ART. XXXIV.—*Fundamental Distinctions Special to the Process of Transmission of Terrestrial Radiation by the Atmosphere, and the Value which is Obtained for the Coefficient of Transmission when these are Considered*; by FRANK W. VERY.

IN finding the transmission of terrestrial radiation by the atmosphere, I have hitherto assumed that it is unnecessary to measure more than the zenithal radiation, for the following reason: If we consider the radiation to a limited area of the sky from an instrument having a very small surface, normal to the direction of the rays, the radiation falls off as the pointing departs from the zenith and is practically zero close to the horizon. Hence some have supposed that a complex summation of the radiation by zones is needed in order to get the actual "sky radiation." But in nature, the absorption is exerted in a comparatively shallow layer of air close to the surface and the radiator is not a minute area, or almost a point, but is an indefinitely extended surface faced by a parallel and closely juxtaposed absorbent layer. It is, therefore, only necessary to consider the transference between two layers in a normal direction, that is, vertically.

In proof that this is so, we have only to try a still more direct experiment by making the moon our distant radiant source, after eliminating that part of its rays (both visible and invisible) which is simply reflected solar radiation, and getting the transmission of the true lunar emission through an entire atmosphere. On trial, the result demonstrates that the zenithal observation with a radiator of limited surface, and radiating to a limited angular area, is the one to be used; and that the zonal integration which gives a smaller apparent transmission and one which does not represent a natural fact, is at fault, because the details with which the summation is concerned are purely those of a laboratory experiment, while the conditions in nature are entirely different.

The fallacy just noted may have arisen from a common practice of measuring what is sometimes called "nocturnal radiation," or the radiation of a thermometer-bulb to either a part or the whole of the night sky. As an instrumental method, this is perfectly legitimate, but the result should not be confounded with the radiation of a widely extended surface of the earth to space, which is the true terrestrial nocturnal radiation.

In this Journal for April, 1913, I gave a curve of apparent sky temperature obtained by a thermopile of limited aperture (fig. 2, p. 383). Here the readings were entirely similar to those which might be obtained by a nocturnal radiation ther-

monometer, also of limited aperture; and the curve might be summed zonally, were it not that such a summation could have no useful significance. The really important fact is that given by the *lowest* reading, or that in the direction of the zenith; and since there appears to be an impression among some leading astrophysicists that the day sky ought to give *positive* deflections, I will call attention to the fact that a clear sky never gives any other than negative readings, whether by day or by night; and that on the date of the above-mentioned curve—a hot, sunshiny day in July—the apparent temperature of the sky was *zero Centigrade*.

It is not yet sufficiently recognized that the radiation which proceeds from the earth's surface, or at least that portion of it which is absorbed by the atmosphere, does not continue very long as rectilinear propagation in the original directions, but becomes almost immediately involved in the meshes of molecular kinetics, and thenceforth is handed on in a *vertical* direction in connection with those processes by which the normal upward change of air pressure is maintained.

At my present station, which is not far from Boston, skies good enough for measurements of air transmission are rather rare in winter. This may possibly be due to the neighborhood of the ocean, since, when the water is considerably warmer than the land, the diffusion of water vapor from the ocean into colder air over the land may very likely produce a thin mist in certain layers. It is extraordinary how a scarcely perceptible mist will take down the sky transmission, and, indeed, my experiments on the transmission of radiation from a boiling radiator at a distance of about 100 meters suggest that it is not necessary for the atmospheric water to be actually precipitated in liquid form in order that it shall do this. It is enough that saturation be imminent, because this condition conduces to the formation of highly absorbent hydrols, even before actual precipitation has begun. This will be made evident when my long-continued observations on these radiations under every possible condition of atmospheric moisture shall have been published.

In summer the land is warmer than the ocean on sunny days, and any vapor coming from the ocean to air over the land is in a fair way to recede from the saturation point. Hence there are plenty of days in summer when transmission measures can be made. From long experience at the Allegheny Observatory, I can say that, notwithstanding Pittsburgh smoke which sadly dims the visible rays, nevertheless, transmission of terrestrial radiation is but little affected by the smoke, unless saturation is so near that the carbon particles serve as condensation nuclei; while the absence of the ocean is very likely

the reason why it was easier to find suitable occasions for such measures in winter at Allegheny than it is at Westwood. Out of twenty-one observations of sky radiation made here on six days in winter between Jan. 20 and Feb. 3, 1909,* only one was good enough to give a genuine *air* transmission; but all of the nineteen summer measures on three days in July were good, and many more as good could have been given.

