The Density of Matter*

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Density is the amount of matter in a unit volume of space. In this paper it will be expressed in grams per cubic centimeter. As a rule we think of density as being applicable to the things we deal with in everyday life, forgetting that it is an important characteristic of matter, from atomic nucleus to the stellar universe. To a great extent the behavior of matter may be explained by a knowledge of density.

Often the nature of a chemical reaction depends upon the concentration of the substances involved. In biology the relative density of two interacting agents may determine the character of the operation of life-sustaining processes. In meteorology the variations in the density of the atmosphere cause the winds to blow, bringing the rain that makes land-life possible; while variations in the density of the waters of the sea, combined with the friction of the winds, cause ocean currents that sustain a large part of marine life. The astronomer knows that density often explains the behavior of planets, stars and nebulae. An illustration of the latter is found in "Nebulium." For a long time it was thought that this substance did not exist on the earth. This "strange" element reveals its presence by certain unusual lines in the spectra of many of the nebulae. In recent years it has been found that these lines are due to oxygen and nitrogen existing in a state of very low density and vast extension. The low density means that when an atom loses an electron by the impact of a light-quantum, it may be a long time before one is found to take its place. In other words low density brings about a high state of ionization, and this in turn changes the character of the light that the atom emits.

Some peculiar lines have been found in the spectra of the sun's corona. These lines have in the past been attributed to an element to which was given the name Coronium. Recently, Edlén[1] has found that the "strange" lines are due to the common elements, iron, nickel and calcium, all

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[1]Edlén, Bengt. *Arkiv for Matematik, Astronomi och Fysik*, Apr., 1941.

in a high state of ionization. The identification of nebulium and coronium with well-known earth elements, together with the fact that the periodic table of the chemical elements is completely filled, indicates that our little world contains every elementary substance to be found in the stellar universe.

In some respects density and porosity are reciprocal quantities, for in general they have an inverse relation. This statement, however, requires some discussion before it is taken literally. Consider the stellar universe: in a sense it is composed of galactic systems, and the intergalactic spaces are very large. Hubble[2] estimates the average distance between the galaxies to be about two million light-years. This means that the stellar universe is very porous. The next unit in order of decreasing size is the galaxy. Here again we find that the porosity is great, for the interstellar spaces are large. The third step in order of descent is the individual star. Here again we find porosity, for all of the stars are gases and their molecules are widely separated. The fourth step in descending size may be taken as the solids and liquids found here on earth. The fact that solids and liquids are only slightly compressible, even when great pressure is applied, suggests that the intermolecular porosity is not great. What has been said about the low porosity of molecules holds also for interatomic porosity, and for the same reason.

We come now to the consideration of *intra-atomic* porosity. In all previous downward steps there is seemingly a decrease in the porosity, but within the atom there is a vast and abrupt upward swing in porosity. Why is this true? This is a profound question and has to do with some strange discoveries that men made when they entered the realm that lies within the atom. In the world outside of the atom they were dealing with energy in such large quantities that they failed to realize that it was made of small units which could not be divided; and that if they use energy they must use one, or two, or three, or some whole number of unit-quantities (the unit quantity is called the quantum). We get our radiant energy from within the atom, and in order that the atom may radiate energy in terms of quanta,

[2]Hubble, Edwin. *American Scientist*, Spring Number, 1942, p. 101.

it is necessary that the internal positions and motions of the electrons in the outer shell of the atom shall be varied and complex, and that high velocities shall prevail. To meet these demands there must be abundance of room. And so the atom must be very porous.

Among the interesting discoveries of modern astronomy are the white dwarf stars of high density. Kuiper[3] describes one of these stars that has a diameter only half that of the earth but with a mass 2.8 times that of the sun. Van Maanen's star is estimated to have a density one thousand million times that of water. Every year new white dwarf stars are being discovered, and yet they are so small that only those that are near to the earth can be seen. Luyten[4] states that about eighty of these stars were known at the end of the year 1945.

How it is possible for stars to have the densities found in the white dwarfs, can be explained in terms of the structure and porosity of the atom. This is assumed to have at its center a nucleus that contains nearly all of the mass and almost none of the volume, while the electrons which revolve about the nucleus, account for nearly all of the volume and little of the mass. If some of the electrons are removed (as by very high temperature and short light waves) the atom loses volume far more rapidly than mass, and thus it becomes possible for atoms to be crowded into much smaller space, and material of great density is produced. Eddington[5] states that the temperature at the center of dwarf white stars may be one-thousand million degrees. Under this condition a large percentage of the electrons must be stripped from the nuclei of the atoms.

One of the great problems of modern astronomy is to find the form and volume of the stellar universe. Eddington[6] states that if any one of six basic factors underlying this problem were known, the others could be calculated. Density is one of the six. Hubble[7] lists three factors; if these were known the nature of the universe could be calculated. Density is one of the three. Why should density have so

[3]Kuiper, G. P. Astronomical Society of the Pacific, *Publications*, vol. 47, 1935, pp. 301-313.
[4]Luyten, W. J. Astronomical Society of the Pacific, *Leaflet No. 202*, 1945.
[5]Eddington, Sir Arthur Stanley. *The Internal Constitution of Stars*, 1926, p. 170.
[6]*Idem*, *The Expanding Universe*, 1933, p. 97.
[7]Hubble, *op. cit.*, 1942, p. 106.

much to do with the nature of the stellar universe? The answer is found in the theory of relativity. According to this theory, space is curved and the amount of curvature is proportional to the strength of the gravitational field, and the strength of this field depends upon the density of the matter occupying the field.

