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(Reprinted from Discovery, October, 1928)

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New facts discovered about the chemistry of the stars have altered former ideas, and the whole question of stellar evolution is at present under reconsideration. Theories which seemed tenable two or three years ago are either abandoned or regarded with caution.

THE chemistry of the stars is fortunately not very complex. By far the greater proportion of the matter in the universe is at tremendously high temperatures. According to a recent estimate, ninety per cent of all matter is at a temperature exceeding 1,000,000° centigrade. Here the physical conditions are comparatively simple and molecules are unknown, for the atoms themselves are disrupted into free electrons, protons, and atomic nuclei, all moving about with tremendous velocities in a medium literally filled to bursting-point with penetrating radiation. This is the picture of the interior of a star.

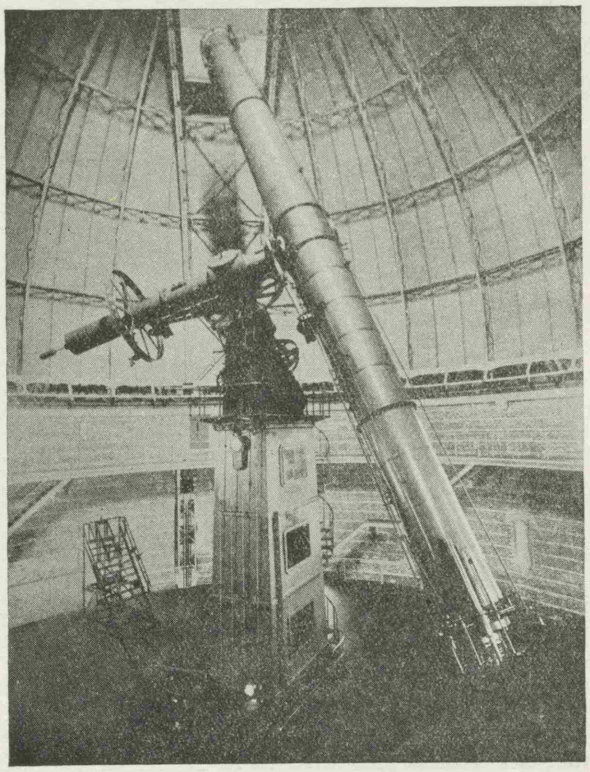

Fig. 1.

FORTY-INCH REFRACTOR.

This giant telescope of Yerkes Observatory, whose lens is 40 inches in diameter, is 62 feet in length and weighs, with its counterbalancing weights and all the moving parts, about 20 tons. The dome is 90 feet in diameter.

Photograph by Prof. F. E. Ross, Yerkes Observatory.

At more moderate temperatures, perhaps 20,000°, most of the atomic nuclei have captured a sufficient number of electrons almost to balance their positive electrostatic charges, while at somewhat lower temperatures most of the atoms are fully equipped with their requisite numbers of orbital electrons and at about 12,000° the linking together of atoms to form simple molecules commences. Down even to the temperature of 3,000°, however, the tendency to aggregate into molecules is not very marked, and only about a dozen chemical compounds are recognized. This is the state of affairs in the atomospheres of the stars.

Thus it is evident that the chemical conditions which we have on the earth are not representative of the universe as a whole. The perhaps not unique but certainly very exceptional conditions of temperature and pressure on the earth have favoured the synthesis of complex inorganic and yet more complex organic compounds, but these diverse forms of matter are not typical of the universe.

How is the chemistry of the stars studied? Obviously it must be learned from the only thing the star sends to us, namely, electro-magnetic energy. The secrets of its nature are imprinted in the starlight. It thus becomes a question of spectroscopy—the analysis of the starlight and the decodifying of the message. Sir Isaac Newton laid the foundation stone when he investigated the prismatic refraction of light in 1672. Fraunhofer first carefully observed the many dark lines in the spectrum of sunlight, Kirchhoff first explained them. The cooler atoms in the outer atmosphere of sun or star are absorbing just those radiations which they would themselves emit if they were at a sufficiently high temperature to radiate, hence it is possible, by matching up absorption lines occurring in a stellar spectrum with well-known emission lines produced in a laboratory by raising known elements to incandescence, to identify the elements in the stellar atmosphere. This was done by Sir William Huggins, Sir Norman Lockyer, Father Secchi, and other pioneer astrophysicists.

