The dayglow of the sodium D lines

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Abstract. Observation of the sodium dayglow in the scattered sunlight observed on the surface of the earth with a magnetic scanning photometer is reported. The intensity (September to November 1960) is unexpectedly strong—30 kilorayleighs toward the zenith—and evidence is that during the period studied the amount of sodium is 4 times as large in the daytime as at twilight. However, a strong correlation is found between the dayglow and twilight intensities. The abundance can be as high as 40×10^9 atoms/cm^2. The possible role of water vapor absorption in the results is discussed.

INTRODUCTION

The day airglow has not been observed until now because of the difficulty of contending with the strong background of white light scattered in the troposphere. In the case of the sodium D lines it was pointed out long ago by *Bricard and Kastler* [1944] that the light available under the most favorable conditions might not be weak compared with that scattered by the lower atmosphere in the same wavelength interval.

The number of sodium atoms present in the upper atmosphere can be as high as 30×10^9 atoms/cm^2 according to measurements made during twilight [*Blamont and Donahue*, 1958; *Donahue and Blamont*, 1960]. If during the day the number does not change appreciably from this value, the optical thickness of the sodium would be almost 0.02 at the center of the lines. This is of the same order as the optical thickness of the atmosphere for Rayleigh scattering. However, even if a spectrograph of resolution adequate to take advantage of this fact were available, there would remain the serious practical disadvantage that the exciting light lies near the bottom of the solar Fraunhofer D lines where there is only about 6 per cent of the continuum left. The problem is thus to detect and measure the intensity of a line about 0.15 A wide near the bottom of an absorption line about 0.23 A wide, where the intensity of the emission line is at most equal to the intensity at the bottom of the absorption line and both combined are only one-tenth as strong as the nearby continuum.

An effective method of discriminating against sunlight outside the band of the emission line is to take advantage of the fact that the D lines are resonance lines and use a sodium vapor cell to scatter the light being studied into a photomultiplier tube. There is, however, the problem of determining what part of the signal obtained has its origin in the sodium of the upper atmosphere and what part arises from Rayleigh scattering. This can be solved by applying periodically to the sodium cell a magnetic field perpendicular to the direction of the incoming and outgoing light and sufficiently strong to shift the appropriate Zeeman component of the lines in the cell away from the atmospheric sodium lines. Instruments based on this principle, destined originally to study the dayglow, have been in use for several years in studying the twilight flash [*Blamont*, 1953, 1956].

APPARATUS

The light to be studied is focused by an $F/2$ lens, $f = 18$ cm (L_1 in Fig. 1), on a diaphragm Δ of 1-cm opening. The lens L_2, $f = 12$ cm, then renders the light parallel so that it can pass through an interference filter of 50 A bandwidth centered on the D lines. It is focused once more

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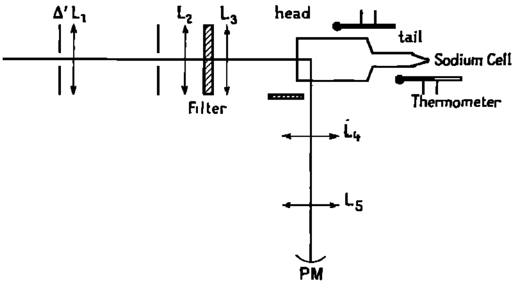

Fig. 1. Schematic of photometer.

by a lens L_3 of 12-cm focal length, this image being formed between the poles of an electromagnet. In the gap, 4 cm wide, is placed an oven containing the sodium vapor cell. This cell is a parallelepipedon of Pyrex 25 by 25 by 50 mm with a cylindrical end 60 mm long. The cylindrical tail serves as light trap in the direction of excitation as well as a depository for sodium when the cell is cold. Light enters the cell through the flat face opposite this tail and is observed through one of the side faces. The head and tail of the cell are placed inside different heating elements whose temperature is maintained within $\pm 0.1°C$ by means of a relay controlled by thermometers with platinum contacts. Normally the temperature of the head is 165°C, and of the tail 150°C. The lower temperature determines the vapor density of sodium, and the higher one sets the line width of the absorption line. The small temperature differential prevents the deposition of sodium on the windows in the head of the cell. Heater, thermometer, and cell are wrapped in asbestos and placed in a brass box which can readily be removed from the photometer and replaced in exactly the same position without difficulty.

A point 5 mm behind the entrance window is focused through the flat side of the cell by a lens L_4, $f/1,4$, $f = 7$ cm, on a lens L_5. The image of L_4 is focused by L_5 on the photocathode of a Lallemand 20-stage photomultiplier.

In the instrument originally used for twilight observations there was a large signal from stray light which could make its way to the photomultiplier by parasitic reflections in the cell. A mirror placed between the filter and L_3 sends a small reference signal to a second photomultiplier that can compensate this parasitic light signal. This arrangement is no longer necessary with an improved oven and cell assembly that has cut the stray light to less than the normally observed twilight signal.

The d-c output of the photomultiplier is fed through an impedance matcher to a Philips electronic potentiometer. The time constant of the instrument is about 5 seconds.

The magnetic field in the gap has a maximum value at present of 4000 oersteds for a magnetizing current of 6 amperes. The magnetic field is controlled by a small programmer and is usually varied from 0 to 4000 oersteds every 30 seconds.

Twilight Observations

Calibration. For purposes of calibration a d-c source of white light is placed in front of L_1. The intensity of this source is monitored with a photocell and adjusted always to the same value. The purpose of the procedure is to permit the comparison of one day's results with another's and not to provide an absolute calibration. The difficulty of absolute calibration is underlined when a resonance source replaces the white light. Results are quite erratic and incoherent with those of the white light, so much does the line shape of the source vary. The procedure is to begin with a cold oven, to heat the oven, cool it, and then heat it again, each time recording the output of the photometer for several values of the magnetic field between 0 and 4000 oersteds. At first thought it would seem that the output should be independent of the field. It is for a cold oven, but when the oven is hot the output increases with field in the fashion shown in Figure 2. The effect is much less pronounced for the lower oven temperature shown. Although no computations are available there is no doubt that this effect is a consequence of the fact that the optical path through the cell is not small at the center of the unsplit hyperfine component. With 4000 oersteds on the cell the appropriate (π) Zeeman components are well separated (Fig. 3) and the optical path is effectively much reduced.

Observations. For the observation of the twilight flash the zenith angle of this photometer is held at 75° and its axis is customarily kept at 0°, 90°, or 180° with the direction of the sun. A magnetic field of 4000 gauss is applied for 30 seconds every 30 seconds. With the field off, the

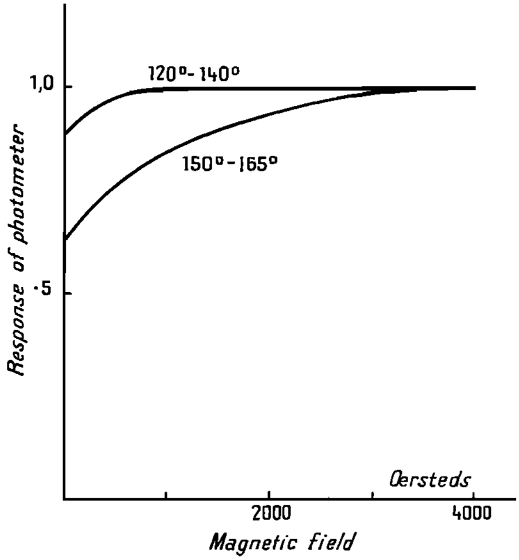

Fig. 2. Response of photometer to white light as a function of magnetic field strength in the sodium cell. Ordinate scale is arbitrary. Temperatures are those at head and tail of cell.

instrument records a signal which is composed partly of the scattered resonance radiation from the atmospheric sodium and the sunlight scattered by the lower atmosphere as admitted by the spectral window of the sodium vapor in the cell. Also present is some parasitic light in the 50 A bandwidth of the interference filter which succeeds in finding its way by multiple reflections into the phototube. With the field on, the π components of the lines in the cell are shifted so far (Fig. 3) that the only light entering the phototube aside from the parasitic light comes from Rayleigh scattering of sunlight slightly away from the center of the Fraunhofer lines.

