REVISED VALUES OF O I TERMS, NEBULAR AND CORONAL LINES OF OXYGEN

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ABSTRACT

The chief triplet of oxygen λ1302 has been measured in the third order of a vacuum grating spectrum having a dispersion of 1.7A per mm.

On the basis of these measurements, the ground triplet term of oxygen $2s^22p^4\,{}^3P_2$, ${}^3P_1$, ${}^3P_0$ has the revised values 109837.1, 109679.17, 109610 .52 giving the *ionization potential of oxygen* as 13.550 volts.

Nebulium lines have been produced in the laboratory for the first time. The two lines λ6300 and λ6364 have been remeasured, and their values, together with the new values of the ${}^3P_{012}$ term, are used to give more accurate values of the metastable levels of oxygen.

The coronal line λ6374.2 is pointed out as being identical within limits of experimental error with the oxygen line λ6374.29. This would indicate the presence of oxygen in the solar corona.

INTRODUCTION

RUNGE and Paschen[1] made the first classification of the spectrum of oxygen. On the basis of their analysis we have known of two types of multiplicity in the terms of this spectrum, namely, those now known as quintet multiplicity and triplet multiplicity. The next extension of our knowledge of this spectrum was the discovery of the ultraviolet triplet series by the author.[2] These series arise from the combinations of a new triplet ground term $2s^22p^4$, ${}^3P_{012}$ with some of the triplet and quintet terms already known.

At about this time the development of Hund's theory of complex spectra made it manifest that the electron configuration $(2s^22p^4)$ of the normal oxygen atom gives rise not only to the $2s^22p^4\,{}^3P_{012}$ term already found, but also to the $2s^22p^4\,{}^1D_2$, $2s^22p^4\,{}^1S_0$ terms as well. These latter terms became as important as the ${}^3P_{012}$ ground term, since they arise from the same electronic configuration.

The first important discovery in the search for these terms was that due to McLennan[3] and his co-workers, who first reproduced the green auroral line λ5577 in the laboratory and showed that it was due to oxygen. This was confirmed in a quite different manner by the author[4] who found that its wave number was exactly the frequency difference of two strong oxygen lines λ1217 and λ999 which were unclassified at that time.

[1] Runge and Paschen, Ann. d. Physik **61**, 641 (1897); Astrophys. J. **8**, 70 (1898).

[2] J. J. Hopfield, Astrophys. J. **59**, 114 (1924).

[3] J. C. McLennan, J. H. McLeod, and McQuarrie, Proc. Roy. Soc. **A114**, 1 (1927); McLennan, McLeod and R. Ruedy Phil. Mag. **6**, 558 (1928). L. A. Sommer Zeits. f. Physik **51**, 451 (1928).

[4] J. J. Hopfield, Phys. Rev. **29**, 923 (1927).

Bowen's[5] discovery that the prominent nebular lines represent transitions between metastable terms of atoms or their ions suggested at once that the auroral line λ5577 might arise in such a transition in neutral oxygen. This was actually found to be the case by McLennan, Sommer[3] and others by the magnetic splitting of the line showing it to belong to the singlet system, and presumably to the transition $2s^22p^4\ {}^1D_2 - 2s^22p^4\ {}^1S_0$. The discovery that the two ultraviolet lines λ1217 and λ999[4] involve a new and common term added another to the list of singlet terms. Too few of these terms were as yet known to form a Rydberg series, and no combinations of them with the known oxygen terms had been found.

Frerichs[6] made a most important contribution to our knowledge of these terms when he found a sufficient number of them to form such a series and thus evaluated the limit of the series the $2s^22p^4\ {}^1D_2$ metastable term. This fixed the position of the singlet terms with reference to the known scheme of oxygen terms.

