HIGH RESOLUTION IN THE INFRARED

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Abstract

An instrument is described which is capable of giving an experimental resolving power of ten thousand in the near infrared region. With this instrument several of the infrared lines of helium I have been examined and their components resolved. The exceedingly faint lines of the neon I spectrum lying between 1μ and 2μ have been discovered and their wave-lengths measured.

THE following paper is the result of the work done during the winter of 1930–31 in an attempt to increase the resolution of infrared spectrometers. The work to be done in the near infrared region now consists almost entirely of the examination of fine structures; a work which is constantly demanding higher resolving powers. With the help of the resonance radiometer[1] and a carefully construrted spectrometer it is believed than an instrument has been developed which partially fulfills the requirements of high resolution and of wavelength accuracy. The resonance radiometer has been used only in those cases where the more easily manipulated direct deflection amplifier has proved not sensitive enough.[2]

Resolving power in the infrared has already been carried as high as ten thousand by Ignatief[3] when he resolved the helium line at 1.0830μ. The method he employed to obtain such high resolution was that of using a Fabry and Perot interferometer arrangement. However, the difficulty of interpreting the results and the minuteness of the spectral range of such an instrument render it unsuitable for most purposes. Therefore the work described here was devoted entirely to the grating spectrometer with the hope of increasing its efficiency to that obtained by Ignatief. This would mean that it would be possible to resolve lines as close together as one frequency unit throughout the near infrared range. The two factors tending to increase the sensitivity of the spectrometer which have been most carefully considered in this paper are the optical perfection of the spectrometer and increased bolometric sensitivity. It is recognized that the matter of suitable sources for infrared use is a most important factor, and although some work has been done along that line nothing very definite has been accomplished.

Pfund and later Barnes[4] have described methods for obtaining very sharp

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[1] J. D. Hardy, Rev. Sci. Inst. **1,** 429–448 (1930).

[2] The instrument referred to here is not the "Moll thermo-relay," but is the Pfund grid amplifier which is used to amplify the deflections of galvanometers. See reference 6.

[3] Ignatief, Ann. d. Physik **43,** 1117–1136 (1914).

[4] R. B. Barnes, Phys. Rev. **36,** 296–304 (1930).

lines by using the mirrors of a spectrometer exactly upon their optic axes. Barnes has discussed the futillity of using very narrow slits, in order to increase the resolving power of an instrument, beyond the point where the defects in the optical images formed by the mirrors become noticeable. The test for this lower value of slit width can be easily made by placing the eye behind the exit slit and observing the illumination of the grating as the slits are narrowed. As soon as it becomes evident that further narrowing of the slits results in rather large unilluminated areas in the grating the narrow limit of useful slit widths has been reached. A further narrowing will not only not increase the available detail in the spectrum but will result in a great loss of energy. Several tests were made by the author on spectrometers whose mirrors were used but ten degrees off their optic axes, and when the slits had been narrowed to 0.1 mm only about sixty percent of the grating was illuminated. It was thus evident that where high resolution is desired more carefully constructed optical systems must be employed. Is is obvious that with more perfect optical systems a saving in energy will be had.

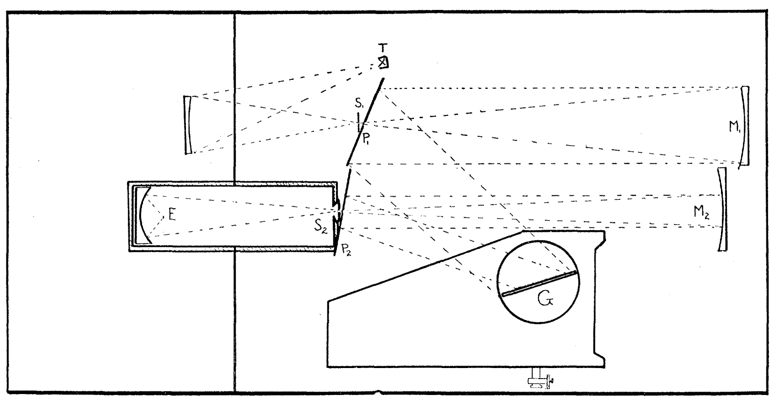

Fig. 1. Diagram of spectrometer.

