Ångström, K. (1900). "**Ueber die Bedeutung des Wasserdampfes und der Kohlensäure bei der Absorption der Erdatmosphäre**." Annalen der Physik **308**(12): 720-732.

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7. About the importance of water vapor and carbon dioxide during the absorption of the Earth's atmosphere

by Knut Ångström

1. The importance of water vapor for absorbing solar and terrestrial radiation is already well known through the work of Tyndall. In contrast, the views about the amount and the intensity of this absorption are more contradictory. Also there are very different opinions concerning carbon dioxide in this regard. I intend to elucidate this question, in the following.

2. The importance of absorption by carbon dioxide in the atmosphere was highlighted by Lecher and Pernter, by Keeler, and by the author. According to his research at Altenberg (1), Lecher argued that solar radiation can, in favorable cases, still contain considerable amounts of energy that falls within the bands of the carbon dioxide absorption. The significance of this observation is twofold: first, solar radiation reaching Earth's atmosphere contains rays of long wave radiation, and second, that a significant fraction of this radiation is absorbed in our atmosphere. This author has already shown earlier (2) that the amount of absorption of this radiation by carbon dioxide was greatly overestimated due to a lack of knowledge of the likely distribution of energy in the infrared solar spectrum outside the atmosphere. It is nevertheless always present, and absorption by carbon dioxide has to be a quite considerable, provided that solar radiation

1) E. Lecher, Sitzungsber. d. k. Akad. d. Wissensch. zu Wien [*Proceedings* of the Academy of Sciences, Vienna] (2) 82. p. 851. 1881; Wied. Ann. 12. p. 467. 1881 [Lecher, E., 1881, Ueber die Absorption der Sonnenstrahlung durch die Kohlensäure unserer Atmosphäre: Annalen der Physik, v. 248, no. 3, p. 466-473 http://dx.doi.org/10.1002/andp.18812480311.].

2) K. Angstrom, Bihang till K. S. Vet. Akad. Handlinger 15. Afd. 1. Nr.9 u. 10; Wied. Ann. 39. p. 267 u. 294. 1890.

Page 721
outside the atmosphere really contains long wave radiation (1).

In recent times, however, people from various quarters have questioned the accuracy of Lecher's observations (2). Consequently, I decided to renew the attempts of Lecher during a trip to Tenerife [Canary Islands] in 1896 for the purpose of studying the solar radiation at different heights above the sea (3).

The apparatus I used is shown in Figure 1. Two glass tubes about 40 cm long were mounted side by side in a wooden pipe. This was attached on a stand and could be set exactly by means of two micrometers in the direction of the solar radiation. The glass tubes were closed airtight by

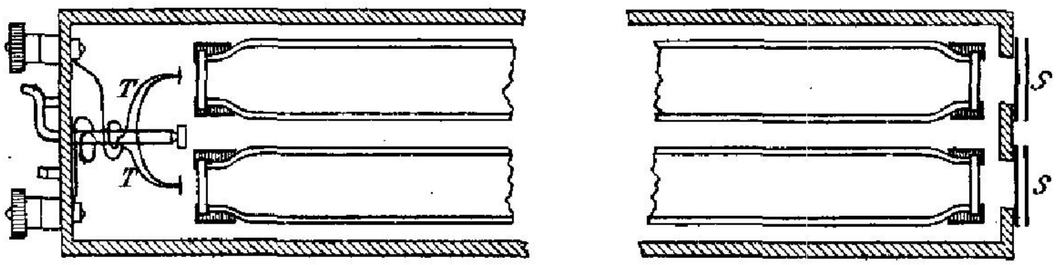

Fig. 1.

beautiful plates of fluorite; one held pure air, the other was filled with carbon dioxide. One end of the wooden pipe was closed by two movable screens (S) with double walls; the other end had a pair of thermocouples (T) fixed so that the solder joints were located in the extension of the glass tube. Special care was taken with the solder joints of the thermocouple to make both as similar as possible.

1. In the given work, I came to the conclusion that the solar constant was probably 4 g / Cal. per minute per square cm because of the investigation of Lecher and mentioned here the upper atmospheric overestimation of solar energy in the spectral region around 4 µ. According to what I will cite below, I can no longer maintain this opinion.