His evaluation of the $2s^22p^4\ {}^1D_2$ term, however, contains two sources of error, first the rather large error in the measurement of ultraviolet lines, and second, the error of fitting these lines into a none too accurate formula when relatively few lines of the series are known. The experimental errors cannot be obviated but they can be reduced by using more precise instruments. The second error, although it may be large, is an additive one and is of no consequence when one is dealing with lines of the same system. It becomes a serious difficulty when one is dealing with lines forming intersystem combinations when these systems of terms have been independently determined. If, however, such combinations are once identified and measured, this source of error immediately drops out and there is left only the experimental values to be improved. Happily, Paschen[7] has now found such combinations in new lines on plates which I took of the oxygen spectrum while working in his laboratory and Sommer[8] has also found them in the spectrum of the aurora. I have now remeasured these lines, fixing the terms more accurately, and I have also redetermined the value of the $2s^22p^4\ {}^3P_{012}$ ground term from new data. These improved values conjointly give a correction of 7.5 cm^{-1} to be added to all the singlet terms. It should be borne in mind that all the singlet terms are not fixed with the same accuracy by this correction. Fortunately, the $2s^22p^4\ {}^1D_2$ term is accurately fixed by these corrections, and also the $2s^22p^4\ {}^1S_0$ term which is linked to the former by the aurora line. Although the same correction has been added to the remaining singlet terms, they still contain the relatively large error of the original ultraviolet measurements. The remaining terms of the table given by Frerichs are already linked to the Paschen-Runge terms of oxygen and need no correction.

[5] I. S. Bowen, Ast. Soc. of the Pacific Pub. **39**, 295 (1927).

[6] R. Frerichs, Phys. Rev. **36**, 398 (1930); Phys. Rev. **34**, 1239 (1929).

[7] F. Paschen, Die Naturwissenschaften, **34**, 752 (1930).

[8] L. A. Sommer, Die Naturwissenschaften **34**, 752 (1930).

