and that its total mass in a given large volume, as compared with that of all of the galaxies in this volume, is presumably very much greater than has been thought by most astronomers.

(2) *Theoretical reasons for the existence of intergalactic matter*

Some time ago I advanced a simple consideration[1] which clearly demonstrates the inevitability of the existence of considerable amounts of intergalactic matter. This consideration starts from the conservative assumption that galaxies are selfcontained units whose dispersion of internal peculiar velocities is too low to allow matter to espace into intergalactic space. In such a unit, according to the virial theorem, the average kinetic energy $\bar{}_k$ per unit mass is equal to

$$\bar{\varepsilon}_k = -\frac{\bar{\varepsilon}_p}{2} \tag{1}$$

where $\bar{\varepsilon}_p$ represents the average gravitational potential energy per unit mass in the system. $\bar{\varepsilon}_p$ is a measure of the compactness and of the total mass of a galaxy.

A galaxy of the type described will, however, be partially or totally disrupted if forces act on it which locally or over large regions generate internal perturbations whose energy per unit mass is of the order of $\bar{\varepsilon}_p$. It is easy to show that forces of this kind actually exist and that they come into play in particular when two galaxies meet in a close encounter.

It is all important for our argument that

$$\bar{\varepsilon}_k \text{ (stars)} \ll \bar{\varepsilon}_k \text{ (galaxies)} \tag{2}$$

Indeed, since

$$\bar{\varepsilon}_k = \frac{\overline{v^2}}{2} \tag{3}$$

where $\overline{v^2}$ is the mean square of the peculiar velocities, the observational data available at the present clearly

[1] F. ZWICKY, Physical Rev. *61*, 489 (1942).

indicate that in order of magnitude for stars in galaxies:

$$0 < (\overline{v^2})^{1/2} < 100 \text{ km/sec} \tag{4}$$

for galaxies:

$$100 \text{ km/sec} < (\overline{v^2})^{1/2} < 2000 \text{ km/sec} \tag{5}$$

The lower limit of the velocity dispersion in (5) refers to the field nebulæ while the upper limit holds for the member galaxies of the largest and most compact clusters known.

In any event the very pronounced inequality (2) constitutes the most powerful argument in favour of the existence of intergalactic matter. In elaboration of this inequality the author at an early date also arrived at the conclusion that the luminosity function of the galaxies, that is their number per luminosity interval, in a large volume of space must be monotonely increasing with decreasing brightness and size. He stated[1] that in *intergalactic space* "individual stars, multiple stars, open and compact star clusters and stellar systems of increasing population will be found in numbers presumably decreasing in frequency as the stellar content of the systems in question increases". This conclusion which at that time was in striking contradiction with the luminosity function established by earlier workers in the field[2] has now been verified in its entirety through work with the 18-inch and 48-inch Schmidt telescopes on Palomar Mountain.

(3) *References to Intergalactic Matter in the Literature*

Many cosmologists and observational astronomers, as well as physicists working in the field of cosmic rays have all realized the importance of well balanced knowledge regarding the true distribution of matter in the universe. In spite of the realization by many that the problem of whether or not intergalactic matter exists in relatively considerable density is an important one, no concerted effort seems to have ever been made to track down this type of matter. Instead, opinions were relied upon which do not have the slightest basis in fact. These opinions ranged from the conviction that practically no intergalactic matter exists at all[3] to statements, that in the perspective of certain cosmological theories such matter exists, but that its average density is such that it cannot be observed[4].

The author's theory[5], which was sketched in the preceding, on the other hand predicts the existence of intergalactic matter in amounts which clearly cannot hide themselves from the eyes of a determined observer. The author therefore several years ago started a program to search for various types of intergalactic matter and to investigate its "geographical" and its kinematical distribution. This program was interrupted by the war but has now come in full swing since all of the large telescopes of the Palomar Mountain and Mt. Wilson Observatories could be made use of. Preliminary, but definite and positive results have already been arrived at and these may herewith be briefly presented. The following short description of results achieved so far is given for the purpose of informing other observers on the possible methods which may serve to open up this new and tremendous field of significant astronomical research.