While the sun is more than 4° below the horizon the Rayleigh-scattered component is small and the difference between the signals with field off and field on ($I_0 - I_4$) can be taken as proportional to the sodium twilight airglow intensity except for the distortion caused by the shape of the effective instrumental spectral window. With the sun higher, however, the signal I_4 begins to increase and eventually $I_0 - I_4$ goes negative, the Rayleigh-scattered radiation on the sides of the Fraunhofer lines becoming stronger than the combined Rayleigh-scattered and resonance-scattered radiation near the bottom of the lines. This is a consequence not only of the shape of the solar absorption lines but also of the fact that absorption in the earth's own sodium layer on the day side of the earth imposes a narrow absorption line on the light scattered by the lower atmosphere [*Donahue*, 1956*b*].

Dayglow Observations

Principle. With this instrument it is in principle possible to detect and measure the intensity of the telluric lines in the daytime as well as in twilight in spite of the presence of the Fraunhofer signal.

The reason is that during the day the ratio I_0/I_4 should remain constant and equal to the ratio R_F as measured in direct sunlight unless a dayglow signal is contained in I_0. In that case the dayglow intensity I_{Na} is given by

$$I_{Na} = [(I_0/I_4) - R_F)]I_4 \qquad (1)$$

Light scattered by the moon. In the course of some observations being made by one us (J. E. B.) with a magnetic scanning spectrometer on sunlight reflected from the moon, it was noticed that the ratio I_0/I_4 found for the moon was considerably different from that received from a part of the sky just alongside the moon during the daytime. This showed that the spectrum of sunlight scattered by the earth's atmosphere near the bottom of the Fraunhofer sodium lines was considerably different from the spectrum of the incident light. A systematic study of the phenomenon was then undertaken.

The Fraunhofer spectrum. It is necessary first to know the ratio $R_F = I_0/I_4$ for sunlight. This is best obtained with the photometer itself viewing the sun directly by means of a coelostat through a pinhole used to reduce the intensity of the incident light sufficiently. Properly, this measurement ought to accompany the dayglow observations as part of the routine procedure, but the lack of a coelostat at the Observatoire de Haute-Provence where these studies are taking place necessitated a special trip to the Observatory of Marseilles in November 1959 to perform just one series of determinations of the spectrum of the sun as a function of the magnetic field for the magnetic scanning photometer. The result (Fig. 4), after correcting for the white light response factor of Figure 2, is $I_0/I_4 = 0.42$. The value of this ratio may also be deduced from the spectra of the Fraunhofer D lines obtained

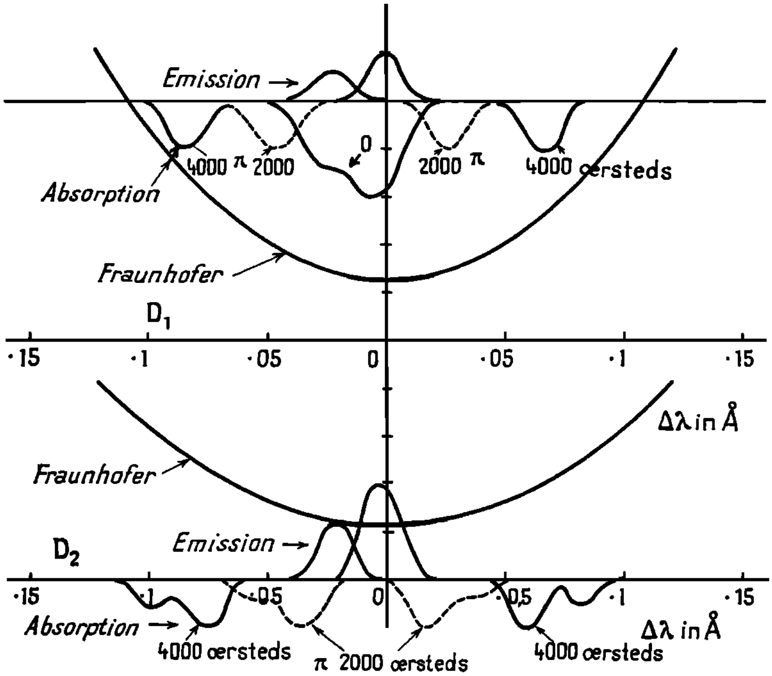

Fig. 3. Profiles of D_2 and D_1 Fraunhofer lines as computed from Priester's observations. D_2 and D_1 terrestrial lines are shown for an autumn evening. The absorption lines are those of the cell at 160° with 0 field and the π components at 2000 and 4000 oersteds.

by *Priester* [1953] as treated by *Donahue and Stull* [1959]. These lines for an autumn morning are plotted in Figure 3, from which it may be estimated that the ratio of the response of the instrument to direct sunlight at zero field to that at 4000 oersteds ought to be 0.45.

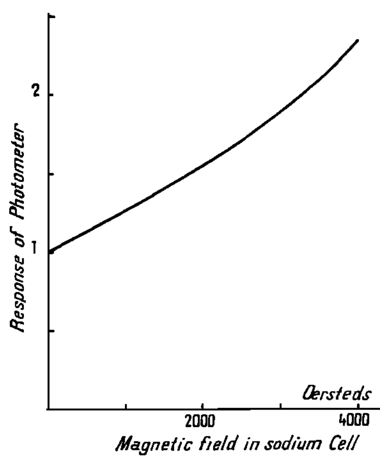

Fig. 4. Spectrum of direct sunlight as measured by the magnetic photometer.

Daytime observations. For observations during the daytime, the axis of the instrument has customarily been pointed in the direction of the pole. A diaphragm Δ' of 4-cm opening is placed in front of L_1. With the oven containing the sodium vapor at room temperature, the signal due to parasitic light I_p is measured by recording the photocurrent with the shutter in front of the instrument first closed and then open (Fig. 5). Afterward the oven is heated, and after equilibrium is established a new zero I_C is determined with the shutter closed. The magnetic field is then set successively at zero, 2000 oersteds, zero, 4000 oersteds, and the cycle is repeated several times. After correction for I_C these values suffice to determine I_0 for zero field, I_2 for 2000 oersteds, and I_3 for 4000 oersteds as measured above I_p. They thus measure the intensity scattered by the sodium vapor in the cell for the several field conditions. The oven is then cooled, and I_p and I_C are redetermined. A complete cycle of this sort requires about 35 minutes. If the measurement of I_2 is omitted, the time can be reduced by a few minutes. I_p is always determined, as indicated in Figure 4, by a linear

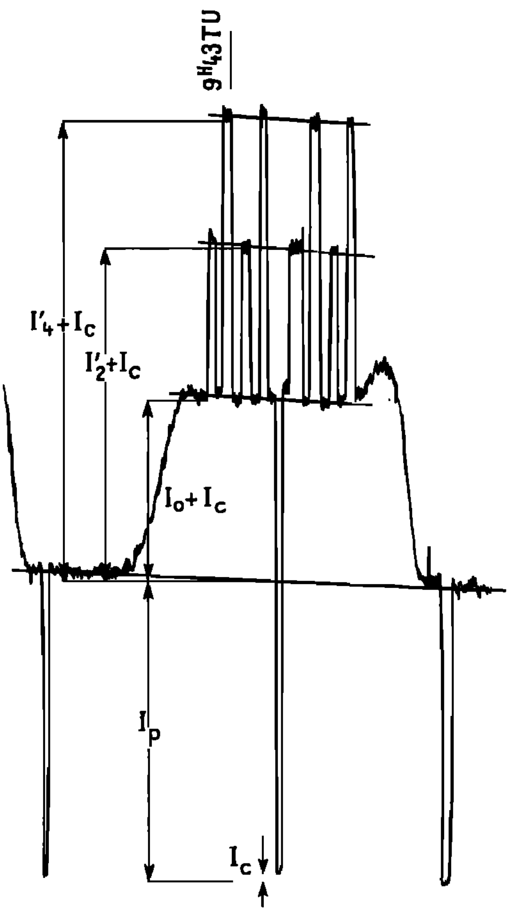

Fig. 5. Sample record October 18, 1960, 9h 43 UT, 32° angle of solar elevation.

interpolation between the measurements made before and after the heating of the oven.

