

Luminous and Dark Formations of Intergalactic Matter

Recent advances in astronomical observation have added greatly to our store of information about the visible universe, but they have also led to a great increase in the number of unanswered questions concerning the distribution and nature of distant galaxies.

By F. Zwicky

AS ASTRONOMY pushed its limits from the solar system to the stars of the Milky Way and to the distant galaxies and clusters of galaxies, the following three problems suggested themselves automatically. Is there matter spread throughout interplanetary space? Is there matter in interstellar space? Are the enormous intergalactic spaces empty or not?

The first two questions were answered in the affirmative long ago. Comets with their gaseous tails, planetoids, asteroids, and meteors travel in great numbers between the planets. Dust is also present, as evidenced in the zodiacal light and in the "Gegenschein". Likewise, interstellar gases and dust particles are distributed irregularly throughout the Milky Way system.

The existence of intergalactic matter, however, could not be definitely established until recently.¹ Theoretical considerations strongly suggest the necessity of the existence of stars, small groups of stars, dust, and gases in the vast spaces between the galaxies.² Observational evidence is now available to prove most of these contentions.

Many extended luminous intergalactic formations have been found, and dark obscuring matter has been discovered to be sparsely distributed throughout the whole of the visible universe, showing cloudy concentrations in various points with particular preference for the central regions of the large clusters of galaxies.

ALTHOUGH we are now in the first stages of this investigation, significant morphological features of intergalactic matter can already be clearly distinguished. Some of these features are as follows:

1. Distortions of galaxies which are probably caused by tidal actions.

2. Single or multiple spiral arms that connect neighboring galaxies, the separation of which is often very large as compared with their "classical" diameters.

3. Filaments and bridges of all kinds which connect many very widely separated galaxies.

4. Halos which extend far beyond the classical diameters of individual galaxies.

5. Large clouds of luminous matter in which groups of galaxies may be imbedded or which are spread throughout extended regions within clusters of galaxies.

Most of these formations are of very low surface brightness, and have therefore not been noticed in the past. They were first brought to light with the help of the large, powerful Schmidt telescope using fast emulsions and, last but not least, by careful work.

Tidal Actions

Tidal effects among galaxies have been known for a long time. Symmetrically placed elongations of galaxies are often clearly visible, indicating the well-known phenomena of tide and countertide.³ A systematic investigation of thousands of physical pairs of galaxies which exhibit such effects is now being carried out by R. G. Harrington. He is using the plates of the 48-inch Schmidt sky survey which are ideal for this purpose.

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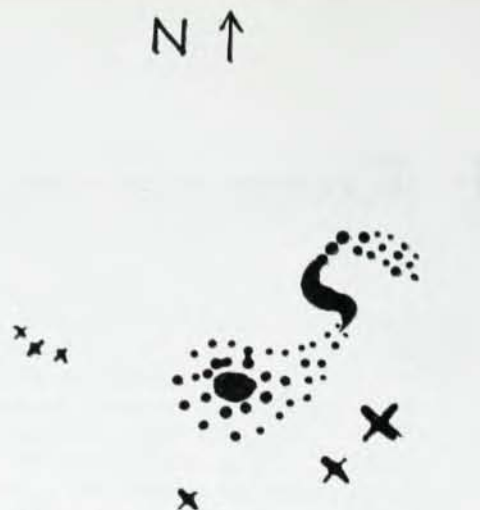


Fig. 1. Connected double galaxy at: right ascension $\alpha = 6^h 41^m 33^s$, declination $\delta = +86^\circ 37' 39''$ (epoch 1950.0). Crosses indicate foreground stars.

Connecting Spiral Arms

It has long been thought that the formation of spiral arms is mainly due to the tide and countertide resulting from the action of the inhomogeneous gravitational fields of two galaxies which have a close passing encounter. This view is strongly supported by the observation of many double galaxies, the components of which are connected by either one or two spiral arms. The following outstanding types have been found:

Two spiral galaxies connected by one spiral arm, an example being the double galaxy NGC 5257-5258. This system was observed by F. G. Pease⁴ with the 60-inch reflector on Mount Wilson over thirty years ago, and is perhaps the first characteristic case photographed.

Two stellar systems of different types. For instance, a spiral and an elliptical galaxy are connected by one spiral arm (see Fig. 1).

Two spirals, or one spiral and a galaxy which is not a spiral, may be connected by two spiral arms (see Fig. 2).

Obviously a tremendous number of intercombinations is possible, and individual examples for all of these are now being searched for. It will be of interest to analyze the morphological features of such systems, as well as the surface brightness, the colors, and the spectra of the faint connecting links between galaxies, since these features will be of importance for the understanding of the structure and the evolution of stellar systems. Also, through the determination of differential radial velocities (Doppler Shifts) of the various galaxies which are involved in an encounter, unique information may be gained on the length of these encounters on differential ages, that is, information which will throw light on the evolutionary effects in stars and galaxies.