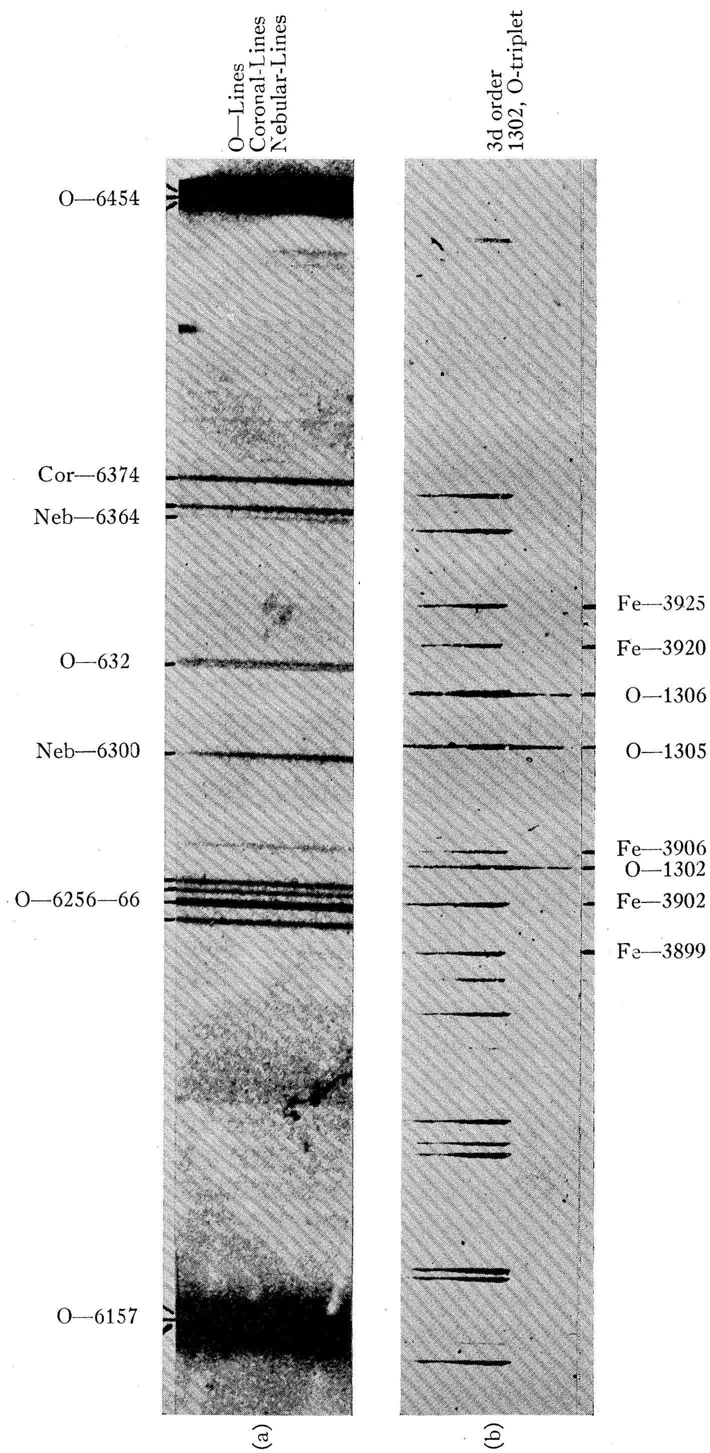

Fig. 1. Oxygen line spectra. (a) Nebular lines and coronal line. (b) Ultraviolet triplet in the third order of spectrum.

Experimental

(a) **Measurements of the λ1302 triplet of oxygen.** The λ1302 triplet of oxygen was photographed in the third order of a 3-meter vacuum grating spectrograph with iron lines of the first order as standards. The spectrograph was designed by the author and built in this laboratory. The dispersion in the third order is 1.7A per mm. Fig. 1b shows these spectra. It is noticed from the figure that the oxygen lines are longer than the iron lines used for comparison. This, of course was due to an adjustable shutter before the plate that limited the comparison spectrum. It was rather fortunate for this purpose that such a shutter had been provided, because two of the lines λλ1305–6 are blended with weak iron lines. λ1302 is quite free from iron lines. The unblended line λ1302 was measured with the iron lines as standards, and a considerable number of iron lines were measured in each direction in order to calibrate the plate. The measurements were obtained from two plates, the one mentioned above and another in which the shutter was not used with the comparison spectrum. The other two lines, λλ1305–6, were measured at the portions showing below the iron spectrum. In this case the plate had not been disturbed from its previous setting in the comparator. λ1302 was used as the reference line and the correction curve already determined for this plate from the iron spectrum was applied.

Since the light from the iron arc was shined through the discharge tube that generated the oxygen spectrum, it is quite certain that the same portion of the grating was illuminated in both cases. Whether the reflecting power of the grating for the regions λ1300 and λ3900 which are here superimposed remained relatively constant for both spectra was of course not determined and would remain as a source of error if the spectra were not exactly focussed. The focus was very sharp, however. The wave-length of these lines, as well as those of the comparison spectrum are given in Table I.

Table I. *Ground triplet term of O I*

λ (vac)	ν (cm^{-1})	Classification	Δν
1302.185	76794.00	$2s^22p^4\ {}^3P_2-2s^22p^3s\,{}^3S_1$	
			158.13
1304.872	76635.87	$2s^22p^4\ {}^3P_1-2s^22p^3s\,{}^3S_1$	
			68.65
1306.042	76567.22	$2s^22p^4\ {}^3P_0-2s^22p^3s\,{}^3S_1$	

Improved values of ${}^3P_{012}$ ground term.

$2s^22p^4\ {}^3P_2$	109837.3
${}^3P_1$	109679.17
${}^3P_0$	109610.52

Ionization potential of O I, 13.550 volts.

Lines used as standards.