(4) *Facts which support the hypothesis that the disruption of galaxies feeds matter into intergalactic space*

The facts which we refer to here concern individual disrupted galaxies as well as pairs and multiples of galaxies which are obviously in the process of a close encounter. A very great number of stellar systems of the type described have now been found. The 48-inch Schmidt telescope on Palomar Mountain has been most successful in bringing to light very faint and very large extensions of various galaxies, as well as making possible the photography of very slight concentrations of intergalactic matter. We present here a few illustrations, resorting to drawings rather than to reproductions of the actual photographs, which because of the faintness of the objects involved are very difficult to reproduce in print.

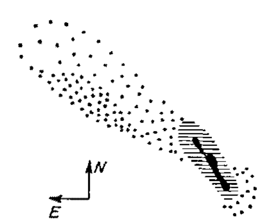

Fig. 1. – Irregular Galaxy NGC 4747 in Coma.

Figure 1 shows a drawing of NGC 4747 as it appears on photographs taken with the 48-inch Schmidt telescope.

It is seen that to one side of what appears to be a normal galaxy, an enormous plume of low surface brightness extends to a great distance from the nucleus. This plume clearly cannot be a part of a galaxy in dynamic or in statistical mechanical equilibrium. The plume is blue in color, a fact which presumably indicates the presence of a relatively great number of hot blue stars.

The photography of plumes of the kind shown is very tricky as the surface brightness becomes fainter and fainter. For this reason many objects of faint surface brightness have been missed both with the large reflectors and with the small wide angle telescopes whose scale is too small although their speed is sufficient.

[1] F. Zwicky, Physical Rev. *61*, 489 (1942).
[2] E. Hubble, *The Realm of the Nebulæ* (Yale University Press, 1936). – W. Baade, Astrophysical J. *88*, 112 (1938).
[3] P. Jordan, Nature *164*, 637 (1949).
[4] T. Gold, Nature *164*, 1006 (1949).
[5] F. Zwicky, Physical Rev. *61*, 489 (1942).

As an example of a group of galaxies with intergalactic matter between them clearly visible we choose three galaxies 1, 2 and 3 whose coordinates for the year 1950 are respectively, Right Ascension $\alpha_1 = 12^h30^m21^s$, Declination $\delta_1 = +11°40'8$; $\alpha_2 = 12^h30^m26^s$ $\delta_2 = +11°40'0$; $\alpha_3 = 12^h30^m38^s$, $\delta_3 = +11°37'4$.

Photographs taken with the 48-inch Schmidt telescope reveal the conditions shown in Fig. 2.

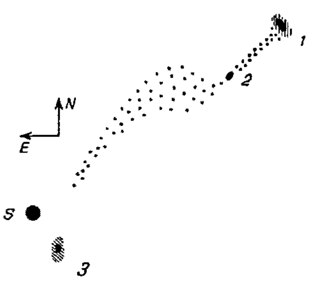

Fig. 2. – Intergalactic Matter between three galaxies in Virgo. S = foreground star.

Between the galaxies 1 and 2 there lies a strange band of luminosity with the sharp delineation of a lighted boulevard. Between the galaxies 2 and 3 the luminous intergalactic matter occupies a more extended region of much more irregular shape. Two very good plates each were taken of the group with the 48-inch telescopes using red and blue filters respectively. From these photographs it appears that the intergalactic matter, in this particular case is quite reddish in color. In many other analogous configurations, however, it is blue, and it seems that many shades in color exist, indicating that intergalactic matter may be quite different in composition from one region to another. The most obvious explanation is, of course, that the different colors are due to different relative numbers of blue and of red stars.

Attention should be called to the important fact that the ratio of the angular distance between the galaxies 3 and 2, respectively, 2 and 1 to the diameter of the largest of the three galaxies is 17:1 and 5:1 respectively. The actual distance from the earth and the real dimensions of the three galaxies discussed are not known at the present time but are subject to a current investigation.