In Fig. 1 we reproduce a sketch of an open barred spiral, one arm of which is free. The other arm, however, swings around, and after the fashion of a tentacle envelops the neighboring elliptical (or perhaps an S_0) galaxy. As the linking spiral arm opens up to the right its surface brightness becomes so low that under ordinary conditions it is difficult to photograph. Also, when the two galaxies move further apart they will presum-

ably separate completely. The clear linking of the two galaxies suggests on closer analysis that a barred spiral is formed from a properly rotating elliptical galaxy as the result of an encounter with a compact globular or S_0 type galaxy.

The Whirlpool nebula (Messier 51), at $\alpha = 13^h 27^m 8$ and $\delta = +47^\circ 27'$ (1950), has been known for centuries. It is a double system composed of the great spiral NGC 5194 whose one arm obviously swings around to connect with the irregular galaxy NGC 5195. The second arm on all old photographs, however, points into empty space and has been universally assumed to be a free arm. A close inspection, by the author, of a long series of films and plates obtained with the 18-inch and the 48-inch Schmidt telescopes revealed the surprising fact that the second arm also swings around in a wide arc to abut finally on the small companion galaxy (see Fig. 2). The fact that so startling a discovery could have been made on a bright and near-by galaxy, which has been photographed and closely viewed ten thousands of times by competent astronomers, means that many further discoveries may be expected as we improve our observing techniques.

Since the Whirlpool nebula is one of the relatively close stellar systems whose main body is resolved into stars, the greatest efforts will be made to locate individual stars in the newly discovered extension of the second spiral arm.



Fig. 2. The Whirlpool Nebula. The heavy lines show the structure of the double nebula as it has long been known. The crosses indicate a flare (I) as it appeared on photographs obtained with the Schmidt telescopes. The shaded parts (II) are extremely faint and were definitely identified only recently as being the extension of the second spiral arm connecting the two galaxies. The reality of the faint dotted cloud (III) is still in doubt. The seven large dots are some of the brighter foreground stars.

NORTH



Fig. 3. Photograph obtained on an Eastman 103A-O plate with the 200-inch telescope, shows a well defined intergalactic filament connecting two galaxies near $\alpha = 23^h 29^m 22^s$ and $\delta = -3^\circ 55' 42''$ (epoch 1950.0). The system in Fig. 3 was found independently by A. G. Wilson and the author with the 48-inch and 18-inch Schmidt telescopes respectively. Some of the other systems were found on plates taken in the course of the Sky Survey sponsored by the National Geographic Society.

Filaments and Intergalactic Bridges

Luminous filaments often connect the individual members of small groups which contain two or more galaxies. The connecting links are either diffuse bands or, very often, surprisingly narrow and distinct filaments. When more than three galaxies are involved, the connecting links generally become diffuse and form luminous clouds in which the group of galaxies appears to be immersed.

The oldest known cases in this category are multiple galaxies actually merging into one another (see NGC 5544-5545, or Stephens Quintet).⁴ Next come double galaxies with slight separations and faint luminous connections, for instance, NGC 750-751 which has the appearance of a stubby dumbbell.

The dynamics of most of these long-known cases is rather difficult to interpret. Without some proof to the contrary it may be assumed that the intergalactic matter between galaxies that are not very far apart actually constitutes a dynamic unit with these galaxies from which it cannot escape. Such intergalactic matter cannot therefore be considered as entirely free and thus contributes little to the problems which concern us most and which are essentially twofold, namely:

1. Is there matter which is entirely detached from all conventional stellar systems?
2. How much of this free intergalactic matter is there in a given large volume as compared with the total amount of matter which is located within the conventional galaxies?

The first step toward an answer to these questions was made when the author^{1,5} discovered numerous

widely separated galaxies which are connected by luminous formations. In a geometrical sense, these new cases may be thought of as extrapolations of the previously known more compact groups. In a dynamic sense, however, they involve a *decisively new feature*. Much of the matter between widely separated galaxies is *potentially free*, and thus truly intergalactic in the sense that it eventually will escape into intergalactic space where we can no longer assign it to any specific galaxy or group of galaxies. This conclusion appears inevitable when we study the geometrical aspects of the formations mentioned; it can also be strictly proved through observations of the relative radial velocities of the galaxies involved, as well as of the formations between them.

A photograph, taken with the 200-inch telescope, of a most peculiar intergalactic filament is reproduced in Fig. 3. On close inspection this amazingly well-defined and thin luminous filament reveals itself as a spiral arm of the southern galaxy whose second spiral arm projects itself in the opposite direction.

Since both galaxies are seen on edge, the spiral arms may actually be very much more curved in the plane of sight and may, in fact, be broad sheets in this plane, rather than filaments. On 18-inch Schmidt films it appears that the northern galaxy is connected by a thin luminous veil with the nebula IC 1505, which is located on the upper right. The reality of this veil, however, has not been definitely established.