When the measures of terrestrial radiation, obtained from zenith-sky observations on these suitable occasions, are plotted with the surface pressures of water vapor as abscissæ, they are well represented by the curve which Mr. Anders Ångström has published.† My measures were all made several years before Mr. Ångström's paper appeared, and by an entirely different method. They are, therefore, completely independent. This being so, and the agreement between our separate experimental work being very nearly perfect, it may well be asked how it is that such diverse conclusions in regard to transmission can be drawn from what are practically the same data; for, whereas I have maintained for many years that the atmosphere in middle latitudes transmits, on the average, about 40 per cent of radiation,‡ the observed values varying between 26 per cent in summer and 58 per cent in winter,§ Mr. Ångström, on the other hand, states his belief|| "that the transmission for clear sky seldom is greater than 25 per cent and seldom is less than about 5 per cent." If this statement referred to those imperfect skies which, however much they may delight the farmer praying for rain, are the bane of astrophysics, no fault could be found; but on referring to the accompanying text, this reading is seen to be inadmissible. The discrepancy arises from the aforesaid diverse modes of reduction, but the smaller values have also been supported by further erroneous arguments.

In his note¶ Mr. Ångström illustrates by assuming a surface temperature of 283° Abs. C. which "should, if no atmospheric radiation existed [that is to say, if the atmosphere were absolutely transmissive], radiate to space $0.490 \frac{\text{cal.}}{\text{cm}^2 \text{ min.}}$ "

The "effective" sky radiation is then taken as -0.15 , which

* Published in this Journal for April, 1913, pp. 379-380.

† Astrophysical Journal, vol. xxxvii, p. 319, fig. 2, June, 1913. It is a pleasure to note one more point on which we coincide. This is Mr. Ångström's recognition that dry dust alone, suspended in air, has almost no influence on the transmission of terrestrial radiation, confirming results reached during my work at Allegheny.

‡ See Astrophysical Journal, vol. xxxiv, p. 375, December, 1911, and also earlier papers.

§ See also Science, N. S., vol. xl, p. 420, September 18, 1914.

|| Astrophysical Journal, vol. xxxviii, p. 200, September, 1913.

¶ Op. cit., p. 198.

I endorse, at least as a good average summer value; but the "conclusion that about 0.07 gr. cal. or only about 14 per cent of the radiation from the earth's surface will escape the absorbing atmosphere and go out to space"* does not follow. For, let it be noted, the observed radiation of 0.15 to the sky is the radiation immediately to space from the surface of the earth. The restriction that "a part of the observed nocturnal radiation is not transmitted entirely through the atmosphere, but merely to its colder layers,"† can not be admitted.

The "nocturnal radiation" which is "observed" gets through to space. The statement made that, because certain observers had given the value of $0.12 \frac{\text{gr. cal.}}{\text{cm}^2 \text{ min.}}$ for "atmospheric radia-

tion" at a height of 3000^m, we must therefore "consider about 0.06 gr. cal. [assumed to be the *mean* "atmospheric radiation" of an air layer 3000^m deep] of the nocturnal radiation as intercepted by colder layers of the lower atmosphere"‡ is certainly incorrect. Actually, $.49 - .15 = .34$ gr. cal., or between five and six times as much, has been intercepted! The "colder layers" of the atmosphere could be obliterated completely without altering the transmission of *terrestrial* radiation appreciably, for it is the lower warm and moist layers in contact with the surface which do the work. The amount specified by Ångström could be easily intercepted in the first 100 meters of air (this is known from the experiments with the distant radiator), and almost all of the radiation which the atmosphere is capable of absorbing will be taken out long before the level of 3000^m is reached, because, after the readily absorbable rays have been struck out, the passage through subsequent layers adds little to the absorption.

