"On the Order of Appearance of Chemical Substances at different Stellar Temperatures." By Sir Norman Lockyer, K.C.B., F.R.S. Received February 17,—Read February 23, 1899.

In a paper on the "Chemistry of the Hottest Stars,"* in 1897, I stated the results so far arrived at concerning the order in which certain spectral lines appeared and others disappeared in stars arranged in a series of ascending temperatures. Since that paper was written many important advances have been made, so that I have been able in the meantime to considerably extend the research. Among these advances I may mention the following:—

1. With regard to the metals, my recent note on the enhanced lines in the spectrum of α Cygni† enables us to deal with the lines observed at the highest temperature in the spectra of the following substances, Fe, Mg, Ca, Sr, V, Ti, Ni, Mn, Cr, and Cu.

The temperature ranges of the enhanced lines of these metals have been investigated with the following results:—

Metal.	Range of temperature (upward series).	Range of temperature (downward series).
Mg	α Ursæ Min. to γ Argûs	α Eridani to Procyon.
Ca	α Tauri to γ Argûs	α Eridani to Arcturus.
Fe	α Tauri to ζ Tauri	β Persei to Arcturus.
Ti	α Tauri to ζ Tauri	β Persei to Arcturus.
Cu	α Ursæ Min. to α Cygni	β Persei to Procyon.
Mn	α Ursæ Min. to α Cygni	β Persei to Procyon.
Ni	α Ursæ Min. to α Cygni	β Persei to Procyon.
Cr	α Ursæ Min. to α Cygni	γ Lyræ to Procyon.
V	α Ursæ Min. to α Cygni	Sirius to Procyon.
Sr	α Tauri to α Cygni	Sirius to Arcturus.

I pointed out in the note referred to that the enhanced lines of the above substances seemed to account for almost all of the more marked lines in α Cygni. It is on this ground that I have investigated their behaviour in other stars before waiting for the results of the complete inquiry. Another reason has been that although in addition to the enhanced lines of the metals shown in the foregoing table, those of

Ba, Cd, Mo, La, Sb, Pd, Ta, Rh, Er and Yt, Ce, Wo, U, Zr, Pb, Co, Bi,

have already been investigated with lower dispersion, and a spark obtained with the use of a much less jar capacity, so far I have no

* 'Roy. Soc. Proc.,' vol. 61, p. 148.

† *Supra*, p. 320.

certainty that any of these substances exist in the reversing layers of stars of intermediate temperature.

2. The temperature ranges of the arc lines of some of the metals have also been investigated, and the results are shown in the following table:—

Metal.	Range of temperature (upward series).	Range of temperature (downward series).
Fe	α Tauri to α Cygni	α Canis Majoris to Arcturus.
Ca	α Tauri to α Ursæ Min.	α Canis Majoris to Arcturus.
Mn	α Tauri to α Ursæ Min.	α Canis Majoris to Arcturus.

3. The new series of lines discovered by Professor Pickering, and described by him as representing a new form of hydrogen,* has been found in the spectra of ζ, ϵ, δ, and κ Orionis photographed at Kensington in 1892, and Mr. McClean has traced the lines in γ Argûs.

We are therefore now in a better position to determine the relation of this new gas to other gases, both known and unknown, appearing in stars of nearly equal temperature.

4. In addition to the unknown lines at $\lambda\lambda$ 4089·2 and 4649·2, referred to in my last communication on this subject,† three other unknown lines occur in γ Argûs.

As these most probably reveal still undiscovered gases, I include them in the following table, showing the limits of stellar temperature to which the various known and unknown lines, probably of gaseous origins, extend.

Origin.	λ of chief lines.	Range in ascending series of stars.	Range in descending series of stars.
Unknown.	4457, 4451, 3876	Seen only	in γ Argûs.
Hydrogen (new)	4544·0, 4200·4	ζ Orionis to γ Argûs	No stars available.
Unknown.	4089·2	α Crucis to ζ Orionis	
,,	4649·2	,, ,,	α Eridani.
Helium ..	4471·6, 4026·3	Rigel to γ Argûs	α Eridani to γ Lyræ.
Asterium..	4388, 4009	,, ,,	α Eridani to γ Lyræ.
Hydrogen.	complete series	Aldebaran to γ Argûs	α Eridani to Arcturus.

* 'Astrophys. Journ.,' vol. 5, p. 92 (1897).

† 'Roy. Soc. Proc.,' vol. 62, p. 52.

5. Mr. McClean has stated that certain of the oxygen lines (amongst which is the strong triplet at λλ 4070·1, 4072·4, and 4076·3) appear in the spectrum of β Crucis and other stars of nearly equal temperature. My own observations so far as they have gone tend to confirm this view, but other photographs and more laboratory work are needed to explain certain changes of intensity which have been observed. The lines attributed by Mr. McClean to oxygen have been noted between α Crucis and ζ Orionis in the upward series, and in stars at about the α Eridani stage of temperature in the downward series.