If possible, the instrument is kept operating during twilight, and twilight measurement is made in the customary fashion, at 15° above the horizon and with the stop removed. Several times, however, the photometer has been shifted during twilight toward the pole, and Δ' has been inserted in front of L_1, so that the daytime signals can be compared directly with the twilight signals.

At the beginning and at the end of the day the instrument is calibrated in terms of the white light source with fields of zero, 2000, and 4000 gauss. After correction for the factor given by this calibration (Fig. 2) the signals of interest, I_0, I_2', and I_4', become I_0, I_2, and I_4. The ratios I_0/I_4 and I_2/I_4 are then compared with the values 0.42 and 0.66 obtained from direct sunlight. I_0/I_4 is always larger than 0.42. Typically it is 1.1 or larger when the sun is just a few degrees above the horizon and then decreases toward a value between 0.45 and 0.65 at noon. A day-long sequence of measurements for the first day on which observations were made, September 21, 1960, is exhibited in Table 1. The dayglow signal I_{Na} is computed from equation 1 in terms of the recorder deflection. It will be seen in Table 1 that this signal rises rapidly with the elevation of the sun and eventually reaches a value near 35 mm toward noon. In twilight the corrected deflection when the sun is about 6° below the horizon is 4 mm, and so the dayglow signal is of the order of 10 times the twilight signal. This is greater by a factor of 5 than the theoretically expected value. The point will be discussed more fully in the following section.

Absolute intensity. To put the dayglow measurements in absolute units depends on the twilight calibration for this instrument. None of the standard methods of calibration may be used safely on an instrument of this sort, particularly when it is to observe light whose spectrum is severely distorted by various kinds of absorp-

TABLE 1. Measurements on September 21, 1960
Sunrise: 5h 23 UT
Sunset: 17h 37 UT
Evening twilight: Solar elevation, −6°
I_{Na} arbitrary, 4

Universal Time	Solar Elevation, degrees	I_0 Arbitrary	I_4 Arbitrary	I_0/I_4	I_0/I_4 −0.42	I_{Na} Arbitrary
5 26	0.5	23	20.2	1.14	0.72	14.5
5 42	3	24	27.8	0.86	0.44	9.3
5 50	5	57	0.58	0.98	0.56	33
6 24	10.5	32	45.5	0.70	0.28	13
6 52	14.2	54	65	0.83	0.41	27
7 37	21	66	86	0.77	0.35	30
11 19	43	96	151	0.63	0.21	33
11 49	43	104	161	0.65	0.23	37
14 53	32	72	101	0.71	0.29	29
14 57	28.5	76	101	0.75	0.33	33
15 09	26.7	72	93	0.77	0.35	33
15 48	21	69	83	0.82	0.40	33
16 26	12.8	64	73	0.88	0.46	34
16 41	10	58	64.5	0.90	0.48	31
17 14	3.3	42	42.8	0.98	0.56	24
17 28	1.5	15	18.3	0.82	0.40	7.3
17 30	1	11	12.6	0.87	0.45	9

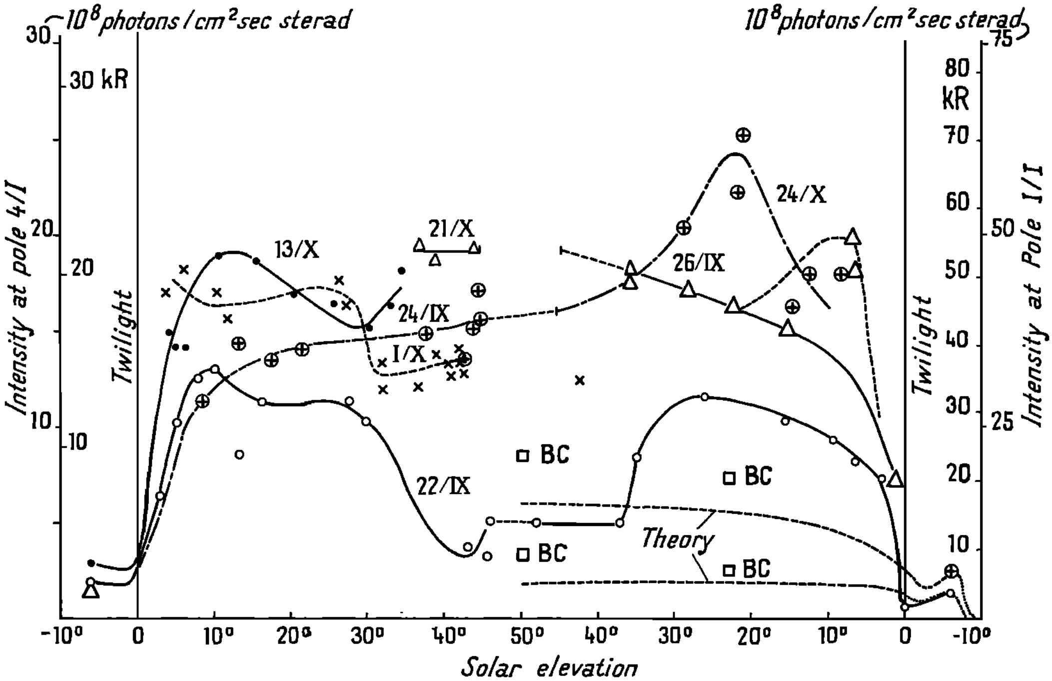

Fig. 6. Observed sodium dayglow and twilight intensities. The scale on the right is the old one from the calibration based on equal amounts of sodium day and twilight. On the left is the scale based on 4 times as much sodium in the daytime. The intensities in kilorayleighs ($\mu 4\pi I$, where μ is 0.67) are reduced to the zenith. The theoretical curves are to be used with the scale to the right and are those for the twilight abundances, in 10^9 atoms/cm², given by the twilight glow of September 24 and 22. The calculations of Brandt and Chamberlain (*BC*) are shown for the same abundances.

tion, reflection, and multiple-scattering processes. For the sake of calibration the data for many hundreds of twilight observations have been fitted to a family of curves giving intensity versus angle of solar depression as calculated from a theory of the twilight flash developed by Donahue and his collaborators [*Donahue and Stull*, 1959].

That calculation is based on a model in which the sodium in a uniform spherical shell 85 km above the earth varies vertically as a gaussian distribution of 7-km width. Resonance absorption, multiple scattering both in the sodium layer and in the troposphere, and reflection at the surface of the earth are taken into account. As a consequence of resonance absorption in the long path through the sodium which the sunlight must traverse in twilight the variation of intensity with sodium abundance exhibits a maximum. As a function of the angle of solar depression the intensity has a minimum at about 2°, after which it increases to a maximum at about 6.5°. The rate of increase in intensity with angle divided by the intensity at 6.5° is a dimensionless parameter characteristic of the abundance (or of the intensity). It is to the curve giving this parameter as a function of the twilight intensity that the experimental values of the parameter are fitted and thus the response of the instrument is converted into absolute units of intensity (see Fig. 15).

The dayglow intensities obtained by means of this calibration are plotted as a function of the angle of elevation of the sun[2] in Figures 6, 7, and 8. For days on which they are available the twilight intensities toward the pole are also plotted. Even if the absolute calibration is in error the relative values are correct.