Stellar spectra are now photographed at most of the leading observatories. Either the starlight passes first through the telescope and then through the pirsms to the photographic plate (see Figs. 1 and 2), or else the prism is placed in front of the objective glass of the telescope, and then the light passing on through the telescope falls on the photographic plate. In the former case one star at a time is photographed, in the latter arrangement all the stars in the field of view impress their spectra on the plate simultaneously.

Careful study of stellar spectra shows that there are many different types, but that they grade imperceptibly one type into the next. They were classified at Harvard Observatory in a sequence of increasing complexity of appearance, but subsequently it was realized that an order was possible which represented the changes resulting from gradually decreasing temperature. The main portion of this sequence is shown in Fig. 4.

Of the ninety-two elements recognized by modern atomic physics only two remain unidentified by chemical or by spectroscopic analysis of terrestrial matter. The elements not as yet detected in the stellar spectra are sixteen in number, namely: boron, fluorine, neon, phosphorus, chlorine, argon, arsenic, selenium, bromine, krypton, antimony, tellurium, iodine, xenon, gold, and radon. In addition to these there is considerable uncertainty with regard to some of the elements known as the rare earths and the following other elements: beryllium, germanium, indium, tantalum tungsten, osmium, iridium, platinum, mercury, thallium, bismuth, thorium, uranium.

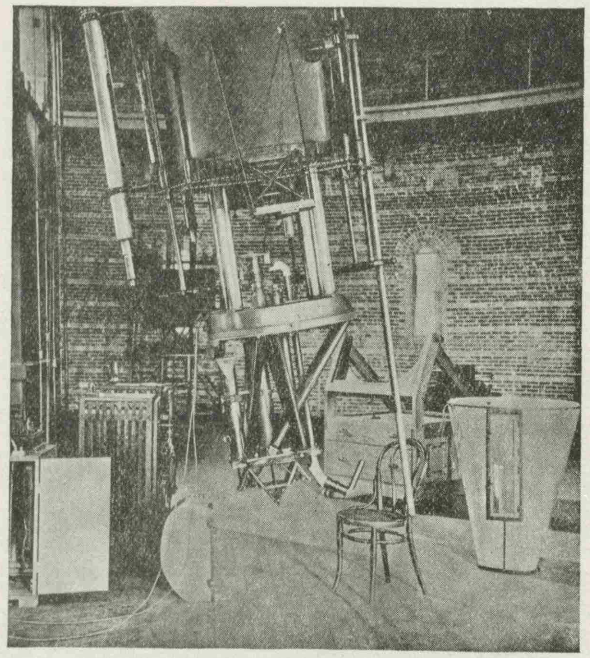
FIG. 2.

THE BRUCE SPECTROGRAPH AT YERKES.

The spectrograph is attached to the lower end of the great Yerkes telescope. The light from the star, focussed by the telescope on the slit of the spectrograph, is made to pass through one, two or three prisms before falling on the photographic plate. To ensure steady conditions the spectrograph is enclosed in the constant temperature case seen at the right of the photograph.

From a Yerkes Observatory photograph.

It should be remembered, however, that because the lines typical of these elements are not definitely identified in the stellar spectra, we need not draw the conclusion that these elements are absent. Various factors might enter into the question—the conditions required to excite the radiations or absorptions might not be exactly those of the stellar atmospheres, or the typical lines might fall in a region of the spectrum not obtainable, that is, too far in the infra-red or too far in the ultra-violet to be photographed. The amazing thing is not that so many elements are unidentified, but that so many are known beyond any shadow of doubt to be present in the stars.

The spectra of the hottest stars reveal the presence of hydrogen and helium and many ionized atoms of various elements, that is, atoms with an excess positive charge owing to the fact that not all the required electrons have been captured by the nuclei. An atom lacking one electron is said to be once ionized, if two are missing it is doubly or twice ionized and so on. In these hottest stars are ionized oxygen, nitrogen, carbon, silicon, calcium, magnesium, and the first four of these also appear in the twice ionized state.

As we pass to somewhat cooler stars some of the ionized lines fade out while others appear and also many lines due to neutral atoms—iron, titanium, strontium, barium, vanadium, aluminium, etc. It is at this stage, in the Class A stars, that molecular structure first puts its impress on the spectra. A molecule radiating or absorbing light does not do so as distinct lines, but as one or more bands. Thus a whole region of the spectrum will be affected if molecules are absorbing light in the star's atmosphere, and a dark patch or band is produced, usually sharply defined at one extremity and gradually fading off at the other. This is best seen in the K and M stars in Fig. 4. In the A stars band structure is first seen and is due to the carbon nitrogen compound cyanogen.