2. For example, G. B. Rizzo, Mem. della Soc. Spettroscopisti Italiani 26, p. 25. 1897.

3. A Full Report for this investigation is in Acta Reg. Soc. Ups. Published in 1900.

Page 722
The thermocouples were attached to an axis in a way that allowed you to change the position of the solder joints by rotation. First, the apparatus was tested by filling the two tubes with clean air. When the thermocouples were located in connection with a galvanometer of moderate sensitivity, and only one solder joint is illuminated, a deflection was observed of about 400 scale units. In contrast, when the two solder joints were illuminated simultaneously, the deflection was only 1-3 scale units. The symmetry of the apparatus was therefore close enough.

With this apparatus, several attempts were made on 23, 24 and 27 June, 1896. This observation was in the local shelter at Alta Vista on Pico de Teyde at an altitude of 3252 meters above sea level. The humidity was approximately 2.5 mm, the temperature was about 10°, the solar radiation in the middle 1.60 g / cal. per minute per cm^2. The tests showed no positive result. A greater absorption was not observed by the tube containing carbon dioxide. Given the accuracy of these tests, I can say with certainty that, under these circumstances, not 1.5 percent of the radiation was absorbed by carbon dioxide in the tube. But this result does not seem consistent with the experiments of Lecher, in which an absorption of 13 percent was observed through a tube 105 cm long. Since both the height of the sun as well as the altitude was significantly greater in my observations over the ocean, we should expect, according to Lecher's provisions, a significant absorption of more than 6 percent. According to this study, it seems clear, therefore, that the absorption capacity of carbon dioxide in the band Y [~4.3 µm] is so strong that the relevant absorption is already saturated before the radiation arrives to us, and as for the weaker band X [~1.7 µm], then the effect is similarly not noticeable because the absorption bands overlap the absorption bands for water vapor.

We cannot assess yet, how big absorption by carbon dioxide is in the higher parts of the atmosphere.

Page 723

3. It is much easier to evaluate the influence of carbon dioxide in the absorption of terrestrial radiation. In addition to the two detected bands X and Y (1) already mentioned by me, Rubens and Aschkinass show (2), a very strong band of wavelengths from 14.0 to 15.5 µ. This is of the utmost importance for the terrestrial radiation. We know the energy distribution in the spectrum of a solid body through the work of Langley, and especially of Paschen, Lummer and Pringsheim. An estimate of the absorption exerted by a sufficiently long carbon dioxide layer is so easy to run graphically. I did this calculation for several different temperatures assuming the width of the absorption bands was as large as possible, sometimes as small as possible. The energy curves are plotted with the help of the equation

$$E= C\lambda^{-5}e^{-c/\lambda T}$$

calculated using the constant c = 14700 for the radiation of a black body according to Lummer and Pringsheim (3). In Figure 2, the energy curves are for t = 100°, t = 8° and t = - 72° drawn together with the absorption bands of carbon dioxide. Of course, the greatest absorption of radiation from heat sources is at a very low temperature where the maximum energy is in the spectrum that coincides with the heat source's absorption band. This occurs at an absolute temperature of the heat source of approximately 196°, where the absorption amounts to 10-16 percent. For a heat source of 100°, the absorption amount to 12.5 to 19 per cent, a little more than the first-mentioned, as also the absorption band λ = 4.18 µ comes into effect.

1) K. Ångström, Öfversigt af K. Vet. Akad. förhandl. p. 549. 1889; Physikalische Revue 1. p. 606. 1892.

2) H. Rubens und E. Aschkinass, Wied. Ann. 64. p. 584. 1898.[Rubens, H., and Aschkinass, E., 1898, Observations on the Absorption and Emission of Aqueous Vapor and Carbon Dioxide in the Infra-Red Spectrum: Astrophysical Journal, v. 8, p. 176. http://dx.doi.org/10.1086/140516]

3) O. Lummer und E. Pringsheim, Verhandl. d. Deutsch. Physikal. Gesellsch. 1. p. 221. 1899.