[2] The angle should be the angle of elevation of the sun for the point where the line of observation intersects the sodium layer. Unless the layer is very high this does not differ significantly from the angle at the observatory.

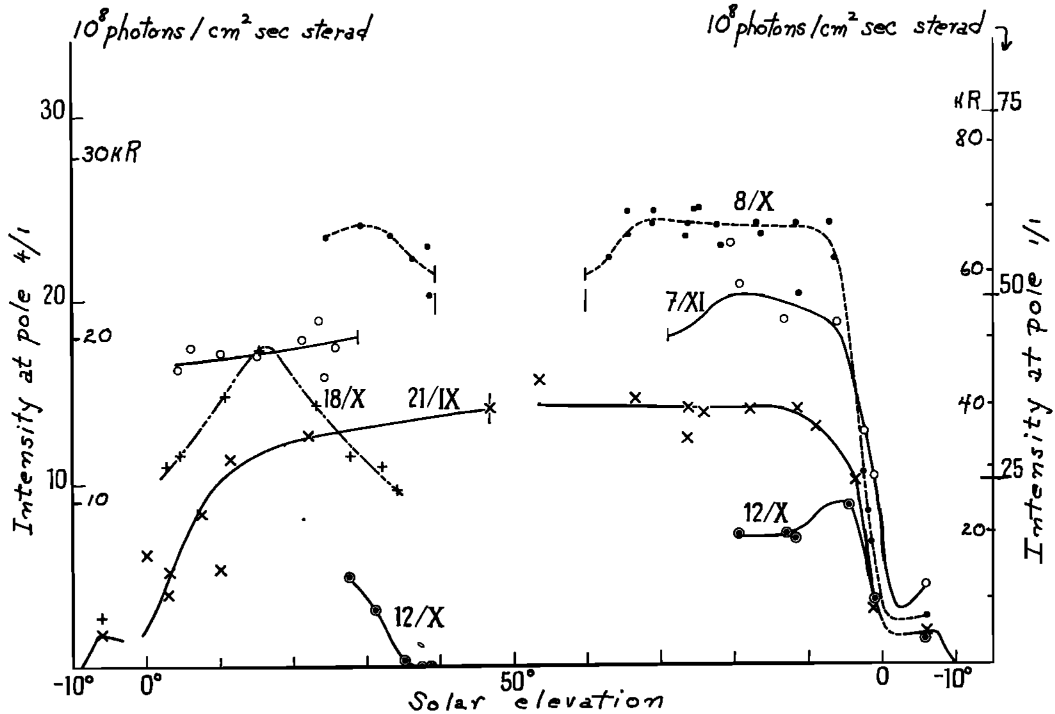

Fig. 7. Observed sodium dayglow and twilight intensities.

A particularly curious feature of the observations which appears only sometimes is the large peak at about 10° angle of solar elevation. But also very surprising is the generally very large intensity of the emission. It is inevitably far above the value expected for the sodium abundance determined from the corresponding twilight observations.

Theories of the Dayglow

There have been two attempts at calculating the sodium dayglow intensity, one by *Donahue* [1956*a*] and the other by *Brandt and Chamberlain* [1958]. The approaches are the same as those followed by Donahue and Chamberlain respectively in their treatments of the twilight glow. Donahue uses a spherical shell geometry and computes in turn the contribution of single scattering, single scattering after reflection, and higher orders of multiple scattering including reflection. The technique is presented in detail in a paper by *Donahue and Stull* [1959], and results for single scattering and reflection are in papers by *Donahue, Resnick, and Stull* [1956] and by *Donahue* [1956*a*].

The dayglow intensity at the zenith has been computed from the formulas given by *Donahue and Stull* [1959]. The results are plotted for several angles of solar elevation in Figure 9 as functions of the vertical optical thickness of the layer, τ_0. An albedo of 50 per cent was assumed, and the contributions of multiple scattering as well as of reflection were taken into account. The intensity plotted is for unit incoming solar intensity. For each hyperfine line in the dayglow and for any desired value of the abundance L_{Na} the appropriate intensity may be found by computing the optical thickness for each hyperfine component,

$$\tau_0(D_{2a}) = 8.94 L_{Na} \times 10^{-12}$$

$$\tau_0(D_{2b}) = 5.53 L_{Na} \times 10^{-12}$$

$$\tau_0(D_{1a}) = 4.47 L_{Na} \times 10^{-12}$$

$$\tau_0(D_{1b}) = 2.72 L_{Na} \times 10^{-12}$$

reading off the appropriate intensity from Figure 9 and multiplying each of these by the intensity of incident sunlight given in Table 4 of the paper by *Donahue and Stull* [1959].

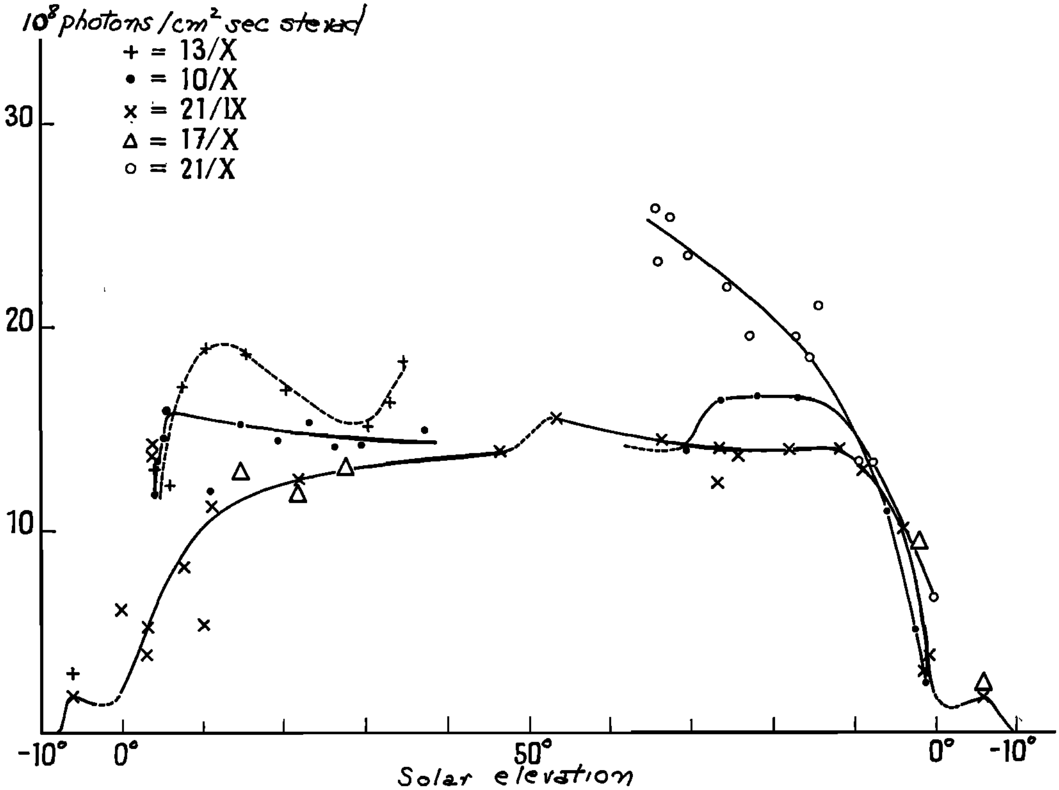

Fig. 8. Observed sodium dayglow and twilight intensities.

Such a computation leads to the curves of Figure 10, which show the intensity toward the pole at Haute-Provence. The expected intensity toward the pole is also plotted in Figure 6 for 4×10^9 atoms/cm² and for 14.6×10^9 atoms/cm², corresponding to two values of abundance found during twilight.

The ratio D_2/D_1 may readily be computed from the subtotals obtained from the addition of hyperfine intensity components. The result as a function of angle of solar depression and as a function of abundance is presented in Figure 11.

