The Refractive Index of Air in the Visible and Photographic Infra-Red

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The refractive index of dry CO_2 free air has been measured from 5300A to 11177A by means of a Fabry-Perot interferometer with invar separating posts. The following dispersion curve was obtained for standard conditions (λ in microns):

$$(n_0-1)10^7=2885.59+15.77/\lambda^2+0.421/\lambda^4.$$

A comparison of the present results with those of other observers shows that this curve is higher by about 10 parts in 10^7, and that all curves are nearly parallel. This suggests that the discrepancies are due to systematic errors providing, as seems to be the case, that the constitution of air remains sufficiently constant. In the present experiments systematic errors due to phase change at reflection, methods of purification of the air, and bulk modulus of the invar posts were considered. A calculation concerning the oxygen absorption band at 7600A indicates that this band has no measurable effect on the dispersion of air.

FOR many purposes, in particular in astrophysical work, it is important to know the index of refraction of air to the limit of the photographic infra-red. In addition there exist discrepancies of the order of 10 to 15 parts in 10^7 among the results of various observers in the visible region. Such discrepancies might be attributed to variations in the composition of the air, but experiments carried out since 1850 indicate that the percentage of oxygen in normal, (0°C and 760 mm pressure) dry, CO_2 free air does not vary more than ± 0.2 percent.[1] This much change in the relative amount of oxygen and nitrogen would cause a change in the index of refraction of approximately 0.5 parts in 10^7, which is far too small to account for the discrepancies. For both of these reasons a precision study of this quantity seems justified.

In previous experiments the index of refraction has been measured out to approximately 9000A. The present experiments have pushed that limit more than 2000A farther into the red and show that, despite the inaccuracies accompanying measurements in these longer wave-length regions, the dispersion of air behaves normally. Because of this fact and the fact that the varying terms in the dispersion formula decrease toward the red, the curves of other observers can be extrapolated in this direction as much as two thousand angstroms with little loss in accuracy. In fact the consistency of this extrapolation as compared to observations throughout the regions considered, might well be a criterion for judging the validity of a given dispersion formula.

The method of obtaining the index of refraction used in the present experiment was to observe the change in the order of interference for each wave-length on a Fabry-Perot interferometer when it was placed in a vacuum and when it was placed in dry CO_2 free air. The temperature of the brass vacuum chamber was held constant by thermostat controls which kept the temperature of the air just outside the chamber within a range of ± 0.05°C. This temperature (taken as the temperature of the air in the vacuum chamber) was measured on a thermometer graduated in tenths of degrees and carefully checked against a similar one calibrated by the National Bureau of Standards. The pressure of the air was measured on a large closed tube manometer by means of a cathetometer, the glass scale of which had been previously calibrated by Campbell.[2]

The lines used were neon lines with only one exception, the mercury line at 10140A. For the lines out to 8800A the tube was operated under conditions which conformed to the requirements set by Jackson[3] for obtaining the neon secondary standards of wave-length. For lines farther out the current in the tube was increased from 25 milliamperes to 52 milliamperes in order to shorten the exposure. The lines out to 10000A could be obtained nearly as sharp as the shorter wave-lengths, but beyond that point the ex-

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[1] M. S. Blanchard and S. F. Pickering, Nat. Bur. Stand. Sci. Papers **21**, 167 (1926).
[2] Campbell and Houston, Phys. Rev. **39**, 601 (1932).
[3] C. V. Jackson, Proc. Roy Soc. **A143**, 124 (1933).

posures were so long (as much as twelve hours in some cases) and the lines so faint and broad that in this region the accuracy of the results is poor. The mercury line is inherently broader than most of the neon lines but it turned out that the neon lines at 11000A were of comparable broadness.

In order to obtain dry CO_2 free air several procedures were tried. Many of the runs were treated as follows: after first drying the air over calcium chloride and phosphorus pentoxide, it was passed through coils immersed in liquid air. This method will definitely remove the carbon dioxide and the water vapor, but it was thought that cooling the air might also remove a fraction of the oxygen. To investigate this, results were obtained when the carbon dioxide was removed by bubbling the air through a six normal solution of potassium hydroxide before it was dried over calcium chloride and phosphorus pentoxide. The results of the two methods were indistinguishable from one another. The final arrangement adopted was a combination of these two. After passing through the potassium hydroxide solution and over the calcium chloride and magnesium perchlorate, the air was passed through the cooled coils shielded with cylindrical copper jacket from direct contact with the liquid air. Never was there a trace of frozen dioxide or of frost that could be seen in the coil when the liquid air and the shield were quickly removed.