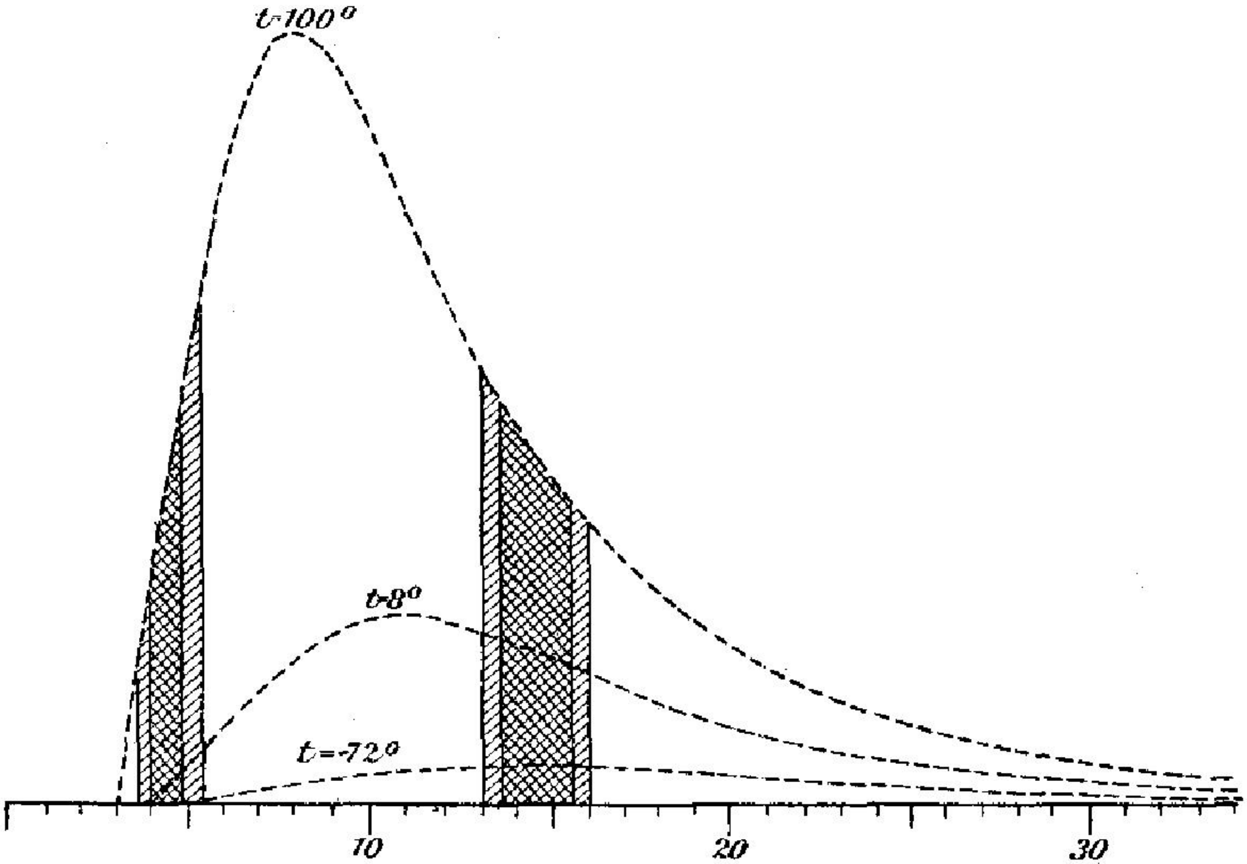

Fig. 2.

Because different parts of these broad absorption bands are certainly not of the same intensity, and because we cannot assume the spectrum from the spectrobolometric tests to be absolutely pure, the amount of absorption by a layer of carbon dioxide of any thickness cannot be precisely determined. To determine the relationship of the absorption rate and the layer thickness, however experiments with heat sources of various temperatures are desirable, and Mr. J. Koch in the local Institute of Physics was employed to make such an attempt. From the results of this investigation, which Mr. Koch published himself, it shall only be noted that only about 10 percent of the radiation from a black body at 100^{o} is absorbed by a carbon dioxide layer of 30 cm length at 780 mm pressure, and that when the pressure is reduced to $2/3^{rds}$, the absorption rate change is insignificant - a maximum of 0.4 percent of the total radiation. A layer of 30 cm length thus has the effect of almost complete absorption of the radiation from a heat source of 100^{o}. From these studies and calculations, it is clear, first, that no more than about 16 percent of earth's radiation can be absorbed by atmospheric carbon dioxide, and secondly, that the total absorption is very little dependent on the changes in the atmospheric carbon dioxide content, as long as it is not smaller than 0.2 of the existing value.