The calculation by Brandt and Chamberlain makes use of the radiative transfer theory of Chandrasekhar for a plane layer infinite in extent in two dimensions above a diffusely reflecting plane surface. This layer is taken to be illuminated from above at selected angles corresponding to various angles of solar elevation and observed from below at various angles of observation. The results are presented for different assumptions about albedo. We show in Figure 6 their calculated intensities for 50 per cent albedo. They obtain considerably more dayglow than Donahue but not enough to remove the fundamental conclusion that a disagreement exists between the dayglow intensities observed and those expected from the twilight observations. In the paper by Donahue and Stull reasons are given why the Chamberlain calculation should predict more scattered photons than the Donahue calculation. It is interesting that the total intensity computed by Brandt and Chamberlain for a 64° angle of solar elevation is greater than that given by the simple single-scattering approximation which neglects all absorption. Chamberlain (private communication, 1961) has pointed out that this is a consequence of large multiple-scattered contributions from photons originally scattered in the plane of the sodium layer for the plane parallel layer that these authors use.

Ratio of Daytime to Twilight Sodium Abundance

The conclusion from this comparison of dayglow and twilight intensities appears to be that

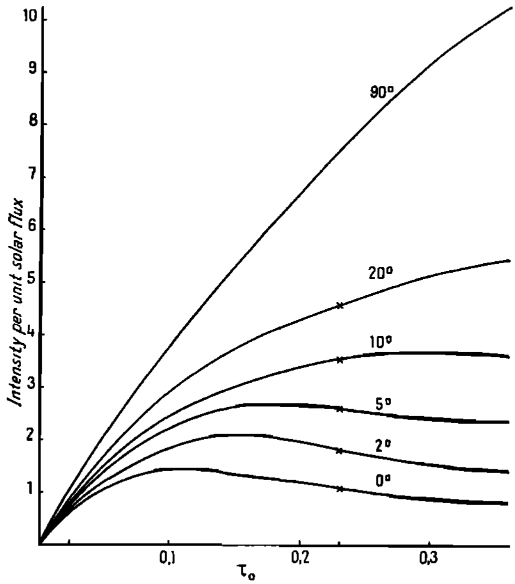

Fig. 9. Intensity at the zenith per unit solar flux in the dayglow as a function of the optical thickness (vertical) at the center of a sodium hyperfine component. Parameter: angle of solar elevation.

there is considerably more sodium during the day than during twilight, at least for the period of these observations, September to November 1960, and at this observatory. In fact, this seems to be true even when the sun is less than 5° above the horizon. If so, our previous conclusions about sodium abundance in twilight are incorrect.

The calibration of the photometer was based on a theory that assumed a 1/1 ratio of daylight and twilight sodium. An increase in this ratio would, for a given twilight abundance, reduce the twilight intensity and also increase the slope of the twilight curves. Of course, this is on the assumption that the abundance is not varying markedly for solar elevations between 4.5° and 6°. Hence a given ratio of slope to intensity would correspond at once to less twilight sodium and to less intensity than in the 1/1 theory, and so the sensitivity of the photometer would have been severely overestimated.

Calculations of the twilight intensity expected at 6° and at 4.5° angle of solar depression have been made for models involving more sodium on the day side of the earth than on the twilight side. The calculations can ignore what happens between +4.5° and −4.5° angle of solar elevation. This calculation follows the same lines as the calculation discussed by Donahue and Stull. There is no formal difference; only the calculation of L_1, the thickness of sodium traversed between the sun and the scattering volume, is changed. For a layer containing four times as much daytime as twilight sodium the results for $D_1 + D_2$ and for D_2/D_1 at 6° and 4.50° are presented in Figure 12 along with the corresponding curves for the uniform layer. The maximum permissible signal at 6° solar depression, for a zenith angle of 75°, is reduced from 15.6×10^8 photons/cm² sec sterad to 5.2×10^8 (1.9 kR reduced to the zenith), and the twilight abundance of maximum intensity is reduced from 25 to about 9×10^9 atoms/cm². D_2/D_1 is considerably reduced for a given abundance, or twilight intensity, and thence the expected correlation between D_2/D_1 and plateau intensity is considerably altered.

The intensity at 6° is plotted in Figure 13 as a function of the relative amount of daytime and twilight sodium for various values of the twilight abundance between 2 and 20×10^9 atoms/cm². These curves are for observations at a zenith distance of 75°. In combination with the curves

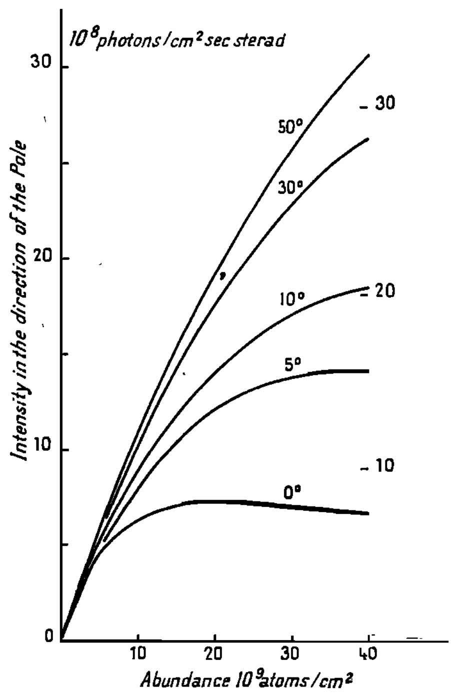

Fig. 10. Dayglow intensity toward the pole at Haute-Provence (1.5 times vertical intensity) as a function of sodium abundance. Units at the right are kilorayleighs toward the zenith.

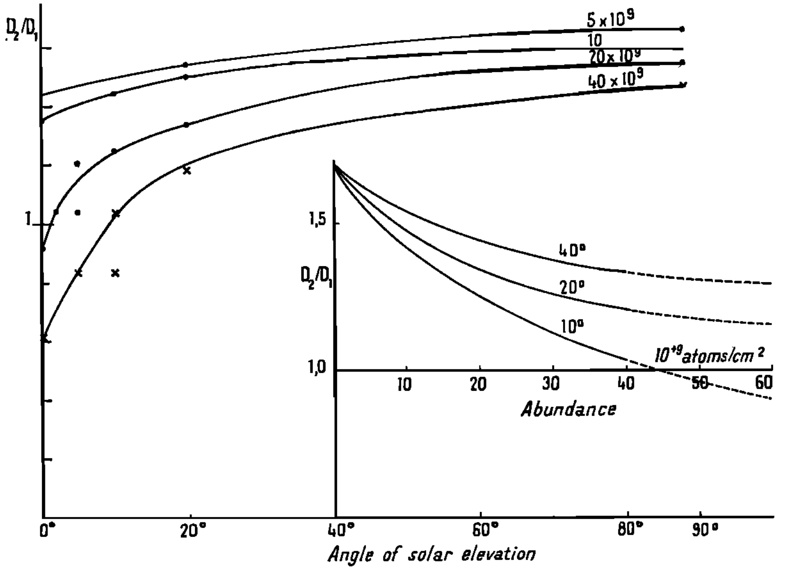

Fig. 11. D_2/D_1 during the day.

of Figure 10 for the dayglow intensity they permit us to determine what should be the relationship between the dayglow intensity at, say, 30° solar elevation and the twilight intensity at −6° for various assumptions about the relative abundances in day and twilight. Curves showing this relationship are presented in Figure 14. The peculiar form of these curves is a consequence of the fact that both twilight and dayglow intensities have maxima as functions of abundance.