λ (I.A.)	λ (I.A.)
3897.898	3906.484
3899.713	3920.266
3902.950	3924.916

(b) **Nebular lines λλ6300, 6364, coronal line λ6374.** Since the two oxygen lines λ6300 and λ6364 are the only "nebulium" lines yet produced in the laboratory, it seems worth while to relate under what laboratory conditions they appeared. The discharge tube was made of quartz. It was Π-shaped, had an internal diameter of about 8 mm and a total length of about 80 cm. It contained large nickel electrodes in the two legs. The horizontal part of the tube faced the slit of the spectrograph end-on. The whole tube was immersed in a bath of running water for cooling. Pure oxygen was obtained electrolytically. It was dried by passing it over phosphorus pentoxide. The gas was allowed to flow through the discharge tube continuously, being admitted by a torsion capillary valve of glass and pumped out by oil and mercury vapor pumps. The pressure in the discharge tube was not measured but it was estimated to be between 1 and 2 cm. A 5000 volt 5 kilowatt transformer was used without auxiliary inductance or capacity, and the current employed was between 1 and 1.2 amperes being regulated by a flowing water rheostat in series with the discharge tube. After the discharge tube was well cleaned by long running, the spectrum, a part of which is shown in Figure 1a, was photographed. The spectrograph used for making the picture was a Zeiss 3-prism instrument giving a dispersion of 29A per mm at λ6300. Neighboring oxygen lines were used as standards, and the Hartmann interpolation formula with a correction curve was used in measuring the plate. Visual observation of the appearance of the discharge might be of interest. When the tube was viewed end-on through the plane quartz window the discharge formed a red core down the axis of the tube, and this core became gradually more diffuse off the axis. When viewed with the spectroscope the green aurora line was very prominent, being about as strong as the neighboring green triplets. Besides the oxygen lines the only visible lines were Hα. Long exposure photographs also showed traces of the Angstrom CO bands.

The plate used was a panchromatic plate sensitized for infrared as well. The duration of exposure was twelve hours, although two hours' exposure was sufficient to give the "nebulium" oxygen lines.

Table II gives the wave-lengths of the nebular lines and the previously unidentified coronal line λ6374.

TABLE II. *Nebular lines and coronal line of oxygen.*

	λ	I	ν	Classification	$\Delta\nu$
Nebular	6300.23	4	15868.05	$(^4S)2s^22p^4\,{}^3P_2-(^2D)2s^22p^4\,{}^1D_2$	158.70
Nebular	6363.88	1	15709.35	$(^4S)2s^22p^4\,{}^3P_1-(^2D)2s^22p^4\,{}^1D_2$	
Coronal	*6374.292	6	15683.64	Unknown	

Metastable ground terms.

Term	Term values (revised)	Distance from ground level $^3P_2$
$(^2D)2s^22p^4\,{}^1D_2$	93969.5 cm^{-1}	1.957 volts
$(^2P)2s^22p^4\,{}^1S_0$	76044.5	4.168 volts

Oxygen lines used as standards.

λ (I.A.)	
6256.616	6323.283
6264.346	6324.682
6266.692	6366.282

* This value is that obtained from Frerichs' table (loc. cit). The value which I obtain is λ6374.24, and is less accurate than his.

Table III is a list of revised values of the terms of oxygen. The table is copied from Frerichs' work. The corrected terms are indicated by asterisks.