As the astronomer has gone further and further out into space he has discovered an unexpected effect known as the "red shift" of the spectral lines of the spiral nebulae. The strange thing about this shift is not that it exists, but rather that for all nebulae (except a few that are relatively near by) it is always *towards the red end* of the spectrum, and is directly proportional to the distance of the spiral under investigation. By this we mean that a nebula at one hundred million light-years distance would show twice as much shift as one at fifty million light-years.

There has been a great deal of speculation as to the cause of this "red shift," and so far no final conclusion has been reached. The idea that it is a Doppler effect seems to be the most popular theory. The Doppler effect may be illustrated as follows: Suppose that we hear the sound of the whistle of an approaching train; in this case the sound waves will be crowded nearer together and the pitch of the sound apparently raised. If the train is receding, the waves will be drawn out and the pitch lowered. Similar effects are observed when a light-emitting object moves towards or away from us. If a star is moving away from us, its light waves will appear to be longer, or in other words redder; and if coming towards us, the waves will be shortened and the star will be bluer than it would otherwise be. This method is often used to measure the velocity of a star either toward or away from the observer. So the Doppler effect is to be expected; but that it should always be toward the red, and the amount of shift should be proportional to the distance of the nebula, was not expected.

If all of the spiral nebulae are moving away from us with a velocity directly proportional to their distance, then the universe is expanding, and the greater the distance the greater the rate of expansion. The shift of spectral lines of some of the more distant nebulae indicates outward velocities of 25,000 m.p.s. It is hard to believe that this is true, and yet how else can the facts be explained? Why should the universe expand? If it were contracting we could attribute this to gravitation. Eddington[8] has suggested that when material bodies are very far apart, Newtonian gravitation is replaced by a "cosmical constant" of repulsion. But there is no reason for making this assumption, other than the fact that it would explain the red shift.

The figures found near the close of this paper were calculated from the latest data available. It will be of interest to compare some of these values with those of earlier years. In 1923 Steinmetz[9], from calculations based on the theory of relativity, found the volume of the stellar universe to be 4×10^{63} cubic miles, or 1.6×10^{79} cubic centimeters. This volume is less than that given in our tables for the fraction of the universe that is now within reach of telescopes. Obviously Steinmetz's figures are too small. In 1933 Eddington[10] gave figures for the *initial* volume of the universe which were about ten times that which may now be seen with the largest telescopes. He estimates[11] that since the beginning, the radius has expanded about five-fold. He gives the initial density of the universe as 1.05×10^{-27} grams per cc.[12]. On correcting this figure for expansion, the present density turns out to be 4×10^{-29} grams per cc., a figure remarkably near to that given in the table below for the visible part of the universe. That the fraction of the universe that may now be seen should have the same density as the universe as a whole is to be expected; for as Hubble[13] has said, the part now visible is a fair sample of the whole. Obviously, Eddington's figures, which were obtained from theory, were well-founded.

Here are some of the more important facts that were used in calculating the densities found in the table below:

Radius of the visible part of the universe, 4.73×10^{26} cm. (Hubble[14].)

Volume of the visible part of the universe, 4.47×10^{80} cc.

Mass of the visible part of the universe, 4.0×10^{52} grams.

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[8]Eddington, Sir Arthur Stanley. *New Pathways in Science*, 1935, p. 214.
[9]Steinmetz, Charles P. *Four Lectures on Relativity and Space*, 1923, p. 65.
[10]Eddington, *op. cit.*, 1933, p. 96.
[11]*Ibid.*, 1933, p. 100.
[12]*Ibid.*, 1933, p. 96.
[13]Hubble, *op. cit.*, 1942, p. 99.
[14]*Ibid.*, 1942, p. 101.

Diameter of the galaxy, 9.46×10^{22} cm. (Skilling[15].)
Thickness of galaxy, 9.46×10^{21} cm. (Skilling[16].)
Mass of galaxy, 4.0×10^{44} grams. (Baker[17].)

Density Table

Visible part of the Universe, 9.0×10^{-29} grams per cc.
Galaxy, or Milky Way, 6.0×10^{-24} grams per cc.
Solar System, 1.75×10^{-11} grams per cc.
The Sun, 1.41 grams per cc.
The Earth, 5.52 grams per cc.
Water Molecules, 1+ grams per cc. (incompressibility)
Atomic Nuclei, 1×10^{12} grams per cc. (Meitner[18].)

From the Atomic Nuclei to the Stellar Universe, the density of the one is 1×10^{42} times greater than the other, and yet they are made of the same stuff. The extremely high density of the atomic nuclei explains why nearly all of the energy of the universe is locked up in these exceedingly small bodies. Matter and energy are identical.

We have gone downward from the visible part of the universe to the atomic nucleus. Is this the end of the downward journey? Are there no organized units of matter below the level of the atomic nucleus? Perhaps no scientist would be willing to give a positive answer to this question. But it is true that our concepts of matter undergo a great change when we try to understand the structure of the atom. It is here that the wave-picture takes the place of the particle-picture, and as Jeans[19] has said our concepts of matter become wholly mental constructs; or to quote from Scandone[20] "Science, seeking for the eternal and unchangeable laws ruling the relationships between the fundamental entities, raises us to an abstract world where, in the extreme rarefication of all sensory representation, we behold that 'harmony' of the universe which the ancients symbolized as the 'music of the spheres'." How is it possible to measure mental constructs, or the music of the spheres in terms of grams per cubic centimeter?

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[15]Skilling, William T. & Robert S. Richardson. *Astronomy*, 1939, p. 521.
[16]*Ibid.*, 1939, *l.c.*
[17]Baker, Robert H. *An Introduction to Astronomy*, 1935, p. 487.
[18]Meitner, Lise. In *Fortune*, March, 1946, p. 141.
[19]Jeans, Sir James. *Physics & Philosophy*, 1943, p. 202.
[20]Scandone, F. In *Sperryscope*, vol. 11, no. 1, p. 21, 1947.