Now it is a striking feature of the results obtained and most strongly in support of the identification of I_{Na} with sodium that there exists a strong correlation between I_{Na} and the twilight intensity for the same half day. In Figure 14 we plot the intensity observed toward the pole at 30° angle of solar elevation against the twilight intensity observed 15° above the horizon for 6° angle of solar depression. The correlation is the same as that expected for a ratio of 4/1 in the daytime and twilight abundances at least for September and early October. We can conclude then that the sensitivity of the photometer is 0.435×10^8 photons/cm² sec sterad per millimeter recorder deflection with the diaphragm Δ' in place. This is about 2.5 times smaller than the factor previously used. The previous calibration of the photometer was based on an evaluation of the quantity $(\Delta I)/I_M = [I(6°) - I[4.5°)]/I(6°)$ and a comparison of this quantity plotted against $I(6°)$ with the theoretical function derived from a 1/1 theory. In Figure 15 it can be seen that the effect of the introduction of a 4/1 ratio of day to twilight sodium on this quantity is indeed to squeeze the intensity scale by a factor of 2.5.

When the observed intensities I_{Na} are put on an absolute scale on the basis of the correlation in Figure 14 they frequently vary during the day in a fashion agreeing very satisfactorily with theory. This is illustrated in Figure 16 for several cases selected from the curves of Figures 6, 7, and 8. The predicted twilight intensities for a 4/1 model are also indicated along with those observed. About half the time the intensity increases with the elevation of the sun as expected for a uniform and constant sodium abundance, at least until the sun is fairly high. The departure from the high-abundance values of daytime occurs when the sun is very low, apparently below 5°. Note on September 21, for example in the evening where the intensity corresponds to 15×10^9 atoms/cm² at 3.6° angle of elevation but has dropped to about 4×10^9 atoms/cm² at 0.8° and is 3×10^9 atoms/cm² in twilight. On September 22 the intensity remains on the 11×10^9 atoms/cm² down to 2.7°; at 0° it is very low; and in twilight, 2×10^9 atoms/cm².

On other days the intensity does not increase during the day in anything like the expected

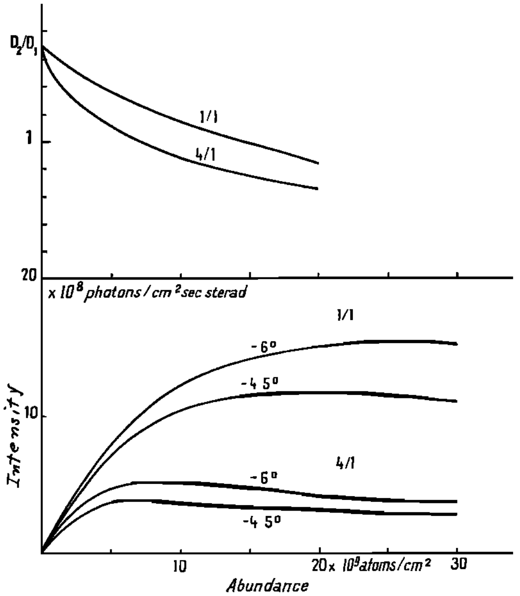

Fig. 12. Intensity in twilight as a function of abundance at 6° and 4.5° solar depression for two models, one with equal amounts of sodium on both sides of sunset and sunrise, the other with 4 times as much in the day. D_2/D_1 is also plotted at $-6°$ for the same models.

fashion. In place of the slow increase with angle the observed intensities frequently are observed to increase very rapidly at low solar elevation but then to flatten out or even to decrease again sharply toward midday. The reason for this behavior remains obscure. The most promising possibility is that it is associated with water vapor absorption near the center of the D_2 line with a peak of absorption occurring near noon. Experiments are in progress to assess the exact role that water vapor plays in the phenomena reported here. It is to be noted, however, that if such absorption has severely reduced the intensity near 30° angle of solar elevation the deductions from Figure 14 are false and an even greater daytime–twilight ratio is possible. This is suggested also by the fact that on the days when the observations fit the theory even up to 30° the ratio of the day to twilight appears to be higher than 4/1.

Of course, great irregularities are to be expected. A variation in albedo is sure to occur, and that will change the intensity considerably. Furthermore, from twilight observations [*Donahue and Blamont*, 1960] we know that the sodium is very likely distributed in great clouds 1000 km or so in extent moving aloft at the speed of the very high winds at those levels. Thus it is not surprising to find frequent departures from a smooth variation. However, the low values through the middle of the day, particularly compared with the theoretical increase, appear to have a strong tendency to recur regularly. Consider, for example, the results for September 22 and October 1, 8, 10, 12, 13, and 18. Moreover, these values are mainly for October and account for most of the points off the theoretical curve of Figure 14 for a 4/1 ratio.

During late October and November the twilight intensity increased toward the usual autumn maximum. From Figure 14 it can be seen that apparently this increase in twilight abundance is not accompanied by an increase in the daytime abundance, so that the ratio has decreased first to about 3/1 and in early November to about 1.5/1, with 32×10^9 atoms/cm² in daytime, 20×10^9 atoms/cm² in twilight, and a twilight flux of 3.7 kilorayleighs reduced to the zenith. Of course, data are extremely sparse as yet, and these indications are to be taken very lightly until there is much more firm evidence. Furthermore, if it is assumed that some mechanism such

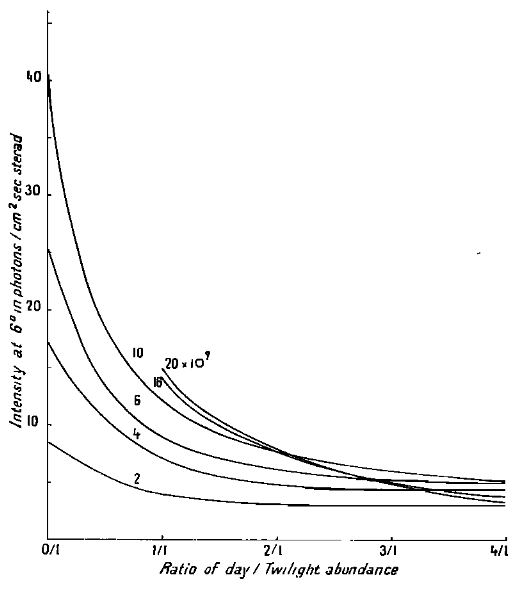

Fig. 13. Twilight intensity at $-6°$ for various abundances as a function of the relative amount of day and twilight sodium. Parameter is abundance in 10^9 atoms/cm².

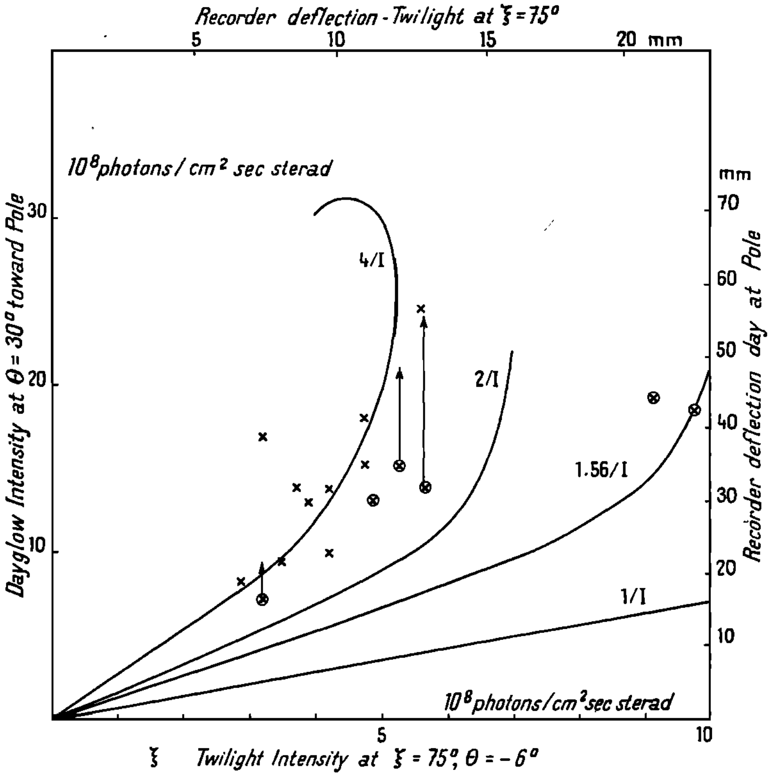

Fig. 14. Dayglow at 30° toward pole at Haute-Provence compared with twilight at 75° zenith angle for various ratios of day to twilight sodium. The points plotted are the recorder deflections observed for the same conditions. Circled points are for late October and November. Arrows indicate where the points would be if initial trend of dayglow were continued to 30°.

as water vapor absorption is reducing the intensity near 30° during October as discussed above, and if the initial rate of increase with angle is extrapolated to 30°, even the late October points would lie very close to the 4/1 curve, as is indicated by the arrows in the figure.