(5) *Evidence for the existence of intergalactic matter as derived from the most recent researches on the luminosity function of galaxies*

From the original work with the large reflectors on Mt. Wilson the luminosity function of galaxies, that is their number in a large volume of space in dependence of their absolute luminosity L or their absolute (photographic) magnitude M_p was thought to be of the approximate shape of a Gaussian error curve. This curve was claimed to have a sharp maximum at about $M_p = -14{\cdot}2$ or a luminosity of about 80 million times that of the sun[1].

In particular, the absolute photographic magnitudes of galaxies in the large clusters in Virgo, Coma, Cancer and Perseus[2] were thought to be limited to the range in M_p given by the inequality (6)

$$-12 < M_p < -18 \qquad (6)$$

Recent work with the 18-inch and 48-inch Schmidt telescopes has shown that the originally derived luminosity function is completely inadequate. As far as the observations in the Coma cluster, in the Cancer cluster and in the local group of galaxies are concerned the supposed maximum in the luminosity function is entirely non-existent. The number of nebulæ in a given volume of space rather increases monotonely as their intrinsic brightness decreases.

A great number of very faint galaxies of all types, spiral, globular, elliptical and irregular have been discovered during the past decade by the author[3] and his colleagues[4], whose existence was not known or even suspected in the 1930's. The faintest ones among them are hardly brighter than the brightest known permanent stars and might thus well be classed as intergalactic matter. There is no doubt that, as the search goes on intrinsically fainter and fainter isolated stellar systems and groups of stars will be discovered in increasing numbers. It then becomes a somewhat academic question of what should be classed as a galaxy and what should be called intergalactic matter. But even if we define intergalactic matter to consist of individual stars and smaller units of mass such as "stones" and perhaps dust particles, the existence of this type of matter can now definitely be regarded as established.

(6) *Intergalactic matter which is spread throughout a cluster of galaxies*

One of the outstanding physical characteristics of a cluster of galaxies consists in the fact that there exists a relative segregation of the bright and presumably massive galaxies from the faint galaxies whose masses are probably smaller. The bright galaxies are relatively more concentrated toward the center of a cluster. As a limiting case of this segregation of galaxies of different brightness or mass in a cluster one should expect individual stars to be spread throughout any cluster. These stars should show a degree of concentration towards the center of the cluster which is even less pronounced than the increase in the number per unit volume of the intrinsically faint member galaxies of the cluster.

[1] E. Hubble, *The Realm of the Nebulæ* (Yale University Press, 1936). – W. Baade, Astrophysical J. *88*, 112 (1938).

[2] E. Hubble and M. L. Humason, Astrophysical J. *74*, 43 (1931).

[3] F. Zwicky (The Halley Lecture of 1948); The Observatory *68*, 121 (1948).

[4] A. G. Wilson and R. G. Harrington, Publ. Astron. Soc. Pacific.

After a lengthy search with various telescopes the predicted intergalactic population of stars has now been definitely established in and around the center of the Coma cluster of galaxies (1950: $\alpha = 12^h 56^m$, $\delta = +28° 35'$). Photographs taken with the 48-inch Schmidt telescope in various wave length ranges reveal the general continuum between the individual galaxies to be blue in colour. This is an indication that a major part of the luminosity of the intergalactic matter in the Coma cluster is due to blue stars.

The intergalactic continuum in the Coma cluster can easily be traced to a distance of several hundred thousand light years from the center, a distance which is very much greater than the diameter of the largest individual galaxies known. Attempts are in progress to record the surface brightness of the intergalactic continuum quantitatively. This must be done under the most favorable conditions of lowest sky brightness.

Unfortunately no very large and compact cluster of galaxies is known which is much nearer than the Coma cluster and which is conveniently located for observations with the 200-inch telescope. Efforts with this telescope therefore must be concentrated on the task of resolving into stars some concentrations of intergalactic matter of the type shown in Figure 2. One special case of this type of matter is naturally to be looked for in the immediate neighborhood of our own galaxy. This leads to:

(7) *The search for intergalactic stars at great distances in the direction of the galactic pole*

There are many ways to track down individual stars which are at a great distance from the Milky Way plane. The present author has concentrated his efforts on two lines of attack. These efforts are as yet in a preliminary stage but some interesting results have already been achieved.