4. To calculate the absorption of solar radiation by atmospheric water vapor, I will use my observations during the summer of 1896 on Tenerife of solar radiation at different altitudes above sea level (1). The following small table shows the main results of these observations, the solar radiation in g / Cal. per minute and per cm^2 and the thickness of atmospheric layers in a vertical direction at 760 mm pressure is taken as a unit. [Labels in table: Location of observation, Height above sea level, Barometric Pressure, Water layer, Layer thickness 1 to 6]

Tabelle 1.

Beobachtungslokale	Guimar	Cañada	Pico de Teide
Höhe über dem Meere	360 m	2125 m	3683 m
Barometerdruck	734 mm	597 mm	493 mm
Wasserschicht	2,6 cm	1,2 cm	0,7 cm
Schichtendicke 1	1,39	1,51	1,54
„ 2	1,17	1,33	1,37
„ 3	1,03	1,20	1,24
„ 4	0,92	1,09	1,14
„ 5	0,82	1,00	1,05
„ 6	0,73	—	0,97

We see from this table - which, incidentally, was known before - that solar radiation passing through the same layer thicknesses is not of the same strength as the radiation from layers lower in the atmosphere that are richer in dust and water vapor and are thus absorbed more strongly. On the distribution of atmospheric dust at different heights above the sea, we know very little, but certainly the dust content decreases greatly with altitude, while the particles are smaller. The assumption seems therefore not too bold that the effect of dust on the two highest stations of Cañada and the Pico de Teide, was approximately the same at the same layer thickness, and that the difference in the absorption is mainly due to water vapor. If we calculate the water vapor originating from the absorption of solar radiation under this assumption, we can find at least an upper limit of this amount.

1) The observation results, are fully explained in Acta Reg Soc. Upsal. 1900 Intensité de la radiation solaire à différentes altitudes, Recherches faites à Ténérife 1895/96.

Page 726

Unfortunately, it is only possible to approxmately estimate the water vapor content over the Pico de Teide and Cañada using the equation of Hann (1). I have calculated that condensed water vapor on Pico de Teida would form a water layer of 0.7 cm thickness and on Cañada a water layer 1.2 cm thick (see Table 1). These observations and calculations result in the following small table. The total radiation passing through the water from the layer $(l_1 + l_2) / cm^2$, the absorption $J_2 - J_1$, which is caused by the water layer l_2-l_1, and the transmission coefficient (p) calculated by the equation

$J_2 = J_1\ p^{l2-l1}$, are shown therein.

[Table headings: Absorbing layer of water, Permeated layer of water, Absorption, Transmissions coefficient]

Tabelle 2.

Absorbirende Wasserschicht $l_2 - l_1$	Durchgedrungene Wasserschicht $\frac{l_1 + l_2}{2}$	Absorption $J_2 - J_1$	Transmissions-coefficient p
1,1 – 1,5 = 0,4	1,3	1,54 – 1,51 = 0,03	0,952
2,2 – 3,0 = 0,8	2,6	1,37 – 1,33 = 0,04	0,964
3,3 – 4,5 = 1,2	3,9	1,24 – 1,20 = 0,04	0,973
4,4 – 6,0 = 1,6	5,2	1,14 – 1,09 = 0,05	0,972
5,5 – 7,5 = 2,0	6,5	1,05 – 1,00 = 0,05	0,976

These results can now be compared to some extent to the observations by Schukewitsch in Pavlovsk [Saint Petersburg] (2) Irish control. Mr. Schukewitsch has compiled averages of his observations at various moistures in a table. From this table, allow me to cite the following short extract, which contains the most reliable results, as I have excluded observations at sun elevations of less than 15^o and at a moisture pressure of greater than 13 mm.

1) J. Hann, Meteorol. Zeitschr. **11.** p. 194. 1894.

2) J. Schukewitsch, Rep. für Meteorol. 17. Nr.5. 1894.

Tabelle 3.

Sonnen-höhe	Schichten-dicke	Feuchtigkeit in mm Druck						
		1	2—3	4—5	6—7	8—9	10—11	12—13
15°	3,81	1,06	1,00	1,00	0,97	0,95	0,98	—
18	3,20	1,15	1,11	1,07	0,09	1,04	0,98	—
24	2,50	1,30	1,23	1,20	1,19	1,17	1,13	1,03
30	2,00	1,37	1,32	1,27	1,29	1,21	1,24	1,19
40	1,56	—	1,40	1,32	1,29	1,28	1,33	1,26
45	1,42	—	1,40	1,36	1,34	1,33	1,29	1,27

Using Hann's equation, I also calculated the water vapor content, representing the different observations, then the transmission coefficient p determined from two consecutive observations, J_1 and J_2 at the same height of the sun. It is therefore assumed that different dust content does not significantly change the composition of the solar radiation. I then divided the 32 values of the transmission coefficient obtained in this way into six groups and calculated average values. Table 4 contains the resulting values of transmission coefficient (p) for the corresponding values of the total irradiated water layer (ω):

Tabelle 4.