A striking feature of a yet cooler spectrum, the solar type of Class G, is a narrow band at wave-length λ 4314, known as Fraunhofer's G-band, identified by Newall, Baxandall, and Butler with some hydrocarbon molecule. Stars cooler than type G whose spectra are chiefly distinguished by the bands of cyanogen, carbon monoxide and hydrocarbon, are classified R and N according to the development of these bands.

The majority of the stars cooler than Class G stars, however, are not of Classes R and N, but belong to what is known as the *main sequence* which terminates with Classes K and M. Their spectra are free from the bands of carbon compounds, but in the M stars the bands of titanium oxide are the dominant characteristic. No star is known whose spectrum shows both carbon compounds and titanium compounds, these two seem to be mutually exclusive. A small class of the cooler stars, very analogous to the M stars, are designated as Class S. Zirconium oxide bands are present in their spectra. Occasionally, but not always, titanium oxide is also present, but the zirconium oxide molecule appears to persist to higher temperatures than the former molecule can stand. Fig. 3 illustrates the sequence of stellar types above mentioned, though one cannot attempt to read into the diagram a simple evolutionary scheme. The whole question of stellar evolution is at present under reconsideration. New facts have altered old ideas. Theories which seemed tenable two or three years ago are either abandoned or regarded with cautious suspicion.

The spectrum of sunspots presents an interesting field of study, for their conditions are not typical of the undisturbed solar surface. Vast vortices of rising gas suddenly reach a level of lower pressure in the higher portion of the sun's atmosphere and, rapidly expanding, the gases cool down producing absorption spectra more nearly resembling that of stars of Class K. Sunspot spectra reveal the presence of water vapour and magnesium and calcium hydride. Bands of ozone and water vapour do appear in the spectra of stars, but can be shown to be of telluric origin, that is to say, to be effects produced in the spectrum as a result of the passage of the light through the earth's atmosphere. If these bands were strengthened in the spectra of sunspots and the cooler stars, this would be evidence of the presence of these compounds at the source. This is so with the water vapour, but not with the ozone. Theoretically, ozone might be expected in the atmospheres of M stars, for Fowler and Strutt calculated its maximum thermal formation to be at a temperature of 3,500° centrigrade at a pressure 10^{-7} atmospheres, conditions probably existing in the outer portions of the M stars.

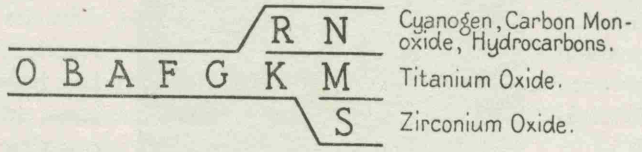

FIG. 3.

MAIN SEQUENCE OF STELLAR SPECTRA AND BRANCHES.

This diagram illustrates the sequence of stellar types, as exemplified by their spectra, though one cannot attempt to read into it a simple evolutionary scheme.

In the ultra-violet spectrum of sunlight the bands due to ammonia have been identified by Fowler and Gregory.

The spectra of the planets are, of course, due to reflected sunlight, but they show certain absorption bands not present in direct sunlight and therefore due to the planetary atmospheres. In the case of Venus and Mars the effect is almost negligible, but Jupiter, Saturn, Uranus and Neptune certainly have atmospheres differing somewhat from that surrounding the earth. Unfortunately the bands in their spectra are of unknown origin as yet. Chlorophyll may be responsible for some of the bands, but the evidence is inconclusive.

The spectra of comets exhibit many features of interest. There are several bands as yet unidentified, while other conspicuous bands are due to carbon monoxide, cyanogen, and the hydrocarbons, possibly acetylene and methylene. The elements responsible for the line spectra are hydrogen, helium, sodium, and iron. Meteors are generally supposed to be typical of the material composing the head of a comet. This seemed definitely proved in the case of Biela's Comet, which returned once or twice showing signs of disruption and then was seen no more, but in its place at the appointed time there came a meteoric shower of considerable brilliance. The analysis of meteorites is therefore of significance — iron, nickel, calcium, silicon, gallium rubidium and magnesium.