In accord with this idea a spectrometer was constructed on the plan suggested by Barnes with the difference that the mirrors were of one meter focus and that the last focusing mirror could be replaced by a mirror of four meters focus when high dispersion was desired. A diagram of the spectrometer is shown in Fig. 1. The light from the source T is received by a convex mirror and brought to a focus upon the entrance slit of the spectrometer. (While investigating emission spectra between 1μ and 2μ no fore-prism was used to separate the orders, but an infrared filter was placed in the path when wavelengths longer than 1.2μ were to be examined.) The light on passing through the first slit passes through a hole in the center of the plane mirror P_1. It is then received by the parabolic mirror M_1 and returned directly back to the plane mirror P_1 which reflects the parallel beam onto the grating. The diffracted beam is received by a second plane mirror and sent to the focusing mirror M_2 which focuses the light through a hole in P_2 onto the exit slit. The image thus formed is very sharp and well defined on both sides even when examined under considerable magnification. The light is finally received by a short focus mirror and brought to a focus upon the thermocouple.

The mirrors M_1 and M_2 are parabolic mirrors with their optic axes through the centers; they are eight inches in diameter and of one meter focus. They were tested and found to be acceptable, although no by and means perfect, as were also the plane mirrors. The last mirror M_2 could be removed and a spherical mirror of four meters focus substituted for it. The reason for substituting such a long focus mirror is simply to spread out the spectrum and allow the use of slightly wider slits, because after the width of the slits has been reduced to a certain point the dust lines, slit imperfections, and diffraction become very important. The introduction of this mirror causes a decrease in energy of six fold, due to the increased size of the image formed; the increase in dispersion is four fold. The grating used in this experiment was a five inch Rowland grating with 15,000 lines to the inch, which gives very sharp lines and a good intensity in the first order. The position of the grating was determined by means of a graduated circle provided with a reading microscope, and any position could be determined with an accuracy of one second of arc, which corresponds to 0.2A.

The thermocouple is of Pfund's design and was constructed by the author. It is exceedingly sensitive and was so constructed that its action in a vacuum is rapid enough to permit its being used with the resonance radiometer without appreciable loss of sensitivity. Direct comparisons, under identical conditions, were made between the thermopiles (three junctions) constructed by Firestone[5] and the single junction element in use in the spectrometer. It was found that in vacuum the single junction thermocouple would give more than three times the deflection produced by the three junction thermopile and its action more than twice as rapid. More recent experiments with thermocouples of this type have lead to the conclusion that an additional increase in sensitivity of five fold can be expected when the elements are used at the temperature of liquid air.

The thermocouple, by a switching arrangement, could be connected to either the resonance radiometer or to a Leeds and Northrup galvanometer. The Pfund thermoelectric amplifier[6] served equally well for both instruments. The amplifier, set upon a small table, could be set up in front of the first resonance galvanometer, and with the second thermocouple connected to the second resonance galvanometer the spectrometer was ready to be used with the resonance radiometer. By moving the table with the amplifier over in front of another shelf, upon which were mounted two Leeds and Northrup high sensitivity galvanometers, with one galvanometer connected to the thermocouple in the spectrometer and the other connected to the thermocouple in the amplifier, a very efficient steady-deflection amplifier could be obtained. (This arrangement, which is more rapid in its response, was used for all survey work and was replaced by the resonance radiometer only in those cases where the highest possible sensitivity was needed.) The amplifi-

[5] F. A. Firestone, Rev. Sci. Inst. **1,** 630–649 (1930).