A layer of air extending from the surface up to 3000^m is assumed by Mr. Ångström to be "the effective radiating layer of the atmosphere." But the lower layers of the atmosphere are prevented from radiating directly to space on account of the absorption of their peculiar radiations by higher layers. Still less can air raised some hundreds or thousands of meters above the surface radiate downward to the ground to any appreciable extent, because the lower layers have greater absorbent power for the air's own peculiar radiation, and besides, the lower layers are apt to be hotter than those above. Moreover, all of the lower layers of air lose their heat to some extent in other ways than by immediate radiation. For example, a good deal of the hotter air is cooled by simply being mixed with colder air, being transported as wind to distant localities where the temperature is lower. Not that

* *Astrophysical Journal*, vol. xxxviii, p. 200, September, 1913.

† *Op. cit.*, p. 199.

‡ *Op. cit.*, p. 199.

this constitutes a final disposal of the heat. The thermal energy is still imprisoned. Its only way of escape is through the gradual processes of internal radiation which are found to be most fundamental and at the bottom of all of those physical properties which we call "atmospheric."*

If any layer of the atmosphere deserves to be called "the effective radiating layer," it is the isothermal layer, where convection being no longer potent, the heat obtained by absorption of the incoming solar rays must be radiated back to space, since it can not accumulate indefinitely. There is no evidence whatever of Ångström's effective radiant layer of the atmosphere at 3000 meters. On the other hand, the peculiarly potent radiation-function of the isothermal layer of the atmosphere has been repeatedly pointed out by me.†

Here is the source of the fallacy: The $0.15 \frac{\text{cal.}}{\text{cm}^2 \text{ min.}}$ of ob-

served terrestrial radiation goes out scot free, and the transmission of terrestrial radiation is truly 30 per cent in the given case. Most of the remaining 70 per cent is not directly transmitted to the "colder layers" at 3000^m, there to be absorbed; and still less does any portion of the 30 per cent linger there, as Ångström supposes; but the 70 per cent is mainly absorbed within a few hundred meters of the surface, at most, and is thereafter indirectly transmitted to space through the step-by-step process of alternating gaseous absorption and reradiation which is described in my treatise on "Atmospheric Radiation," published in 1900. Included in the 70 per cent, there may be an absorption of 2 or 3 per cent which is special to ozone in elevated regions of the air.‡ Unless the 70 per cent absorbed by the air were also "transmitted" in the end, though in its own slow way and through a complex of radiation, convection, penetration, aqueous condensation and evaporation, etc., which can scarcely be attacked in any other way than by the methods of thermodynamics, the earth's surface would all the time be getting hotter, since it receives fresh accessions of heat from the sun's rays every day. Some portions of this atmospheric thermal energy are radiated directly to space by cloud sur-

* In confirmation of this assertion, I will merely note that the first differences of the radiant potential of the air in a vertical section through the atmosphere form a curve which agrees precisely with the curve of the vertical distribution of density, proving that it is the radiation between the air molecules which governs the kinetic mechanism of the gaseous mass.

† Compare "Atmospheric Radiation," Bulletin G, U. S. Weather Bureau, 1900, p. 123; "The Solar Constant," Weather Bureau Pub. No. 254, 1901, p. 25; Astrophysical Journal, vol. xxxiv, p. 386, December, 1911; and especially the paper: "Sky Radiation and the Isothermal Layer," this Journal, vol. xxxv, pp. 369-388, April, 1913.

‡ See my quantitative measurements of this absorption, Science, N. S., vol. xl, p. 421, September 18, 1914.

faces; but the isothermal layer in its more attenuated parts, where at last the air molecules are free to radiate directly to space, is the final dispenser of this accumulated energy.