ω	1,5	2,5	3,8	5,3	7,1	9,7
p	0,961	0,978	0,989	0,991	0,981	0,973

Med. 0,984 (of 3,8–9,7)

If we obtain an upper limit for the absorption of water vapor by the first-mentioned calculations, we find, by contrast, that this is a lower limit, because usually after a rain we have the greatest moisture content and the smallest dust content.

One also sees that the perturbing influences (originating from atmospheric dust, etc.) despite the large number of values from which p is determined here, are valid as p should increase with increasing ω. Besides, the agreement between Tables 2 and 4 is pretty good.

Page 728
No judgment about absorption of water vapor in the first layer can be made on the basis of these investigations. However, an estimate of such absorption is possible through spectral bolometric investigations of the infrared spectrum.

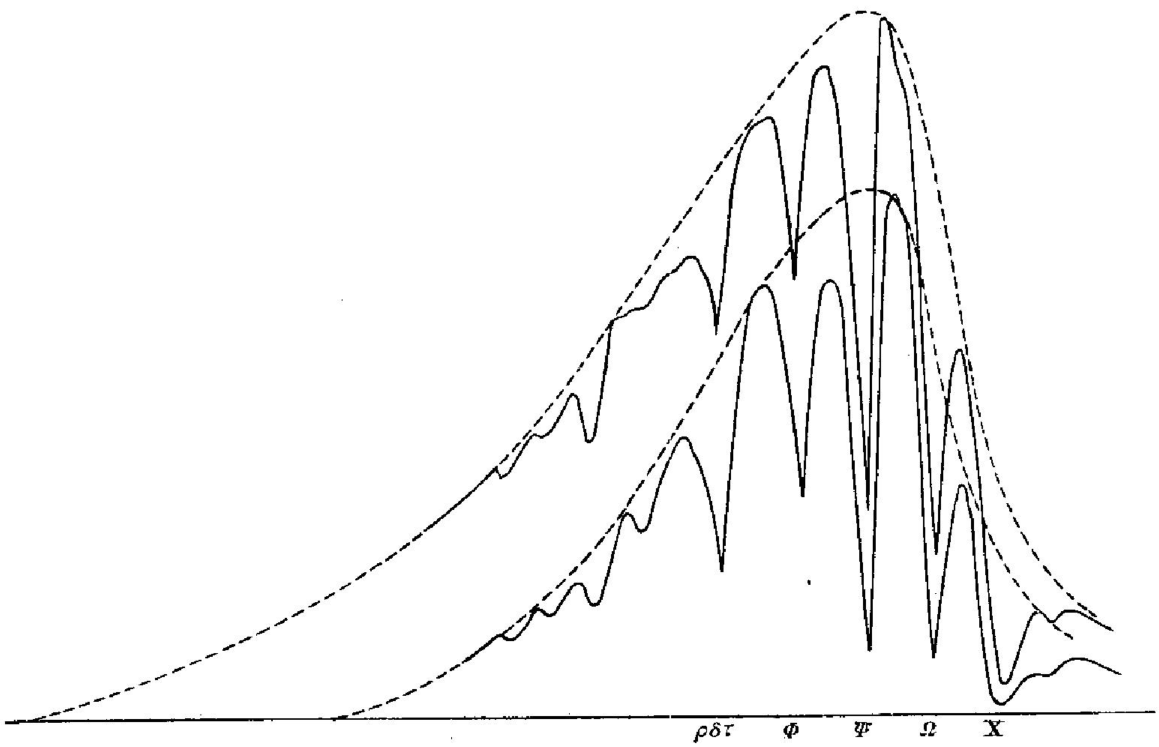

Fig. 3.