[6] A. H. Pfund, Science **69,** 71 (1929).

cation could be varied both by changing the intensity of the amplifier lamp and by changing the spacing of the grids. Two sets of grids were used with this amplifier; one set, with a spacing of 1 mm, to give amplifications ranging from 2500 to 15,000 was used entirely with the resonance radiometer; the other set, with 2 mm spacing, to give a range from 50 to 2500, was used with both instruments. The advantage of this type of amplifier is obviously the large range of amplifications and its steadiness even while being pushed to the highest amplification possible. When working with the Leeds and Northrup galvanometers an amplification of six hundred was used, and the steadiness was such that readings could be made in the daytime as well as at night. The principal source of unsteadiness was found to be of an electrical nature and

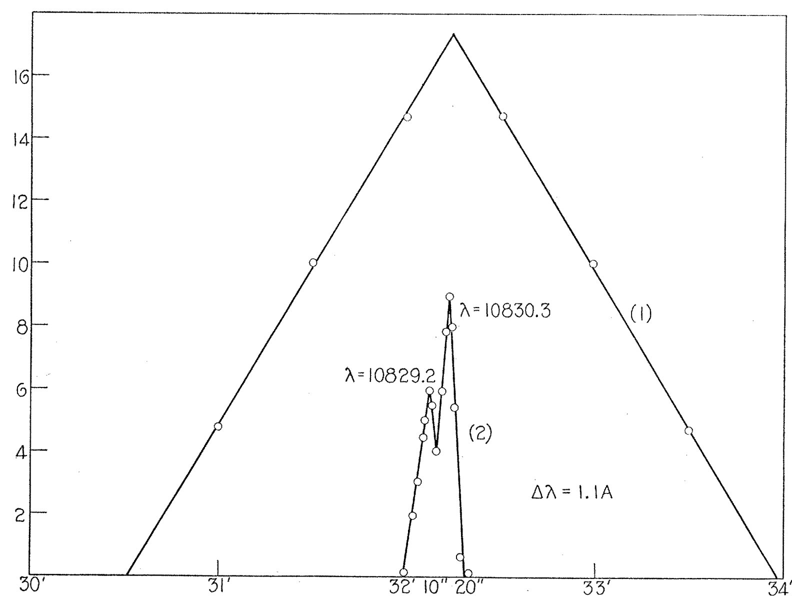

Fig. 2. Helium line at 10,830A. (1) Energy curve with astigmatic spectrometer (unamplified deflections). (2) Energy curve under high dispersion with new type spectrometer (resonance radiometer).

this was reduced, although not eliminated, by carefully shielding every part of the galvanometer circuit. When working with the resonance radiometer an amplification of 6000 was generally used.

After the spectrometer had been set up and focused, tests similar to the ones described above were made to determine the advantage to be gained in line sharpness with narrow slits. It was found that the grating was completely illuminated even with slits so narrow that diffraction prevented further examination. The instrument was calibrated by means of the visual and infrared lines of helium, and the calibration was checked along with the position of the central image at frequent intervals, although they appeared to change very little. The temperature in the basement room in which the spectrometer is located did not vary more than one degree centigrade over long periods of time, and therefore the grating error due to temperature was found to be negligible.

In order to test for the highest resolution that could be realized with the instrument by using ordinarily strong and constant sources, it was decided to examine the 1.0830μ line of helium and see if it were possible to resolve it into its components. The source of radiation was a small glass Geissler tube provided with a capillary 1 mm in diameter. The tube was used 'side on,' and was connected to a neon-sign transformer which was operated from the 110 volt a.c. circuit. The intensity of this source was such that with the spectrometer set on the line and with slits 0.1 mm wide, a deflection of 4 cm was produced by a L and N galvanometer with scale at three meters. The amplifying system was set up and the slits narrowed until no deflection could be detected. However, the helium line could not be resolved. The long focus mirror was then substituted for the parabolic mirror and the slits opened up until the entrance slit was 0.01 mm and the exit slit 0.03 mm. Then with the