TABLE III.—*O I Terms (corrected).*

	$2p$	*$^3P_2$: 109837.3 *$^3P_1$: 109679.17 *$^3P_0$ 109610.52	*$^1D_2$: 93969.5	*$^1S_0$: 76044.5	
		$2s^22p^3$: ^4S	$2s^22p^3$: ^2D	$2s^22p^3$: ^2P	$2s2p^4$
	$3s$	$^5S_2$: 36069.0 $^3S_1$: 33043.3	$^3D_3$: 8702.9 $^3D_2$: 8690.9 $^3D_1$: 8683.0 *$^1D_2$: 7168.5	$^3P_2$: −4072.1 $^3P_1$: −4082.5 $^3P_0$: −4088.8 *$^1P_1$: −6083.5	
	$3p$	$^5P_1$: 23211.9 $^5P_2$: 23209.2 $^5P_3$: 23205.8 $^3P_0$: 21207.7 $^3P_1$: 21207.7 $^3P_2$: 21207.2	$^3F_4$: −3876.1 $^3F_3$: −3883.0 $^3F_2$: −3888.7 $^3D_{123}$ $^3P_2$: −3456.4 $^3P_1$: −3459.8 $^1F_3$ $^1D_2$ $^1D_1$	$^3D_3$: −17443.8 $^3D_2$: −17449.5 $^3D_1$: −17452.9 $^3P_{012}$ $^3S_1$ $^1D_2$ $^1P_1$ $^1S_0$	
$2s^22p^3$	$3d$	$^5D_{01234}$: 12417.3 $^3D_{123}$: 12350.0	$^3G_{345}$ $^3F_{234}$ $^3D_{123}$ $^3P_{012}$ $^3S_1$ $^1G_4$ *$^1F_3$: −14487.5 $^1D_2$ $^1P_1$ $^1S_0$	$^3F_{234}$ $^3D_{123}$ $^3P_{012}$ $^1F_3$ $^1D_2$ $^1D_1$	
	$4s$	$^5S_2$: 14358.5 $^3D_1$: 13612.5	$^3D_{123}$ *$^1D_2$: −12964.5	$^3P_{012}$ $^1P_1$	
	$4p$	$^5P_1$: 10742.5 $^5P_2$: 10743.7 §$^5P_3$: 10744.3 $^3P_{012}$ 10157.5	$^3F_{234}$ $^3D_3$: −15936.6 $^3D_2$: −15944.0 $^3D_1$: −15949.0 $^3P_{012}$ $^1F_3$ $^1D_2$ $^1P_1$	$^3D_{123}$ $^3P_{012}$ $^3S_1$ $^1D_2$ $^1P_1$ $^1S_0$	
	$5s$	$^5S_2$: 7720.8 $^3S_1$: 7425.6	$^3D_{123}$ *$^1D_2$: −19295.5	$^3P_{012}$ $^1P_1$	
	$6s$	$^5S_2$: 4817.9 $^3S_1$: 4672.8	$^3D_{123}$ *$^1D_2$: −22088.5	$^3P_{012}$ $^1P_1$	
	$7s$	$^5S_2$: 3291.9 $^3S_1$: 3210.2	$^3D_{123}$ *$^1D_2$: −23574.5	$^3P_{012}$ $^1P_1$	
$2sp^4$	$2p$				$^3P_2$: −13458.0 $^3P_1$: −13516.9 $^3P_0$: −13548.9

* Altered values of terms: § numerical error corrected.

Tables I and II give excellent agreement of the spacing $2s^22p^4\ ^3P_2-2s^22p^4\ ^3P_1$ ground terms. This confirms also the identification of the lines λ6300 and λ6364 with even greater precision than that given by Paschen. The accuracy of the measurement of these two nebular lines as produced in oxygen together with the more accurate evaluation of the $2s^22p^4\ ^3P_{012}$ ground term justifies the revision of the term values given in Table III.

It is rather remarkable that these nebular lines can be produced in the laboratory when the conditions for their production are extremely low pressures according to Bowen. The pressures in the nebulae are undoubtedly very small, but the pressure in the discharge tube was, as already mentioned, relatively high.

The wave-length of the red coronal line λ6374.2, as given by Campbell and Moore,[9] seems to be identical with the unclassified oxygen line λ6374.29 which is shown as a strong line on the plate, Figure 1a. This line is not entirely new, as Kayser records it in his "Tabelle der Hauptlinien—" as λ6373 and due to oxygen. Frerichs has it in his list of unclassified lines as λ6374.292 This coincidence in the wave-lengths of the oxygen and the coronal line and also the fact that the line occurs in an isolated position in the oxygen spectrum when only lines of O I were present would seem to indicate their identity, and is strong evidence of the presence of oxygen in the sun's corona. Really to prove the identity of these two lines a more accurate determination of the line in the corona is necessary.