Each run consisted of at least three exposures alternately with vacuum and with air. In order to assure temperature equilibrium, the air was let in slowly and the exposure started after 30 to 50 minutes had elapsed. The vacuum was assured by pumping until the system would no longer take a discharge from the transformer used to excite the source.

Despite precautions to keep the temperature constant and to reduce vibration, the orders of interference on the two vacuum exposures failed to agree satisfactorily in almost 80 percent of the runs. These changes were random in direction and merely indicated that a selection of plates was necessary to reduce the accidental errors. A criterion for this selection was immediately available in the reproducibility of the orders of interference of the first and the last exposures. Only those plates on which the zero readings repeated to within 0.0030 fringes on the average were measured (except for wave-lengths beyond 10000A where the tolerance was increased to 0.015 fringes). A variation of 0.0030 fringes corresponds on the average to about one part in 10^7 in the index of refraction.

To find the fractional order of interference at the center of the plate a method of least squares was used on eight consecutive fringes. The method is essentially that developed by Rolt and Barrell.[4] With the observed fractional orders of interference the integral orders of interference were calculated in the usual manner and the index of refraction obtained as the ratio of the complete order of interference in air to the complete order in the vacuum.

The values of the index were obtained at some pressure between 700 mm and 740 mm of mercury and at some temperature between 25° and 31°C. To change the observed values of the index to standard conditions the formula $(n-1)/d = \text{constant}$ (d = density of air) was used. The ratio of the densities at the two conditions was assumed to be that of a perfect gas. Both Meggers and Peters[5] and Perard[6] have given values for the temperature coefficient of the index. Meggers and Peters find that it is slightly larger than the reciprocal of the absolute zero and that it decreases with increasing wave-length. Perard, on the other hand, states that the temperature coefficient is independent of wave-length and gives a value higher than that of the Bureau. At 7000A the error introduced by using the perfect gas coefficient over a temperature range of 30°C is according to the value of Meggers and Peters 0.9 part in 10^7, while according to the

TABLE I. *Distribution of weighting used in different wave-length regions.*

Region	Weighting
5300– 6500A	6.50
6500– 7600A	13.68
7600– 9000A	11.85
9000–10000A	2.61
10000–12000A	0.40
Total	35.04

[4] Rolt and Barrell, Proc. Roy. Soc. of London **122**, 122 (1929).

[5] Meggers and Peters, Nat. Bur. Stand. Bull. **14**, 697 (1918).

[6] Perard, J. de phys. et rad. **6**, 217 (1924).

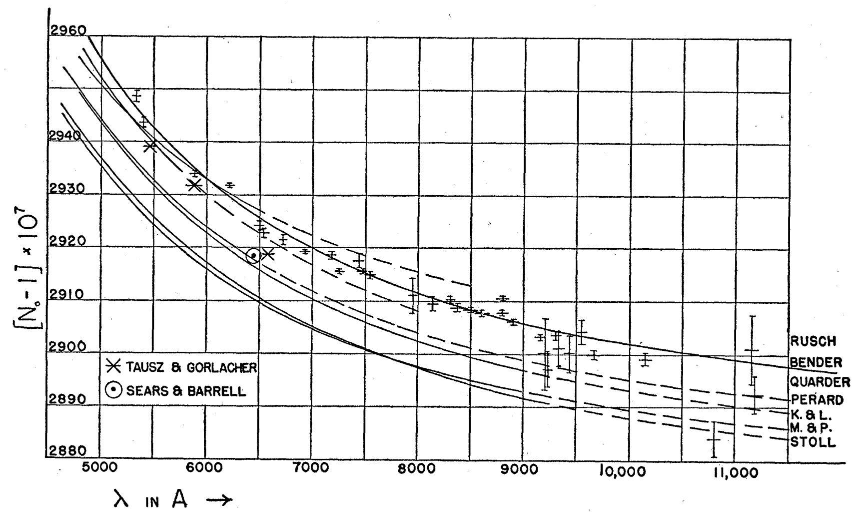

FIG. 1. Dispersion curves for normal air. The curves plotted are those obtained since 1918, except that the curve of Traub was omitted because of its proximity to that of Perard. The lengths of the lines give the estimated probable errors of the points used in the calculation of the author's curve.