The first line of attack is based on the idea that very blue and apparently very faint stars at the north galactic pole are likely to be either nearby white dwarfs or very distant early type (O-, B- or A-) stars of great intrinsic brightness. Very blue stars can and have been picked up by the author with the help of colour filters[1]. With the additional aid of data on the spectra and on the proper motions of the stars thus found it will be possible to determine their distances. A preliminary search of about four hundred square degrees near the north galactic pole netted about thirty blue stars in the range of apparent photographic magnitude $10 < m_p < 16{\cdot}5$. A few among these stars are definitely white dwarfs, because their large proper motions indicate that they are not very distant. The faintest of these blue stars observed so far are fainter than the apparent photographic magnitude $m_p = 16$. This, combined with an absolute photographic magnitude M_p brighter than -2 puts the respective stars at a distance greater than 100,000 light years, or far outside of the galaxy. Since the absolute number of these stars in a given region near the north galactic pole increases with increasing faintness, one may hope to find many blue stars fainter than $m_p = 16$ and thus arrive at more quantitative estimates of the numbers of stars and the average density of matter in the intergalactic space around the Milky Way.

Another investigation which we have just started sets out to discover very faint variable stars at the galactic poles. If the period, the light curve and possibly the spectrum of these stars can be determined one will possess a very good estimate of their absolute magnitude. Since at the galactic poles no serious difficulty due to local absorption is to be expected, the distance of the variables may be determined with considerable accuracy. This method should perhaps provide the most indisputable evidence for the existence of intergalactic matter, that is stars in the intergalactic spaces between the stellar systems of the so-called local group the diameter of which is of the order of two to three million light years.

Some very interesting long period variables of the apparent photographic magnitude $m_p > 14$ have already been found near the north galactic pole. These are now under continuous observation for detailed characteristics.

[1] M. L. Humason and F. Zwicky, Astrophysical J. *105*, 85 (1947).

(8) *Supernovæ on the outskirts of galaxies*

During the author's systematic search for supernovæ it was noticed[1] that these tremendously bright exploding stars seem to favor the outskirts of the extragalactic nebulæ and that they occur uncommonly often in dwarf nebulæ. Some of them have been observed at distances from the centers of the respective galaxies at which the surface brightness of the latter is so low that it cannot be distinguished from the sky background. One of the most striking examples[1] is the supernova of 1937 in NGC 4281.

These occurrences suggest of course a search for supernovæ in the "general field" between the nebulæ, that is among the stars which we now know to populate intergalactic space. Such a discovery campaign which I have suggested previously[1] is of course much more difficult than that which confines its attention to a number of specific galaxies. Because of the importance of the results to be gained, such a search should, if possible, be undertaken.

(9) *Conclusion*

Although the discovery of the existence of intergalactic matter is interesting in itself, some of the conclusions to be drawn promise to be of far-reaching importance. For instance it was thought by the ex-

[1] F. Zwicky, Reviews Modern Physics *12*, 66 (1940); Astrophysical J. *96*, 28 (1942).

perts[1] in the field that the average density throughout the visible universe could not be greater than 10^{-28} grams/cm³. Preliminary calculations however show that because of the tremendous potential number of dwarf galaxies this density may have to be increased to 10^{-27} grams/cm³ and that the presence of matter through the vast intergalactic spaces may even boost this value to 10^{-26} grams/cm³. As will be discussed in another place such values for the average density of matter in the universe would spell the doom for all cosmological theories which have been presented up to the present and which postulate that the redshift of the light from nebulæ can only be explained through the assumption of an expanding universe. There is thus a close relation between the investigations on intergalactic matter and all cosmological theory. It goes without saying that all theories of the origin of the cosmic rays will also be severely affected by the new discovery[2].

[1] E. Hubble, *The Realm of the Nebulæ* (Yale University Press, 1936).
[2] See also: Annual Report 1948–49 of the Director, Mt. Wilson and Palomar Observatories.