During the winter of 1899/1900, I had the opportunity several times to study the patterns of the infrared spectrum at different low temperatures. I used to a prism of rock salt and an apparatus for photographic continuous recording of the infrared spectrum, which I have already described elsewhere (1). The lowest temperature, -15 °, was observed on 10 February. The moisture pressure was 1.3 mm. Most of the major absorption bands in the infra-red spectrum, especially those which Langley has designated ρ σ τ Φ Ψ X and Y were then reduced significantly, which therefore shows that the same result as the water steam. On 24 March several complete recordings of the spectrum were obtained.

1) K. Angstrom, Acta Reg. Soc. Upsal. 1895; Physical Review 3. p. 137. 1895.

Page 729

Figure 3 reflects a faithful copy thereof which was taken from 11:40 a.m. to 11:55 a.m. and 5:17p.m. to 5:25 p.m.. At the same time determining the absolute heat radiation with the electric compensating pyrheliometer (1) was performed.

These provisions, as well as those of temperature, etc., are listed below as kindly made available by Mr. Prof. Hildebrandsson in the Journal of the Meteorological Observatory:

	Noon	5 p.m.
Pressure		
Temperature		
Humidity		
Wind		
	11:50 a.m.	5:20 p.m.
Heat radiation		

	12^h Mittags	5^h Nachm.
Luftdruck	762,8	758,7
Temperatur	$+ 0,4^0$	$+ 1,2^0$
Feuchtigkeit	3,3 mm (70 %)	3,7 mm (73 %)
Wind	S.S.W.	S.W.
	$11^h\ 50^m$ Vorm.	$5^h\ 20^m$ Nachm.
Wärmestrahlung	1,320	0,627 g/Cal. pro Min. u. cm^2

The ratio of the thermal radiation at 11:50 am to 5:20 pm is 2.12 in absolute terms, 2.05 after calibration; the meaurements are almost even, hence very good.

From these two curves, the energy curve was calculated for the radiation outside the atmosphere, and from this again the curve for the sun heights of 32^{o} and 5^{o} 40' assuming uniform absorption. These two curves are shown by dotted lines in Figure 3. The difference between the two curves for the same solar altitude was probably caused mainly by the absorption of water vapor and is approximately 15 to 27 percent of the total radiation between the wavelengths of 0.3 to 4 µ. This must be considered as a minimum value of the absorption of atmospheric water vapor, because the parts of the solar spectrum of wavelengths larger than λ = 4 µ have been not included. If we may assume that these parts of the spectrum outside the atmosphere are not lacking in the absorption of solar radiation by water vapor, the values must still be increased by about 5 percent.

1) K. Ingstrom, Wied. Ann. 67. p. 633. 1899.

Page 730

Figure 4 gives a representation of the absorption of solar radiation by water vapor, the same as we have now found. The radiation outside the atmosphere is assumed equal to 100, the ordinate is the intensity of the radiation, the abscissa the proportion of irradiated water vapor layers (in centimeters of water). The dotted lines (s) refer to the measurements of Schukewitsch, the solid lines (a) carried out by the author, the points marked X were obtained by spectral bolometric measurements. The two upper curves assume the smallest possible in the first water vapor layers, the lower two lower assume the largest possible absorption in these layers.