value of Perard, it is 4.0 parts in 10^7. In view of these conflicting reports it seemed advisable simply to use the perfect gas coefficient.

In the estimation of probable error for each observation the following factors were taken into account: the error introduced because the zero readings did not repeat exactly, the error of measurement of the order of interference (of the same magnitude as the first) and the error due to the uncertainty in the pressure and temperature (always the smallest). At each wave-length used an average value was obtained from the observed values and weights calculated from the above errors. In order to calculate the weight of these averages (or probable errors as shown on the dispersion curves) several factors were considered. The total of the previous weights as well as the number of observations and the agreement among them entered into calculations. The final distribution of weighting among the wave-length regions used is given in Table I.

In order to make sure that the change of phase at reflection was a negligible factor, two separators were used in the interferometer: one of 14 mm, and one of 21 mm. No systematic difference in results was apparent between these two sets of measurements.

The posts in the separators were made of invar steel, which has a bulk modulus of about 12×10^{11} dynes/(sq. cm). This means that a pressure change of one atmosphere will cause a change in length of 2.8 parts in 10^7. Since the posts were free to expand against small springs, the value of the index will be in error by just this amount and must be increased. This correction was made.

The usual Cauchy dispersion formula was used to describe the results at standard conditions. (0°C and 760 mm of mercury.)

$$(n_0-1)\cdot 10^7 = A+(B/\lambda^2)+(C/\lambda^4).$$

The method of least squares applied to the observed averages at each wave-length and their probable errors gave for standard conditions (with λ in microns):

$$(n_0-1)\cdot 10^7 = 2885.59+15.77/\lambda^2+0.421/\lambda^4 + [\pm 2.16 \pm 2.19/\lambda^2 \pm 0.52/\lambda^4].^7$$

The dispersion curves show the observed values and the differences from calculated values. The lengths of the lines show the probable errors as obtained from the averaging of the separate measurements at each wave-length. In Table II there are compiled the constants in the dispersion formulae for the observers of the index of refraction of air, since 1918, several values calculated

[7] Obtained with the aid of equations, Whittaker and Robinson, *The Calculus of Observations*, second edition, p. 241.

from these constants, and the range over which measurements were taken. No extrapolations of greater than 2000 angstroms were made except in the case of Perard's curve. Not all data deal with CO_2 free air, but deal with dry air. The error introduced by the CO_2 in the air is quite negligible compared to the differences between observers. The values obtained by the various observers for n_0-1 are plotted in Fig. 1.

Since there exists at about 7600A, a strong oxygen absorption band, it becomes necessary to see theoretically whether or not this band and others near by could effect the dispersion enough to be measured. This band has been analyzed by Badger and Mecke,[8] who find it to extend over a range of nearly 70A and to have about forty lines. The f value for the band as a whole has been given by Childs and Mecke[9] as 0.4×10^{-9}. That is, there are Nf dispersing electrons per cu. cm where N is the number of molecules per cu. cm. From this we obtain the value of $(n-1)$ for these electrons at a point 50A away from the band center to be 0.42×10^{-10}. Since the band is broad and since it is composed of many lines, it is at once apparent that the effect of this band and any other fainter bands on the dispersion of air is negligible, as the results show.

It is apparent that the dispersion curves run in general parallel to one another. Consequently the present experiments, which cover a range of nearly 6000A, show, in comparison with other curves, that the dispersion of air can be adequately expressed throughout the whole visible and photographic infra-red by the Cauchy formula.