Zusammenfassung

Der Begriff «intergalaktische Materie» wird genau definiert. Eine vom Verfasser vor längerer Zeit ausgearbeitete Theorie führt zum Resultat, daß solche Materie nicht nur existieren muß, sondern daß die in ihr verkörperte Gesamtmasse im jetzt erforschbaren Teil des Weltalls mit der in den extragalaktischen Nebeln (Sternsytemen) enthaltenen Gesamtmasse vergleichbar ist. Die neuesten mit den großen Schmidt-Teleskopen gemachten Beobachtungen bestätigen diese Voraussagen. Das Auftreten leuchtender intergalaktischer Materie (hauptsächlich Einzelsterne und sehr ausgedehnte Sternschwärme) wurde bis jetzt insbesondere in der weiteren Umgebung unserer Milchstraße, sodann in den großen Räumen zwischen den Mitgliedern kleiner Nebelgruppen und endlich in den ungeheuer ausgedehnten Regionen der großen extragalaktischen Nebelhaufen festgestellt. Anstrengungen, intergalaktische Staub- und Gaswolken zu identifizieren, haben noch keinen bestimmten Erfolg erzielt. Auf Grund der oben erwähnten Entdeckungen wird die mittlere Dichte der Materie in dem uns bekannten Teil des Weltalls auf 10^{-27} bis 10^{-26} Gramm/Kubikzentimeter geschätzt.

Hundert Jahre Ionenaustausch

Von H. Deuel und F. Hostettler, Zürich[1]

1. *Einleitung*

Ionenaustauscher bestehen aus Teilchen mit *großen* äußeren oder inneren, *elektrisch aufgeladenen Oberflächen.* Ihre chemische Konstitution ist außerordentlich mannigfaltig; es kann sich um amorphe oder kristalline, um anorganische oder organische Verbindungen handeln. Die Partikel der Ionenaustauscher stellen Riesenmoleküle, Molekülaggregate oder Salzkriställchen dar.

Vor allem *hochmolekulare, unlösliche Elektrolyte* werden als Ionenaustauscher betrachtet. Die Teilchen dieser Polyelektrolyte stellen meist *dreidimensionale, lockere Netzwerke* dar, die starr oder quellbar sind. *Dissoziationsfähige Atomgruppen* sind durch kovalente Bindungen am Netz fixiert. Beim Vorhandensein von sauren Gruppen trägt das Gerüst negative Ladungen und ist zum Ladungsausgleich von einer äquivalenten Menge Kationen umgeben (*Kationenaustauscher*). Teilchen mit fixierten basischen Gruppen sind positiv aufgeladen und daher mit Gegenanionen versehen (*Anionenaustauscher*). Es gibt auch Ionenaustauscher mit Ampholytcharakter; hier sind saure und basische Gruppen in die Oberfläche eingebaut.

Im idealen Fall werden die Gegenionen von den Austauscherteilchen rein elektrostatisch festgehalten. Man kann daher ein bestimmtes, weitgehend frei bewegliches Gegenion nicht einer bestimmten, entgegengesetzt geladenen Stelle auf der Partikel des Austauschers zuordnen; dies gilt besonders in Gegenwart geeigneter Flüssigkeiten wie Wasser. Es kann jedoch zur Ausbildung gerichteter, fester Bindungen kovalenter oder koordinativer Natur kommen (Wasserstoff, Schwermetalle).

Die Gegenionen können nun teilweise oder völlig durch eine *äquivalente Menge anderer Ionen gleichen Ladungssinnes ersetzt* werden. Ein solcher topochemischer Vorgang wird als *Ionenaustausch* bezeichnet; er entspricht weitgehend der doppelten Umsetzung oder Neutralisation zwischen niedermolekularen Elektrolyten. Es findet ein reversibler Austausch von Ionen zwischen der Lösung und den festen Partikeln statt; Das Netzwerk des Austauschers bleibt dabei im Prinzip unverändert.

Wenn man einen Ionenaustauscher mit einer Elektrolytlösung schüttelt, stellt sich früher oder später ein

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