Other Experimental Results

No correlation with Rayleigh scattering. In contrast with the correlation found between I_{Na} and the twilight flash intensity there is no correlation between the intensity attributed to sodium and the total signal recorded with 4000 gauss on the sodium cell (Fig. 17). This total would be almost entirely caused by Rayleigh and Mie scattering. Thus it appears that what has been extracted as presumably sodium emission from the intensity observed with zero field contains no important component arising from other scattering processes.

D_2/D_1 ratio. In principle the measurement of the ratio D_2/D_1 during the course of the day would provide another method of verifying that a true dayglow is being observed, of measuring the abundance, and of settling the question of the origin of the intensity maxima at small angles of solar elevation. D_2 and D_1 may be observed separately by means of the magnetic scanning photometer with the help of a quartz filter placed in front of $L_1 + \Delta'$ (Fig. 1). This consists of a quartz plate 4 by 4 cm placed between an analyzer and polarizer. The thickness of the plate is such that it is a wave plate for one of the lines and a half-wave plate for the other.

The temperature of the filter is maintained within 0.01°C of a predetermined value by a platinum contact thermometer relay and heater. The temperature is determined before each experiment by viewing a sodium source through the filter with a spectrograph. The quartz plate

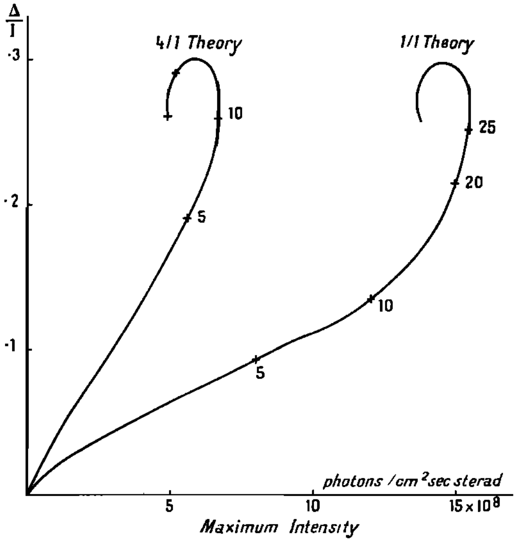

Fig. 15. The theoretical relative slope of twilight glow as a function of maximum intensity for two models.

has been cut in two as suggested by *Lyot* [1944], and one half of it has been rotated through 90° so as to increase the field of view. Behind the analyzer is placed a quarter-wave plate with neutral lines at 45° with the polarizer plane in order to ensure that the Zeeman components are excited independently of the orientation of the polaroids. Rotation of one of the polaroids through 90° selects D_2 or D_1 for transmission. This system has been used on a number of occasions to measure the D_2 and D_1 intensity during the day. Aside from the interpositions of the quartz and polaroid the experiment proceeds as has already been described. The cycle described above must be repeated for each fine-structure component and for $D_2 + D_1$ as well. Thus, owing to the vitiating effect of the passage of the lightest film of cloud on the observations, the number of measurements available is very small. The difficulty is increased by the much longer time that must elapse between measurements of the zero (shutter closed and oven cold). The intervention of the filter greatly reduces the signal so that the multiplier must be operated with the greatest available dynode voltage. Even then the signal-to-noise ratio is large. The measurements available for one day are presented in Table 2.

The D_2 and D_1 intensities measured contain contributions from resonance scattering and from Rayleigh scattering. The method employed on the total intensity $D_2 + D_1$ to disentangle the two effects cannot yet be used for the hyperfine components separately, since we have not yet used the scanning photometer to observe the spectrum of direct sunlight for the two components independently. Hence the D_2/D_1 ratios

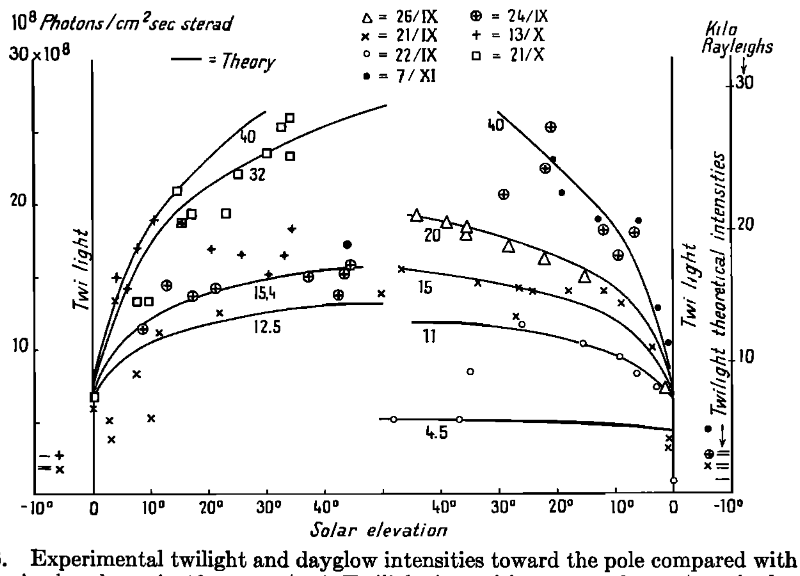

Fig. 16. Experimental twilight and dayglow intensities toward the pole compared with theory. Parameter is abundance in 10^9 atoms/cm². Twilight intensities expected on 4/1 ratio day to twilight are indicated by horizontal lines. Mornings are to the left.

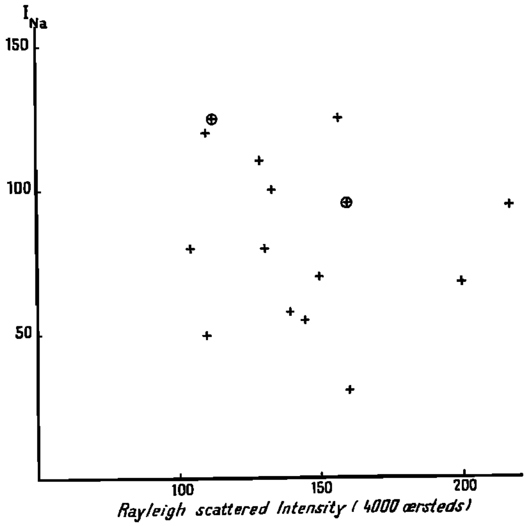

Fig. 17. Sodium dayglow signal compared with corresponding intensity measured at a magnetic field of 4000 oersteds.

reported are for the sum of the contributions of dayglow and Rayleigh scattering. They have been corrected for the instrumental response, which is different for D_2, D_1, and $D_2 + D_1$. This correction is obtained from observations made with a white light source replacing the sky. It is to be noted that the ratio does vary and that it does differ from 0.85. This is approximately the value measured by *Scrimger and Hunten* [1955] for direct sunlight and deduced by *Donahue and Stull* [1959] from *Priester's* [1953] observations on the Fraunhofer lines.