In the nebulæ, the spectroscopist has found hydrogen, helium, carbon, nitrogen, and several strong broad lines usually referred to as "nebulium" lines. Many speculation have been made regarding these. In the autumn of 1927, Dr. Bowen of California, calculated how much energy would be emitted by certain unusual electron movements in atoms of ionized or doubly ionized nitrogen and oxygen, and found very good agreement with many of the nebulium lines. In support of this explanation of the nebulium lines Professor A. Fowler added further evidence, but the question remained:—If oxygen and nitrogen produce these lines, why do we not also find in the spectrum the lines most frequently associated with these ions?

An answer to this was given by Professor Eddington in December last. He drew attention to the change in the relative intensities of probable and improbable emission lines when the stimulating radiation is exceedingly weak, and the density of the gases of the nebula so low that once an atom has become ionized it will wander far and wide before encountering a free electron which it can capture to complete its full quota. The picture we form, therefore, of a gaseous nebula is this: a vast expanse of space (so vast, indeed, that our whole solar system would be but an insignificant portion), filled with about as much gas—hydrogen, helium, oxygen, nitrogen, carbon compounds and so forth—as would altogether make up a mass equivalent to our sun. This tenuous gas is not at a very high temperature, but is being traversed by the light from nearby stars. Much of this light is absorbed by these tenuous gases and then re-emitted in the manner distinctive of the nebular conditions.

The chief debt of the astrophysicist to the chemist is in the development of ionization theory. The physical chemist has elaborated the theory of dissociative equilibrium. Saha, a distinguished Indian astrophysicist, realized that there was a logical analogy between this problem and the problem of ionization in a star's atmosphere. We know that electron bombardment upon a gas, or the passage of X-rays or other penetrating radiation, will disrupt some of the atoms of the gas, thus producing ionization. But ionization can come about in the absence of these agents. This *natural ionization* occurs spontaneously, the energy needed to expel the electron from the atom being drawn from the environment, which thus becomes cooler. This has proved to be a very fruitful line of investigation, but space will not permit of its discussion in this article.

Chemists, for the most part, think in terms of molecules. Biochemists, in particular, are wont to think of some very large molecules. Hæmoglobin, for example, the red corpuscle in the blood, is a molecule of sufficient size and complexity to appal the average mind, for it is said to comprise about 100 carbon atoms, 200 hydrogen atoms, as well as many atoms of iron and other elements. Let not the chemist, however, boast of his giant molecules, for if it came to a contest as to who could think of the largest molecule, it would not be the chemist who would carry off the palm of victory. The astrophysicist would stand *facile princeps*.

There is a class of stars, of which the companion of Sirius is the best known example, called the white dwarfs. Hidden from view beneath the atmosphere of such a star, so much matter is packed so closely together that its density is about 50,000 gms. per c.c., or, in other words, one ton of matter is packed into every cubic inch of space inside the star. Observation and calculation point to this tremendous density and spectroscopic results confirm it, but can one explain it?

The explanation took this form. When we think of the compression of any substance, we picture the limiting density as being attained when the atoms or molecules have been pressed shoulder to shoulder, as it were. Greater density is only possible if each atom can itself be reduced in size. Now the effective volume of an atom is determined by the radius of the orbit around which whirls its outermost electron. The volume of the atom cannot be greatly reduced by compelling the electrons to move in nearer and nearer to the nucleus, but the volume can be reduced, and reduced many thousand-fold, by removing the electrons altogether, that is to say, by completely ionizing the atoms. Our substance is then reduced to a gas made up of myriad electrons each having a diameter of only 0.0000000000001 cm. and each moving with incredible rapidity unconstrained to any orbit, and of the atomic nuclei which, though they be over a thousand times more massive than the electrons, are a thousand times smaller in diameter. Such a gas may be compressed to densities far exceeding that above mentioned. This is apparently what has happened in these white dwarf stars, and in order to maintain their complete or almost complete ionization it is calculated that the temperature within the star must be almost incredibly high—of the order of 100,000,000° centigrade.

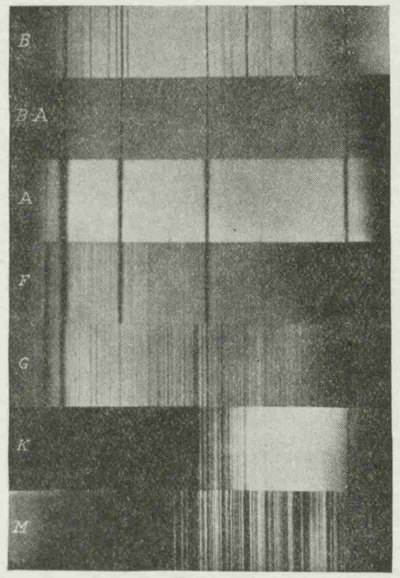

Fig. 4.