As another truly remarkable feature of the whole formation we notice obscured regions which encircle the southern spiral crosswise. These bands are suggestive

of dust being whirled around the nebula in a fashion analogous to the peripheral columnar vortices which are generated in a gas between two rotating cylinders.⁶

Spectra of the two galaxies obtained with the 200-inch telescope were kindly provided by Dr. M. L. Humason. They show respectively an apparent velocity of recession of 7400 km/sec for the northern member, and an undetermined velocity of recession (because of poor spectrum) for the southern member. Assuming with Hubble⁷ an apparent velocity of recession of 530 km/sec per million parsecs (3.09×10^{24} cm) we must put the system in Fig. 3 at a distance of 46 million light years. Since the whole formation is 560 seconds of arc long, its actual dimension, according to the present (not yet revised) distance scale, is 125,000 light years.

Dr. Humason observed several emission lines in the northern galaxy, namely $H\delta$, $H\gamma$, $H\beta$ and very strong $\lambda 3727$ [O II]. Dr. N. U. Mayall kindly had tried a long exposure with the 36-inch Crossley telescope orienting the slit from one nebula to the other along the filament. This was done in order to determine whether the luminosity of the filament might partly or wholly be due to the fluorescent emission from excited intergalactic gases. The emission lines do not, however, extend beyond the nebulae proper. Thus, as was assumed from the start, the bright intergalactic formations are made up of stars. This view is strengthened by the fact that Dr. Humason in some cases has made the most important discovery that the H and K absorption lines of Ca^+ extend way beyond the classical outskirts of nebulae (see the section on extended halos, below).

The most striking feature of the filament in Fig. 3 is its taffylike fiber structure. The same type of structure is found in hundreds of additional cases of similar formations which have been photographed with the 48-inch Schmidt telescope. To most astronomers these string-like structures have undoubtedly come as a great surprise inasmuch as they point to an internal viscosity and cohesion which, according to conventional theory, stellar systems are not supposed to possess. Indeed, most astrophysicists have held to the view⁸ that stellar systems traveling with relative speeds of hundreds of kilometers would pass through one another in the case of a head-on collision, without disturbing each other materially and, at any rate, without expelling many stars into intergalactic space. In the face of the new discoveries these views, however, are hardly justified any longer. The problem thus forcibly arises as to the causes for the high internal viscosity and cohesion which account for stellar systems generating the taffylike strings as a result of close encounters.

Extended Halos

In Fig. 4 we show another interesting double system. The nebula at the left has two large halos around it which on close inspection appear to be hanging on a spiral arm of the irregular spiral at the right. This nebula, on encountering the one at the left, has perhaps rotated around it *twice*, leaving the two halos as a

drawn out spiral arm. If this view is correct it would in any event be new evidence for the amazing taffylike behavior of stellar systems. The structure of the nebula on the left illustrates how large the faint outskirts of a galaxy can become. In fact we do not know yet whether or not these outskirts have any limits at all. As we have already stated, we may very well find in the end that nebulae in themselves have no boundaries at all, but that they extend through what we thought to be intergalactic space. Galaxies may thus be contiguous to one another, without leaving any unclaimed space between them. If this is actually found to be the case, entirely new problems will arise regarding the total brightness of individual galaxies, of their luminosity function, and of the average density of matter in space. In order to get to the bottom of these questions, investigations are now under way at the Palomar Observatory to trace the outskirts of our own galaxy as well as those of the Andromeda nebula (Messier 31) as far out into space as possible.

Luminous Clouds

Clouds of luminous intergalactic matter in clusters of galaxies were actually the first intergalactic formations discovered.¹ Many years ago photographs taken with the 18-inch Schmidt telescope on Palomar Mountain indicated the existence of a faint luminous patch throughout the central parts of the Coma clusters of galaxies $\alpha = 12^h 55^m$, $\delta = +28^\circ 20'$ (1950). On the presently current distance scale the huge luminous intergalactic formation in this cluster has a diameter of half a million light years or more. Although to the eye the respective faint patch on the photographs is clearly visible, it is very difficult to record its characteristics objectively since it is interwoven with a great number of stars and galaxies.

There are some clusters of nebulae in locations in which the foreground stars are less disturbing and in which the nebulae are spaced farther apart than in the Coma cluster. One of these, the so-called A-Haufen, or A-cluster, which is located at $\alpha = 1^h 06^m$ and $\delta = -15^\circ 40'$ (1950.0), contains a most interesting intergalactic cloud, part *B* of which is bluish while part *R* is reddish in color (see Fig. 5).