Since this line is one of the brightest in the coronal spectrum, being second only to λ5303 of the corona, the terms in oxygen which give rise to it become of great interest. The most promising lead in their identification would be a study of the Zeeman pattern of this line. This, so far as I know, has not yet been made.

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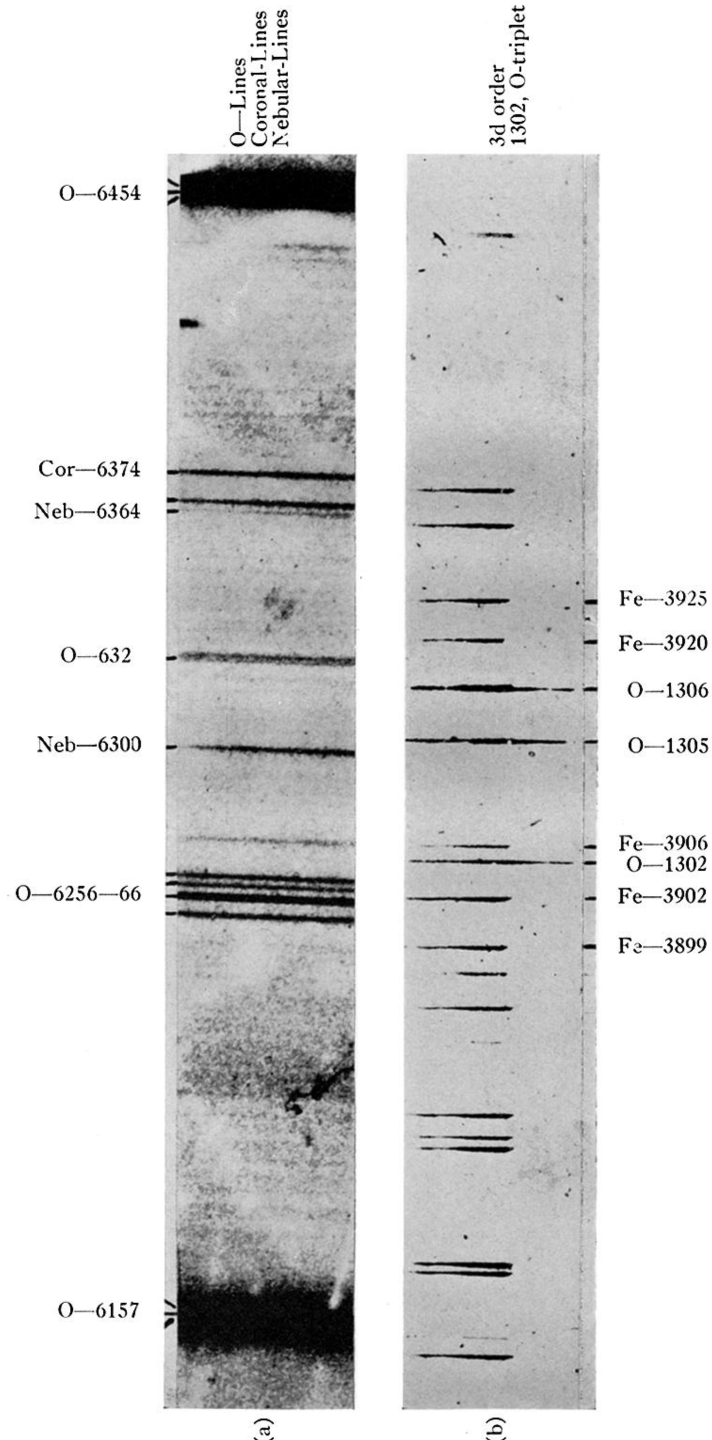
[9] Campbell and Moore, Publications of the Lick Observatory Bulletin **318**, 8 (1918).



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