We reserve the term "transmission of terrestrial radiation" for that portion of the thermal energy at the earth's solid or liquid surface which, being transformed into radiation of such wave-lengths that the air cannot absorb it, escapes directly to space. That this is what happens to the radiation emitted from the earth to the sky is made certain by the following facts: In my paper* on "The Probable Range of Temperature on the Moon" I gave 48 per cent as the transmission, or 52 per cent as the atmospheric absorption of the extreme infra-red radiation emitted by the moon (from winter measures). The earth radiates at a lower temperature than the moon, because the earth reflects the larger part of the sun's rays, falling on it,† and therefore somewhat longer wave-lengths preponderate in its spectrum. These fall outside the region of greatest aqueous absorption, and are therefore *more* freely transmitted than lunar radiation whose maximum falls within the great Ξ band of aqueous vapor. Hence, on the nights in question, a larger percentage of terrestrial radiation must have been escaping than the percentage of lunar radiation then undoubtedly entering through the same absorbent atmosphere; and it is not at all exceptional that I obtain from winter measures of terrestrial radiation the value given in my paper in *Science* on "The Transmission of Terrestrial Radiation by the Earth's Atmosphere in Summer and in Winter," namely, an absorption of 42 per cent, which is comparable with the value given by Dr. Nils Ekholm for absorption of terrestrial radiation by atmospheric aqueous vapor in more northern lands, and is fully confirmed by the same, notwithstanding Mr. Ångström's opinion. "In Sweden the absorption amounts to about 45 per cent and only in the polar regions does it fall below 30 per cent," says Dr. Ekholm;‡ that is, transmissions of 55 to 70 per cent are the rule in these northern lands.

In describing his method which presupposes radiation to an entire hemisphere, Mr. Ångström says:§ "It must always be regarded as a dangerous approximation to calculate the radiation to the whole sky from the radiation to a limited part, assuming a certain standard distribution of radiation." This may also be true as regards radiation to the sky in other direc-

* *Astrophysical Journal* for November and December, 1898; cf. p. 275.

† See my determination of "The Earth's Albedo," *Astronomische Nachrichten*, Nr. 4696, November, 1913; and a more elaborate, or definitive determination in *A. N.*, Nr. 4819-20.

‡ *Om Naturens Värmehushållning*, K. Vetenskapsakademiens Årsbok 1914, p. 314.

§ *Astrophysical Journal*, vol. xxxvii, p. 315, June, 1913.

tions than the vertical, where special reduction to the zenith is required; but nevertheless, with a clear sky, my method of observing the zenithal sky gives nearly the same observed radiation as Ångström's method, as has been shown already. The differences appear only in the further treatment of the observations by diverse and irreconcilable theories. The necessity for my mode of treating the data arises from the fact that the absorption of terrestrial radiation takes place in a layer of air of small depth immediately above the surface. Thus we may regard earth and "sky" as two widely extended parallel surfaces in close proximity; and if we assume them to be "black bodies," we can compute their effective radiations by Stefan's Law. Hence, on the supposition of a normal transference between the two, the zenithal observation of sky radiation virtually integrates the natural process and gives the rate at which heat is lost, rendering unnecessary any complicated summarization by zones. Nor can a small thermometer bulb, for whose radiation a zonal summation would be appropriate, represent the radiation of an extended surface. But each element of horizontal surface may be considered as in radiant exchange with the vertical air column of equal section situated directly over it.

The hemispherical summation of sunlight diffused by the sky upon a given point and the radiation from an instrument of limited area to the sky follow different laws. For if we consider the case of a zenithal sun, it is evident that, within a given solid angle, the reflected skylight comes from greater depths of air according as the direction approaches the horizon, and the light therefore increases in intensity at the low altitudes; but the earth's radiation to the sky, as represented by a circumscribed measuring instrument, is more absorbed in directions near the horizon than at the zenith, and therefore earth radiation (as thus measured) proceeding outward diminishes just where the incoming solar radiation, diffused by the sky, increases. Thus in the summation for the hemisphere, skylight from the hemisphere bears a larger ratio to skylight for a given solid angle of high altitude, than terrestrial radiation to the hemisphere bears to the same solid angle at the zenith. This is the reason why Ångström, who measures the radiation to a hemisphere, always gets a positive value for radiation received from the sun-illuminated sky in the daytime, but a negative value for the night sky, while I find the zenithal value always negative, whether by day or by night. The apparent discrepancy is just what we ought to expect. I have not access to the observations of Homén, who also found negative sky radiation both by day and by night, but if his method at all resembles mine, Ångström's conclusion "that the observations

of Homén were made under conditions that must be regarded as exceptional" is not necessarily justified.