TYPICAL STELLAR SPECTRA.

Well-known stars whose spectra exhibit these typical features are the following: Early B—ϵ Orionis (Alnilam); Later B—β Orionis (Rigel); A—α Canis Majoris (Sirius); F—α Canis Minoris (Procyon); G—α Aurigae (Capella); K—α Bootis (Arcturus); M—α Orionis (Betelgeuse).

Photograph by Harvard College Observatory.

Just here a grave difficulty arose. The old physics teaches that the higher the temperature of a mass of matter the more intense will be the outflow of radiant energy from it. Thus our hot dense star, which to grow denser must grow hotter at its centre, ought to be radiating more and more fiercely as it grows older. But its total energy is finite, and hence the apparent contradiction that the time will come when its store of energy is almost exhausted, it will want to cool down, but will not have retained sufficient energy to expand or lift its outer layers against gravity Such a perplexing situation can never arise in the natural world—it must be our physics that has led us astray.

We of this generation have seen the birth of the new physics, and though few as yet have grasped its full significance and mastered its principles, all may gain some idea of its line of thought and gaze with wonder and admiration at what the new methods have already achieved.

The new methods of physics have been applied by Mr. R. H. Fowler of Cambridge to this problem, with results which may be stated somewhat thus:—There are two definitions of temperature. One states that the faster the motions of the atoms or molecules, the higher is the temperature, and *vice versa*; in other words, temperature is a measure of the average speed of the particles. The other definition states that temperature is a measure of the ability of a body to radiate. Under terrestrial conditions these two definitions agree perfectly and the old physics regarded them as synonymous; but the new physics shows that we cannot generalize and deduce that under all extreme conditions these two definitions will agree. Indeed, they begin to diverge very greatly when very dense matter is being considered. In our dense star the velocities of the free electrons and atomic nuclei are approaching the highest velocity possible, and hence one definition says that this is the hottest matter in the universe. But this very density means that any one particle has no choice as to where it will go next. There is possible but one place and one speed for each particle at any instant. Radiation depends upon there being freedom of motion, choice of next position for any particle, and hence where all such freedom is denied there can be no radiation. Hence by the second definition such a star is approaching the absolute zero and is therefore the coldest matter in the universe. Furthermore, matter in this condition has become strictly analogous to a molecule containing no excess energy which it can radiate away, and so the ultimate state of a white dwarf star is that it will be one great molecule.

Here the story ends, but we cannot do otherwise than demand a sequel. Such a final deadlock as above described is not in accordance with the trend of thought initiated by Galileo and deepened by the investigations of every succeeding natural philosopher into belief in

> " . . . the perpetual round of strange,
> Mysterious change."

If the old physics cannot solve the problem, and the new physics can go thus far and no farther, then we must wait hopefully for a yet newer natural philosophy to carry the final chapter on the chemistry of the stars beyond the *status quo* of the star molecule.

"THE CHEMISTRY OF THE STARS."

To the Editor of DISCOVERY.

SIR,

With reference to my article in your October issue, "The Chemistry of the Stars," I think it might interest some of your readers to know that the progress of science is so rapid that during the period between sending my manuscript to you and its publication, two more molecules have been identified in stellar spectra and several elements.

Spectrograms of the famous variable star, Mira Ceti, when at its recent maximum brightness, revealed bands which have been identified with the chemical compound aluminium oxide, a substance hitherto unrecognized in the stellar atmospheres, and certainly not present in the hotter stars.

In the stars of types R and N, it was stated in my article that the band spectra arose from molecules of cyanogen, carbon monoxide, and hydrocarbons. Two spectroscopists have now put forward evidence for attributing some of these bands to the carbon molecule composed of two carbon atoms.

An exhaustive piece of work at the Mount Wilson Observatory has established with a strong probability the presence in the sun of the "rare earth" elements cerium, lanthanum, neodymium, samarium, europium, and ytterbium; while there is evidence for præsodymium, gadolinium, terbium, dysprosium and erbium, though much less conclusive. The elements illium, holmium and thulium cannot as yet be proved to be either present or absent.

Thanking you for offering me space to publish this "postscript" to my article, I am,

Faithfully yours,

A. VIBERT DOUGLAS.

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McGill University, Montreal.