The spectra of the two nebulae I and II were kindly observed by Dr. Humason at my suggestion. He informs me that a preliminary determination gives the follow-

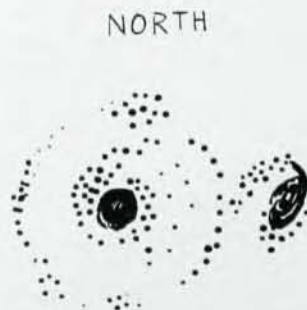


Fig. 4. Connected galaxies A and B at A: $\alpha = 1-17-31$, $\delta = +3^\circ 9'.5$; at B: $\alpha = 1-17-10$, $\delta = +3^\circ 9'.0$ (epoch 1950.0).

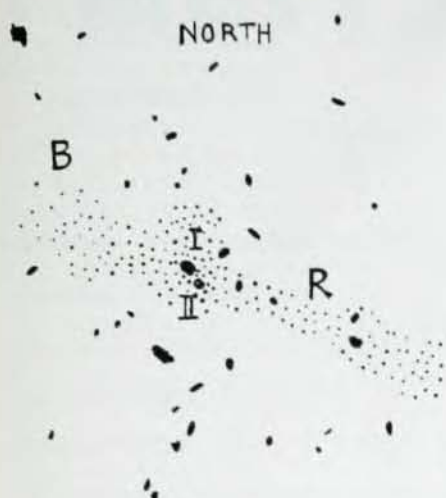


Fig. 5. Sketch of the intergalactic cloud in the A-Haufen (A-cluster) of galaxies. Individual member galaxies of the cluster are indicated by large spots.

ing apparent radial velocities of recession: $V_I = 16,000$ km/sec, and $V_{II} = 15,440$ km/sec. On the presently current distance scale, this puts the A-cluster at a distance of about 100 million light years. Since the mentioned intergalactic cloud has an angular diameter of about 450 seconds of arc, its real diameter is, on the old unrevised scale, approximately 220,000 light years. The differential radial velocity of 560 km/sec of the two galaxies I and II is such that they must be supposed to fly apart eventually. The luminous matter between them is thus truly free and intergalactic.

THE DISCOVERY on 48-inch Schmidt plates of thousands of intergalactic formations of the types mentioned earlier raises a number of entirely novel and difficult theoretical problems as to their character and their evolution. Three of the most puzzling aspects are: the apparently very high viscosity and cohesion of the matter in these formations; the fact that most luminous intergalactic matter seems to be quite blue, matching in color the outskirts of the spiral nebulae and some of the blue, irregular galaxies (color index $c_p \approx +0.3$); and that the luminosity in some of the cases investigated, and probably in most cases, is mainly due to stars.

Although most questions about intergalactic formations must go unanswered for the present, the following tentative alternatives may serve as guides for future investigations:

1. Intergalactic formations of the type discussed here were formed at the same time as the nebulae. This assumption is the least likely since the structure and location of the formations would appear virtually unexplainable.

2. The intergalactic formations, discussed in this paper, were formed as a consequence of close encounters and collision of galaxies. The result of a collision may be expulsion of stars, dust, and gases from both galaxies, or it may be that only dust and gases are ejected. In the latter case stars may either have been formed from the dust and the gases ejected or old stars which were

present previously in intergalactic space grew by accretion and thus took on the appearance of new blue stars.

WITH all of the luminous matter (that is, individual stars and thin clouds of stars floating in intergalactic space) it appears inevitable that intergalactic dust and gases should exist also. We have as yet no observational evidence for gases between the galaxies. The existence of intergalactic dust can, however, now be considered as established by the writer's researches during the past few years. The presence of thinly and unevenly distributed dust clouds throughout the whole observable regions of the universe was deduced by the following methods.

Counts of nebulae in many regions of the sky around the north galactic pole showed that the nonuniformity of their distribution is such that it cannot be accounted for either by clustering of nebulae or by local interstellar dust. It is most significant that by far the least number of faint nebulae is observed in the areas occupied by the nearby large clusters of galaxies such as the Virgo cluster, the Ursa Major cloud, and the Coma cluster. This observation indicates that dust clouds are concentrated within these clusters.

Counts of nebulae with depth lead to the amazing result that in a given fixed area the deviations from randomness increase as we count more and fainter nebulae. This observation is one of the strongest proofs for spotty intergalactic obscuration which is caused by dust clouds at all distances.

Counts of clusters of nebulae, both in breadth and in depth, lead to the same conclusion as the counts of nebulae.

The study of intergalactic matter promises to become of great importance. For the practical astronomer it is necessary to obtain quantitative data on both interstellar and intergalactic obscuration in order to determine the distances, absolute dimensions and luminosities of distant galaxies and clusters of galaxies. For the cosmologist and astrophysicist it is necessary to obtain qualitative and quantitative data on intergalactic matter because of its importance for all questions of the evolution of stars, stellar systems, and the universe as a whole.

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