6. There is evidence that the strongest lines of nitrogen at λ 3995·2 and λ 4630·9 make their appearance in stars at about the temperature of α Crucis. These lines appear from Rigel to ζ Orionis in the upward series, and are present in stars at the α Eridani stage in the downward.

7. I pointed out many years ago* that at high temperatures the flutings of carbon in the violet are replaced by a line at λ 4267·5. There is a line at this wave-length in the spectra of stars ranging in temperature from that of Rigel to ζ Orionis on the up side, and from α Eridani to β Persei on the down side, of the temperature curve.

There is no known line of gases or metals to which this line can be assigned. It is probable therefore that carbon exists in stars of the same temperature as that at which oxygen and nitrogen have been traced.

8. Two lines in the spectrum of silicium (λ 4128·5 and λ 4131·5) have been traced in stars between the temperatures of α Ursæ Min. and α Crucis in the upward series and between those of α Eridani and Procyon in the downward.

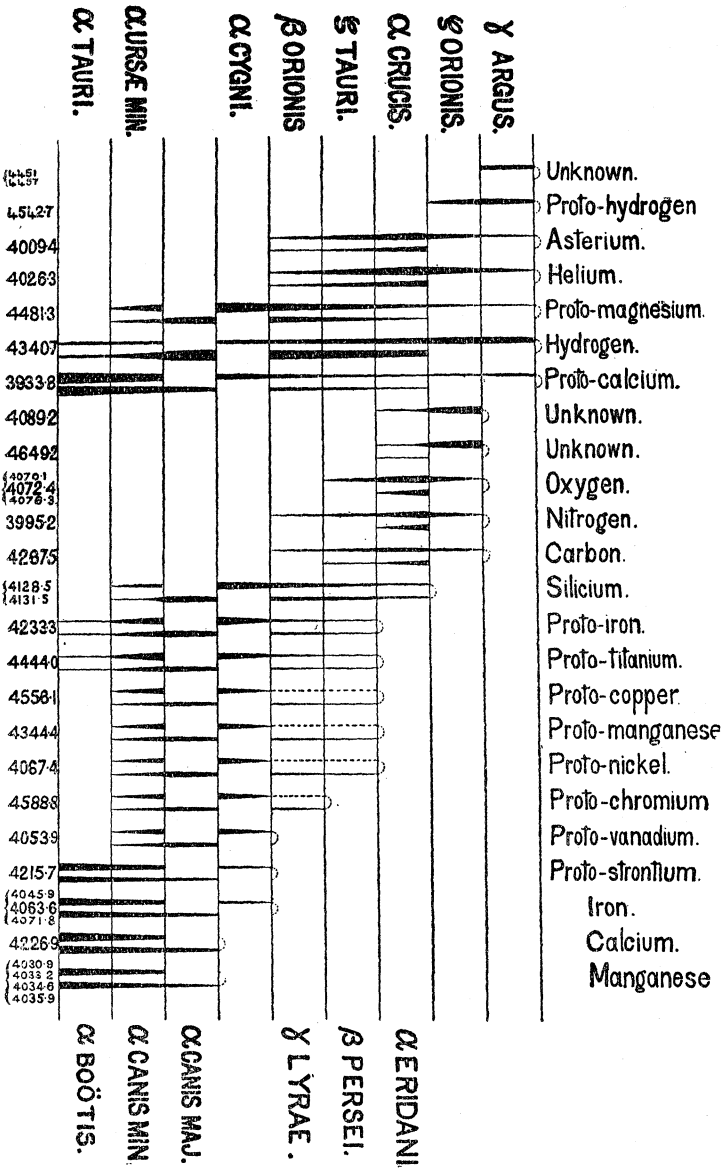
The accompanying map shows the facts relating to stars as hot as, or hotter than, the sun, as we know them at present.

Description of Map.

The map is arranged on the following plan: The temperature of the sun and Arcturus forms the lowest stage. The upper limit is defined by γ Argûs, the hottest star so far known. On the left the stars named are those of increasing temperature; on the right those of decreasing temperature. Those on the same horizon represent equal mean temperatures so far as the cleveite gas and enhanced lines help us to determine them. The blank spaces indicate that so far no star has been photographed in the spectrum of which the enhanced lines exactly match those on the opposite side.

The names of the various chemical substances included in the discussion are given at the top. I have retained the prefix "proto-" to that condition of each metallic vapour which gives us the enhanced lines alone, and I have added it to that form of hydrogen seen only in the hottest stars.