In order to explain the difference between observers of the index of refraction of air we must look for systematic errors. The most obvious possibility is that the composition of the air is not sufficiently constant from place to place and from time to time. As was mentioned above, experiments on the constitution of air seem to indicate that this deviation is not sufficient to cause the large differences that exist between observers. Perhaps insufficient care in the methods of sampling and purifying the air can explain the discrepancies. Simultaneous experiments measuring both the constitution and the index of refraction have not been carried out.

All experiments which measure the index of refraction of air use an air path which must not change in length when the path is evacuated. This ideal condition cannot actually be realized since all substances have definite bulk moduli, but in some experiments, especially those in which the Jamin type interferometer is used, this condition is less important than in others. It should not be inferred from this, however, that the Jamin type is much better, for the windows which are distorted by the change in pressure are in the interference path. For such experiments no correction needs be made, but for those which use a Fabry-Perot interferometer, it is necessary. Many observers, notably Meggers and Peters, have not made this correction, although it is not

TABLE II. *Dispersion formulae and values of the index.*

OBSERVER	REF.	A	B	C	5000A	7000A	9000A	11000A	RANGE A.
Meggers and Peters (1918)	5	2875.66	13.412	0.378	2935.3	2904.6	2892.8	2887.0	2220–9000
Traub (1922)	10	2876.13*	16.397	0.127	2943.8	2910.1			1850–5460
Stoll (1922)	11	2871.87	16.170		2936.6	2904.9	2891.8	2885.2	4390–9220
Quarder (1924)	12	2879.87	18.04		2952.0	2916.7			2620–5780
Perard (1925)	6	2880.2	14.748	0.316	2944.2	2911.6	2898.9		4360–6440
Rusch (1927)	13	2893.19*	14.05	0.068	2950.5	2922.1			5460–6560 and 67,630
Tausz and Gorlacher (1931)	14	Only four measurements			2951.4	2915.0	(estimated)		
Sears and Barrell (1934)	15	Only one measurement (2918.4 at 6438A) = (2911.7 at 7000A)							
Kosters and Lampe (1934)	16	2877.10	15.84	0.194	2943.6	2910.2	2897.0	2890.3	2000–9000
Bender (1938)		2885.59	15.77	0.421	2955.4	2919.5	2905.7	2898.9	5300–11,780

* Formula not given in Cauchy form by author but changed to Cauchy form for better comparison in this table.

[8] Badger and Mecke, Zeits. f. Physik **60**, 59 (1930).
[9] Childs and Mecke, Zeits. f. Physik **68**, 344 (1931).
[10] Traub, Ann. d. Physik **61**, 533 (1920).
[11] Stoll, Ann. d. Physik **69**, 81 (1922).
[12] Quarder, Ann. d. Physik **74**, 255 (1924).
[13] Rusch, Ann. d. Physik **85**, 581 (1927).
[14] Tausz and Gorlacher, Zeits. f. tech. Physik **12**, 19 (1931).
[15] Sears and Barrell, Phil. Trans. Roy. Soc. **233**, 143 (1934).
[16] Kosters and Lampe, Physik. Zeits. **35**, 223 (1934).

nearly as large as the differences to be accounted for.

It is interesting to note that Tilton[17] claims some success in finding a correlation between the values for the index of refraction of air and the sunspot cycle.

It seems clear that no adequate explanation can be given of the various discrepancies, but that one can only attempt to eliminate systematic errors by careful attention to every detail.

In conclusion I wish to acknowledge the assistance and helpful guidance of Professor W. V. Houston and the many valuable suggestions of Professor I. S. Bowen in carrying out this research.

[17] Tilton, Nat. Bur. Stand. J. Research **13**, 11 (1934).

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The Spectrum of Neutral Iridium, Ir I

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A new description of the arc spectrum of iridium has been made. The present data include 3100 wave-lengths of which 1937 have been accounted for as combinations between 214 energy levels. The normal electron configuration of the Ir I is $5d^76s^2$ and the I.P. is approximately 9.2 volts. Tables of the most intense lines and of all of the energy levels are presented.

THE existing wave-length data for the arc spectrum of iridium have been improved and extended. Exposures from a 110-volt 2-ampere arc between rods of extremely pure iridium were taken in the first and second orders of the 35 foot, 30,000 line per inch grating at M.I.T., dispersion 0.4A/mm in the second order. Superimposed spectra from a standard iron arc permitted measurement of the iridium spectrum in terms of internationally adopted secondary standards.