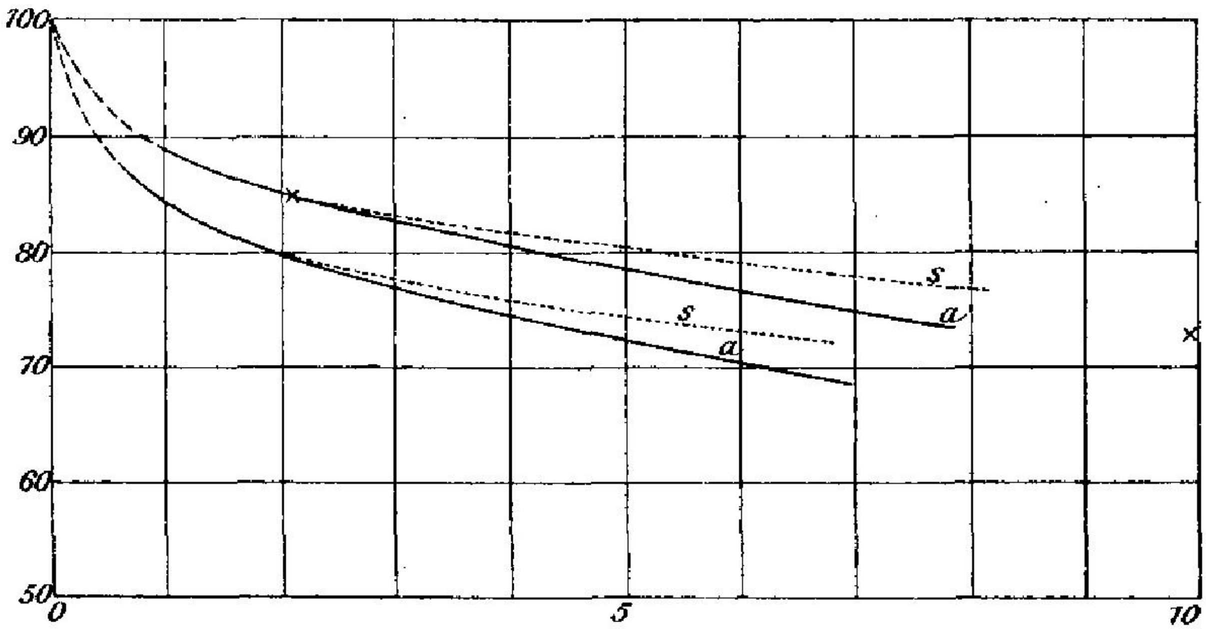

Fig. 4.

That the terrestrial radiation is strongly absorbed by atmospheric water vapor is already known. It is also clear that this absorption extends to the longest wavelengths from the work of Rubens and Aschkinass (1). Quantitative determination of the absorption of radiation of different water vapor layers thicknesses and for heat sources of lower temperature are not available, to the best of my knowledge.

5. Mr. Arrhenius has dealt in some works (2) with the influence of atmospheric carbon dioxide content on the absorption of terrestrial radiation based on the known work of Langley measuring

1) H. Rubens u. E. Aschkinass, Wied. Ann. 67. p.598. 1899.

2) S. Arrhenius, Bihang till K. S. Vet. Akad. Handlinger 22. Md. 1. 1896; Phil. Mag. (5) 41. p. 237. 1896.

Page 731
moon radiation (1) and calculating the absorption coefficient of carbon dioxide in different spectral areas. In general, such a calculation, as I explained above (see p. 723-724), the impurity of the spectrum can only give rather uncertain results because the difficulties multiply significantly when absorption bands of two different elements, in this case water vapor and carbon dioxide, are one on top of the other and therefore it depends on the separation of the two. In this case the observations cannot be treated as Mr. Arrhenius did. Mr. Langley, because of the weakness of lunar radiation, was obliged to work with a large width of the gap opening and wide Bolometer bands; therefore its spectrum was undoubtedly very unclean. One can therefore not expect the results that Mr. Arrhenius received, will agree with accurate direct reliable measurements. While via these measurments only three bands, two of which of precise clarity, were found, Mr. Arrhenius found for carbon dioxide absorption spread over almost the entire ultraviolet spectrum. Under these circumstances, it is clear that the calculation of the quantitative range of absorption must be quite imprecise. The Earth's atmosphere would, according to Mr. Arrhenius, even if it is as dry as possible, absorb about 60 per cent of earth radiation. The changes in absorption would be colossal with increases in carbon dioxide and a large enough carbon dioxide layer would even fully absorb terrestrial radiation (2). Mr. Arrhenius also believes that these findings might be a cause for an ice age. To go into more depths of these findings, which were further developed by Mr. Ekholm (3), does not seem appropriate as stated above.

1) S. P. Langley, Mem. of the Nat. Academy **4.** 9th mem. 1890.

2) Vgl. die Tabelle 1. c. p. 26, bez. p. 251.

3) N. Eckholm, Die Zeitschrift "Ymer" 1899.

Page 732

Under no circumstances should carbon dioxide absorb more than 16 percent of terrestrial radiation, and the size of this absorption varies quantitatively very little, as long as there is not less than 20 percent of the existing value. The main alteration caused by a decrease in atmospheric carbon dioxide content, is that the absorption exerted by the carbon dioxide (about 16 percent of the radiation) is only completed by a thicker atmospheric layer, so that the heat is a little more dispersed in the atmosphere.

Only after finishing this little paper, I received the great work entitled "Atmospheric Radiation" by Frank W. Very (1), who described in detail some of the same issues treated here. I hope that my contributions to the knowledge of the atmospheric absorption will not be without interest.

1) W. Very, U. S. Department of Agriculture, Bulletin G. 1900.

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