* 'Roy. Soc. Proc.,' vol. 30, p. 461.



The behaviour of the most typical line of each chemical substance is indicated by a double line looped at the top at its highest range. The length and varying thickness of the lines in stars on both sides of the temperature curve are derived from the observed appearance and intensity of the lines, noted in the different stars.

The wave-lengths of the lines discussed are shown at the bottom of the map.

ADDENDUM.

The facts embodied in the map present to us the spectral changes noted in stars of Groups III, IV, and V, of my classification,* and are a result of a more general inquiry than those referred to in my previous papers,† the origins of a very considerable number of stellar lines having since then been traced to enhanced lines of metals and to known gases.

It will be seen that this more general inquiry entirely justifies the prior statement‡ that the metallic lines are thickest in stars increasing their temperatures, and that the hydrogen lines are thickest in stars decreasing their temperatures; in other words, on the opposite arms of the temperature curve. I have already stated a possible explanation.§

It will be observed that, so far, I have not been able to find stellar spectra on the downward side corresponding to those of γ Argûs and ζ Orionis; but it is more than probable that near the apex of the curve only a small change will be observed; their default, therefore, is of less consequence than it might have been.

The same remark applies to α Cygni and Sirius; but here it is certain that the differences in the relative intensities of the gaseous and enhanced lines will be considerable, judging from what happens above and below the heat stages represented by them.

The stars used in the discussion give us very definite results, showing that the various chemical forms are introduced at six very distinct heat levels.

I next proceed to make some remarks upon the series of facts now for the first time brought together; it must, however, be borne in mind that all the chemical elements and all parts of the spectrum have not yet been included in the survey.

1. Hydrogen appears throughout both series of stars from top to bottom. Proto-magnesium and proto-calcium follow suit very nearly; but the highest intensity of the former is reached at the stage represented by α Cygni, and of the latter at the solar temperature represented by α Tauri and Arcturus.
2. With the above exceptions, all the chemical forms so far traced are relatively short-lived.

This is the first important differentiation. In the light of (1) we

* 'Roy. Soc. Proc.,' vol. 43, p. 117 (1887).

† 'Roy. Soc. Proc.,' vol. 44, p. 1 (1888); 'Roy. Soc. Proc.,' vol. 45, p. 380 (1889); 'Phil. Trans.,' A, vol. 184 (1893), p. 725.

‡ 'Roy. Soc. Proc.,' vol. 61, p. 182.

§ 'Roy. Soc. Proc.,' vol. 61, p. 183.

are justified in assuming that the substances in (2) would be visible in the stellar reversing layers if they were there.

3. In the stars of higher temperatures we deal generally with gases. Below the stages represented by β Orionis and γ Lyræ we deal with proto-metals and metals, hydrogen being the only exception.
4. The proto-metals make their appearance at about the same heat-level at which the gases (with carbon), always excepting hydrogen, begin to die out.

This is the second important differentiation. It is interesting to notice the distinct difference of behaviour of carbon and silicium in the descending series; the former goes through the same stages as oxygen and nitrogen, the latter behaves like the proto-metals.

5. With the exception of iron the metals, as contradistinguished from the proto-metals, only make their appearance in stars at and below the heat-level of Sirius.

This is the third important differentiation. It is accompanied with a notable *diminution* of hydrogen and proto-magnesium, and with an *increase* of proto-calcium: indeed the latter seems generally to vary inversely with the hydrogen.

In all these changes we seem to be brought into presence of successive polymerisations due to reduction of temperature. Of the origin of proto-magnesium and proto-calcium the stars as yet tell us nothing, but it is difficult to believe that the earliest forms of the other metals are not built up of some of the constituents of the heat ranges represented by those between γ Argûs and α Crucis.

The question arises whether the order of visibility at reduced temperatures now indicated does not explain the absence of proto-hydrogen, oxygen, and nitrogen from the spectra of the sun and nebulæ, the metals present in, and the absence of quartz from, meteorites, and the similarity of the gaseous products obtained from them and metals, native and other, *in vacuo* at high temperatures.

I have finally to express my obligations to those who have aided me in the present inquiry. For some of the metals used I am indebted to Mr. George Matthey, F.R.S., who has kindly placed the resources of his establishment so entirely at my disposal that I feel it is impossible to thank him sufficiently. For the determination of wave-lengths and the correspondence of terrestrial and stellar lines, Mr. Baxandall is responsible, while Mr. Fowler has assisted in the determination of the various stellar groups. The photographs of the enhanced lines obtained by the use of the Spottiswoode coil have been taken by Mr. Butler. The actual construction of the map from the available photographs has devolved upon Mr. Baxandall, Dr. Lockyer co-operating in the case of stars of the highest temperature.