New data are recorded from 4627A to 2159A, supplementing the excellent data of Meggers[1] (8426A to 4500A). Intensity estimates are on a scale of 100 to 1. The present list contains more than 3100 wave-lengths which have been assigned to Ir I by comparison with spark spectra. The earlier analysis[2] has been extended on the basis of new data until now 1937 lines are accounted for as combinations between 214 energy levels.

The complete list of classified lines is not published at this time since it is probable that most of the wave-lengths will be published elsewhere at a later date. A list of the most intense lines is presented in Table I. Column 1 gives the wave-length in international angstroms in air; column 2, estimated intensities (r signifies partial reversal); column 3, the term types of the two energy levels that give rise to the line.

All energy levels are presented in Table II. Column 1 gives the symbol which identifies the level; column 2, the term type; column 3, the energy value expressed in wave number units; column 4, the J value.

The electron configuration interactions are so great that the assignment of terms to definite configurations is nearly without meaning. However, the custom of assigning terms to the configuration which seems to play the most impor-

TABLE I. *Most intense iridium arc lines.*

λ I.A.	INT.	COMBINATION	λ I.A.	INT.	COMBINATION
5449.50	80	$z^6G_{6\frac{1}{2}}^0-e^6F_{5\frac{1}{2}}$	3212.121	60	$b^4F_{3\frac{1}{2}}-z^4G_{4\frac{1}{2}}^0$
4399.473	60	$z^6F_{5\frac{1}{2}}^0-e^6F_{5\frac{1}{2}}$	3198.917	60	$b^4F_{3\frac{1}{2}}-z^4D_{2\frac{1}{2}}^0$
4268.096	80	$b^4F_{3\frac{1}{2}}-z^6D_{3\frac{1}{2}}^0$	3068.897	60	$b^4F_{4\frac{1}{2}}-z^6G_{3\frac{1}{2}}^0$
3992.114	80	$b^4F_{2\frac{1}{2}}-z^6F_{2\frac{1}{2}}^0$	2924.783	100r	$a^4F_{4\frac{1}{2}}-z^6G_{5\frac{1}{2}}^0$
3915.384	60	$b^4F_{2\frac{1}{2}}-z^6G_{3\frac{1}{2}}^0$	2916.357	60	$a^4F_{1\frac{1}{2}}-z^4D_{2\frac{1}{2}}^0$
3800.122	60r	$a^4F_{4\frac{1}{2}}-z^6D_{4\frac{1}{2}}^0$	2882.624	60	$b^4F_{4\frac{1}{2}}-z^4D_{3\frac{1}{2}}^0$
3513.638	80r	$a^4F_{4\frac{1}{2}}-z^6F_{5\frac{1}{2}}^0$	2849.724	80r	$a^4F_{4\frac{1}{2}}-z^6G_{4\frac{1}{2}}^0$
3448.967	60	$a^4F_{1\frac{1}{2}}-z^6D_{2\frac{1}{2}}^0$	2836.394	60	$a^4F_{1\frac{1}{2}}-z^4F_{2\frac{1}{2}}^0$
3437.006	60	$a^4F_{3\frac{1}{2}}-z^6G_{3\frac{1}{2}}^0$	2824.444	60r	$b^4F_{4\frac{1}{2}}-z^4G_{4\frac{1}{2}}^0$
3368.472	60	$b^4F_{4\frac{1}{2}}-z^6F_{4\frac{1}{2}}^0$	2664.783	50r	$a^4F_{4\frac{1}{2}}-z^4D_{3\frac{1}{2}}^0$
3266.446	60	$a^4F_{2\frac{1}{2}}-z^6F_{1\frac{1}{2}}^0$	2639.698	60r	$a^4F_{4\frac{1}{2}}-z^4F_{4\frac{1}{2}}^0$
3220.772	100r	$b^4F_{4\frac{1}{2}}-z^6F_{3\frac{1}{2}}^0$			

[1] Meggers, Sci. Papers Nat. Bur. Stand. **20**, 19 (1925).
[2] Albertson, Phys. Rev. **42**, 443 (1932).