The mean value of 14 per cent which Ångström derives for the transmission of terrestrial radiation by the atmosphere from considerations which I have shown above to be based on fallacies, is further advocated by him because it "is not far from that derived by Abbot and Fowle from the measurements on the absorptive power of the water-vapor"; but the apparent support of these measurements is also fallacious, since, as I proved conclusively in "Atmospheric Radiation" (p. 99), diluted water-vapor, that is, a given depth of water spread in the form of vapor through a very large depth of air, transmits much more freely than the same amount of aqueous vapor in concentrated form and equal equivalent depth. "The same quantity of water in the form of steam takes out about 15 per cent, and distributed as atmospheric vapor only one-half of 1 per cent." I have already pointed out the inadequacy of the theory of aqueous absorption held by these observers.*

Much vagueness and misconception would be removed if it were realized that there is a fundamental distinction between the transmission of a large part of the solar radiation by the atmosphere, and that of terrestrial radiation by the same atmosphere. Diffuse selective reflection enters very largely into the skylight problem and the process is conducted with the speed of light, which for atmospheric distances is practically instantaneous; but the terrestrial radiation which does not immediately escape to space, becomes air radiation and passes from molecule to molecule by a very large number of alternations and thus remains a long time in the medium. This has been shown in my "Note on Atmospheric Radiation," † and also more elaborately in a computation of the flux of volume energy, which appears to constitute air radiation, through the height of the atmosphere, in my paper: "On the Solar Constant," ‡ where it is shown that "the thermal energy which gives air pressure is maintained by the internal radiation between the air molecules."

Certain theorists have attached a great importance to changes in atmospheric carbon dioxide as a climatic factor. It is true that this gas has a strong absorption band at 14.7μ , which looks very imposing when plotted on a percentage scale of absorption; but when it is recognized that there is only a small part of the total terrestrial radiation included within the limits of this band, it may be seen that its effect is relatively insignificant. Ozone also, in spite of some large claims by Mr.

* See *Astrophysical Journal*, vol. xxxiv, p. 373.

† This *Journal*, vol. xxxiv, p. 533, December, 1912.

‡ Ibid., vol. xxxix, p. 204, *et seq.*, February, 1915.

Ångström, is of quite minor importance. He assigns to "the remaining 0.09 gr. cal. which probably are transmitted through the lower absorbing layers" (meaning by this the entire remnant of nocturnal radiation, since, of the original 0.15 of this illustration, 0.06 gr. cal. are supposed by him to be stopped at 3000 m.) a further absorption by "ozone in the higher and colder strata of the atmosphere," amounting in winter to 50 per cent, and on the average to 20 per cent. The ozone band between 9 and 10 μ , discovered by Professor Knut Ångström, sometimes exerts an absorption of 50 per cent in winter, but within the limits of the band only. It is not correct to apply this value of the percentage of absorption, within a limited range of wave-length, to the entire remnant left from aqueous absorption which extends through many times this range. This is not the first time that similar elementary considerations have been pointed out, but since they are frequently overlooked as in the present instance, it is necessary to emphasize them. My measures show that, in winter, between 3.00 and 3.72 per cent of the entire remnant of the spectrum beyond great Ξ , left after aqueous absorption, may be absorbed by ozone, and much less in summer, the remaining radiation, over 96 per cent, falling outside the limits of the ozone band. Compared with water vapor and its products, the hydrols, all other atmospheric absorbents are nearly negligible.

Taking the extremes of the range of terrestrial radiation ($R = \frac{\text{gr. cal.}}{\text{cm}^2 \text{ min.}}$) as influenced by aqueous vapor (pressure of vapor in mm. = a), we have :

Ångström	$a = 3.50$ to 4.50 ,	$R = 0.198$
"	$a = 11.90$ " 13.24 ,	$R = 0.146$
Very (Winter)	$a = 0.63$ " 2.39 ,	$R = 0.222$
" (Summer)	$a = 9.14$ " 12.67 ,	$R = 0.149$
Homén	$R = 0.22$ " 0.13 .	

These results being in good agreement, and since the afore-said lunar observation definitely confirms the larger values of the transmission of terrestrial radiation deduced for middle latitudes by the method advocated in this paper, we may conclude that with the clearest skies and in middle latitudes, transmissions of about 26 per cent are common in summer and upwards of 58 per cent in winter.

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