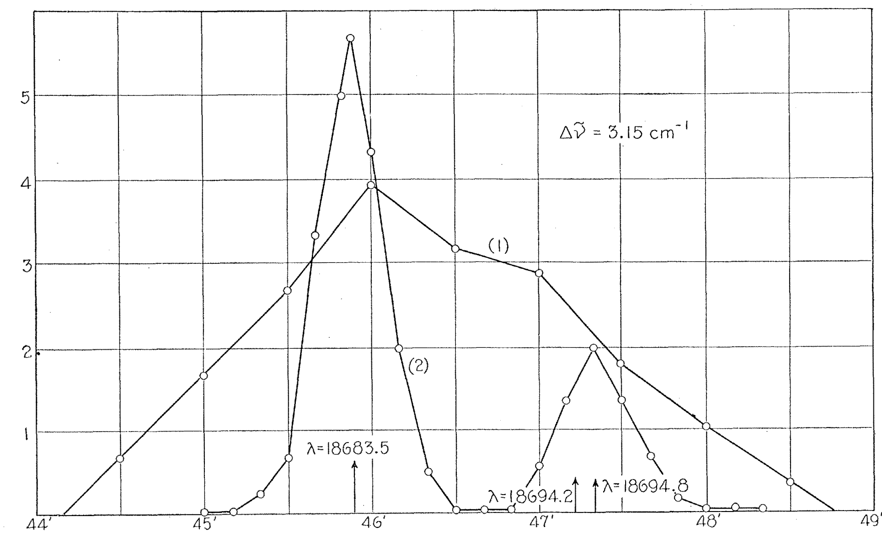

Fig. 3. Helium line at 1.868μ. (1) Curve by Paschen 1908. (λ' position of companion line as deduced by Paschen). (2) Curve with new spectrometer.

help of the resonance radiometer the line could be very nicely resolved. During later experiments a much more powerful source was developed so that it was possible to resolve the line even with the amplified deflections of a L and N galvanometer.

It will be noticed that the "effective slit width" used above is about 0.3A. while the separation between the lines is narly four times that amount. The author has found repeatedly that the "slit-width" must be from a third to a half the amount to be resolved.

Several other lines of the helium spectrum were observed and the line at 1.868μ is shown in Fig. 3, with the line as first observed by Paschen[7] in 1908. This line was observed with wider slits and without the use of the long focus mirror.

The efficiency of the spectrometer was next tested in the matter of energy

[7] F. Paschen, Ann. d. Physik **27**, 537–564 (1908).

conservation. The infrared spectrum of neon, which is very faint, was examined between 1μ and 2μ. The slits of the spectrometer had to be opened to a width of 0.8 mm, with the result that the wave-lengths of the lines could not be determined with as great an accuracy as might be desired. The spectrum of neon had been extended photographically by Gremmer[8] out to a wave-length of 9665.0A, and beginning with this line the region out to 2μ was examined. Most of the lines found gave deflections about one hundredth that produced by the visible yellow line at 5852A.

TABLE I.

Wave-length (vacuum)	Intensity	Frequency		Combination
9667.6	8	10343.8	0.5	$(^2P_{1\frac{1}{2}})3p1_1-(^2P_{1\frac{1}{2}})4s1_2$
10564.3	10	9466.1	0.7	$(^2P_{\frac{1}{2}})3p10_0-(^2P_{\frac{1}{2}})3d12_1$
10624.8	1	9411.8	0.3	$(^2P_{1\frac{1}{2}})3p4_1-(^2P_{\frac{1}{2}})4s4_1$
10800.6	3	9258.7	0.3	$(^2P_{1\frac{1}{2}})3p4_1-(^2P_{\frac{1}{2}})4s3_0$
10849.5	7	9217.5	0.5	$(^2P_{1\frac{1}{2}})3p5_2-(^2P_{\frac{1}{2}})4s4_1$
11142.5	13	8974.9	0.1	$(^2P_{1\frac{1}{2}})3p3_2-(^2P_{1\frac{1}{2}})4s2_1$
11178.8	14	8945.6	0.9	$(^2P_{1\frac{1}{2}})3p2_3-(^2P_{1\frac{1}{2}})4s1_2$
11391.6	4	8778.5	0.7	$(^2P_{1\frac{1}{2}})3p3_2-(^2P_{1\frac{1}{2}})4s1_2$
11410.6	3	8764.0	1.3	$(^2P_{\frac{1}{2}})3p7_1-(^2P_{\frac{1}{2}})4s4_1$
11527.7	25	8674.5	0.1	$(^2P_{1\frac{1}{2}})3p4_1-(^2P_{1\frac{1}{2}})4s2_1$
11540.0	5	8665.5	0.4	$(^2P_{\frac{1}{2}})3p10_0-(^2P_{1\frac{1}{2}})3d6_1$
11616.8	3	8608.0	0.1	$(^2P_{\frac{1}{2}})3p7_1-(^2P_{\frac{1}{2}})4s3_0$
11771.1	4	8495.0	0.3	$(^2P_{\frac{1}{2}})3p9_1-(^2P_{\frac{1}{2}})4s4_1$
11789.4	4	8482.4	0.1	$(^2P_{\frac{1}{2}})3p4_1-(^2P_{1\frac{1}{2}})4s2_1$
11989.5	2	8341.0	0.5	$(^2P_{\frac{1}{2}})3p9_1-(^2P_{\frac{1}{2}})4s3_0$
12069.2	10	8285.7	0.4	$(^2P_{1\frac{1}{2}})3p5_2-(^2P_{1\frac{1}{2}})4s1_2$
12461.0	1	8024.8	0.8	$(^2P_{1\frac{1}{2}})3p7_1-(^2P_{1\frac{1}{2}})4s1_2$
12597.4	1	7938.4	0.2	$(^2P_{\frac{1}{2}})3p8_2-(^2P_{1\frac{1}{2}})4s2_1$
12692.7	2	7878.4	0.6	$(^2P_{1\frac{1}{2}})3p6_0-(^2P_{1\frac{1}{2}})4s2_1$
12770.0	0.3	7830.8	1.8	$(^2P_{\frac{1}{2}})3p7_1-(^2P_{1\frac{1}{2}})4s1_2$
12915.0	2	7742.8	0.1	$(^2P_{\frac{1}{2}})3p8_2-(^2P_{1\frac{1}{2}})4s1_2$
13222.0	1	7563.1	0.2	$(^2P_{\frac{1}{2}})3p9_1-(^2P_{1\frac{1}{2}})4s1_2$
15237.0	2	6562.9	0.1	$(^2P_{\frac{1}{2}})3p10_0-(^2P_{\frac{1}{2}})4s4_1$
17168.0	1	5824.8	0.2	$(^2P_{\frac{1}{2}})3p10_0-(^2P_{1\frac{1}{2}})4s2_1$
18081.0	1	5530.7	2.2	$X-(^2P_{1\frac{1}{2}})3d2_1$
18274.0	3	5472.3	5.0?	$Y-(^2P_{1\frac{1}{2}})3d4_3$
18309.0	1	5462.0	0.2	$X-(^2P_{1\frac{1}{2}})3d3_4$
18389.0	2	5438.0	5.0?	$Y-(^2P_{1\frac{1}{2}})3d6_1$?
18433	1	5425		
18552	1	5390		

In Table 1 are given the wave-lengths, the intensities, and the probable classification of these lines. The intensities given are proportional to the deflections produced and are therefore purely arbitrary. The lines in the region around 1.8μ are apparently due to combinations between the $3d$ levels and the X and Y groups, and although the wave-lengths have been checked as well as possible the agreement with the calculated frequencies from the known terms does not check very well with the experimental values.

The usefulness of the spectrometer in the matter of band spectra has been demonstrated in the examination of the 3μ absorption band of ammonia; the results of which will appear shortly. The infrared emission spectra of krypton and xenon are now under investigation.

The author wishes to express his appreciation to Professor H. M. Randall for his advice and many helpful suggestions.

[8] W. Gremmer, Zeits. f. Physik **50**, 716 (1928).