Discussion

The possible role of water vapor absorption. Since there is water vapor absorption in the neighborhood of the D_2 line, the possibility must be considered that a variation in water vapor absorption during the day is responsible for the effects observed. This might be so if the absorption affected the wings of the D_2 line more than the center and thus caused the ratio I_0/I_4 to be higher than that found on the one occasion for direct sunlight. Against this it may be argued that the ratio is lowest at midday when the vapor pressure is expected to be highest, that a strong correlation is found between the supposed dayglow radiation and the twilight flash, and that toward midday the D_2/D_1 ratio appears to increase rather than decrease.

On the other hand, it would indeed be a comfort to be certain about the part played by water vapor in the phenomena observed. Several experiments are in course to settle this question.

Comparison with absorption measurements. The only earlier observations providing evidence of the amount of sodium in the daytime are those of *Scrimger and Hunten* [1955]. These authors observed the effect of absorption by terrestrial sodium on the Fraunhofer lines during the course of the day, from which they could deduce the amount of sodium present. It is extremely interesting that on two of the three occasions on which they were able to compare twilight and daytime abundances they obtained two to three times as much sodium during the daytime. When their results are corrected for absorption and multiple-scattering effects and for the fact that the hyperfine components in the absorption lines are resolved, they give the abundance shown in Table 3. In general, the daytime abundances they find appear to be rather less than those obtained in our study. Their study, however, covers essentially only the months of January and February (with two observations in April) whereas ours are for September to November. Also entirely different geographical situations and different latitudes are involved. There is abundant evidence that the sodium does not behave in the same way at Saskatoon and at Haute-Provence.

Another curious point is that the Saskatoon results, obtained as they are during the winter at a latitude 52°N, are for very small angles of

TABLE 2. D_2/D_1 Ratio, October 21, 1960

	I_0/I_6 − .42	I_{Na}, photons/cm^2 sec sterad	D_2/D_1
6h 50	.28	16 × 10^8	0.86
7 08	.23	16	
7 40	.27	25	0.54
7 46	.25	22	
8 00	.26	23.5	
8 40	.27	23.5	0.95
9 05	.34	26.5	
9 54	.33	28.3	1.31
10 28	.40	33.0	
11 15	.33	23.7	1.15
11 29	.37	34.3	
11 56	.48	36.7	0.76
16 40	.09	8.3	1.25

TABLE 3

Date	Twilight	Daytime*
Jan. 9, 1956	3.3 or 6 × 10^9 atoms/cm^2	10.5 × 10^9 atoms/cm^2
Feb. 28, 1956	4.6 × 10^9 atoms/cm^2	8.3 × 10^9 atoms/cm^2
April 14	1.6 × 10^9 atoms/cm^2	1.1 × 10^9 atoms/cm^2

* These values depend of course on the choice of absorption coefficient, concerning which there still remains considerable doubt.

solar elevation. Since the abundance begins to be reduced rapidly for elevations less than 5° it is interesting that elimination of points taken at such elevations from the data of *Scrimger* [1956] would lead almost invariably to much greater values for the abundance deduced from the absorption data.

Effect on twilight flash observations. The likelihood that the quantity of sodium during the day—even shortly before sunset or just after dawn—at least in some places and at some times, differs from that existing during the night and during twilight, changes many aspects of the sodium problem completely. Not only is the old measurement of intensity and thence of sodium abundance during twilight incorrect at Haute-Provence, but even at Saskatoon where the intensity measurement is correct the abundance deduced from it would be too low if the quantity of sodium for small angles of solar elevation is also extremely large there. Of course, intensities larger than those permitted on a 4/1 model are observed at Saskatoon during midwinter; but nothing at all is known yet about the geographical distribution of daytime sodium, and indications are that the ratio of day to twilight abundance declines as we go toward winter months. The possibility must now be entertained that some part of the annual intensity variations observed during twilight reflects inversely a variation in daytime sodium abundance. A similar state of affairs exists for the D_2/D_1 measurements. Thus the values of D_2/D_1 found by *Jones and McPherson* [1958] during late summer, considerably lower than expected on the basis of the uniform layer theory during the season of low intensity, could be explained by the presence of a quantity of sodium during the daytime larger than that at twilight. A similar state of affairs has been reported also by *Lytle and Hunten* [1959]. A systematic tendency for D_2/D_1 to be lower than the value expected from the intensity measurement on the basis of the uniform layer theories can be taken as evidence for a systematically asymmetrical distribution of sodium of the sort discussed here. The magnitude of the effect can be estimated from the curves of Figure 12.

Altitude. The altitude of the sodium that so quickly forms in the presence of sunlight remains almost completely unknown and difficult to determine experimentally. The evidence is that it is not very much lower than the twilight sodium (no more than 20 km); otherwise it could not affect the twilight intensities. Various experiments to determine this altitude are being considered.

The time constant. The extremely short time during which the sodium builds up or disappears, of the order of 15 minutes, is very surprising. But what is striking is that this is the same time constant found in artificial sodium cloud experiments for the disappearance of sodium [*Blamont and Donahue*, 1960] in the upper atmosphere. There is an important difference, however. The rocket experiments are performed in twilight and the artificial cloud is definitely in the shadow as far as ultraviolet is concerned, whereas the sodium production with which we deal here seems to depend on the presence of ultraviolet. On the other hand, the artificial cloud experiments find the sodium between 100 and 150 km, whereas it is at least conceivable that the daytime sodium is produced below 100 km and that it begins to appear there after the production at those levels by ultraviolet of an atmospheric constituent, say atomic oxygen, always abundant above 100 km.

Alternative explanations. Among the possible alternative explanations of the effect observed here are two that seem to merit serious consideration. One is the possibility that water vapor absorption affects the wings of the D_2 line in a fashion that varies during the day, and hence increases I_0/I_4 and causes it to vary. We have already discussed this possibility and Hunten and Scrimger have also considered it in connection with their measurements and rejected it on two grounds. One was that D_2 absorption was about twice as strong as that of D_1. This is normal for sodium (it would be fortuitous for water vapor). The other was that the absorption was much stronger in winter when the water vapor pressure was lowest.

Another possibility is that the effect is a result of special instrumental features of the photometer. It has often been urged against this photometer that it is by its nature most sensitive at the center of the atmospheric lines and hence exaggerates all absorption effects since they affect this part of the lines most. Thus it can be said that the decreasing intensity obtained in early twilight by the photometer is more severe than it would be if all parts of the atmospheric line were weighted equally. This argument can be extended to embrace positive angles of solar elevation as well, for as the sun gets higher the self-absorption effect decreases and hence I_0 could be expected to increase relative to I_4.

No doubt this effect exists. The question is its seriousness. That it is of minor importance is demonstrated by the results obtained with a field of 2000 oersteds. This field shifts the Zeeman components well into the wings of the atmospheric lines. From Figure 3 it can be estimated that the ratio of I_{Na} at 2000 oersteds

$$I_{Na}(2000) = [(I_2/I_4) - 0.68]I_4 \qquad (2)$$

to I_{Na} at zero field should be about 0.35. From Figure 18, where I_{Na} and $I_{Na}(2000)$ are plotted for two days, it can be seen that this is approximately the ratio found. What is more important, since at 2000 oersteds the center of the lines in the cell are far removed from the centers of the atmospheric lines, is that both $I_{Na}(0)$ and $I_{Na}(2000)$ vary in the same way as a function of solar elevation. Furthermore, the ratio of the two signals is the same as that found in twilight. This can be seen from an illustration in the paper by *Blamont* [1956], in which the twilight intensity is plotted against magnetic field strength. After correction for white light response, the observed intensities in twilight are:

0 field	4.2 mm
2000 oersteds	2.1 mm
4000 oersteds	0.9 mm

This gives $I_{Na}(0) = 3.8$ mm, $I_{Na}(2000) = 1.5$ mm, which yields a ratio of 0.39 for the two signals as compared with 0.40 on October 18 in the daytime and 0.41 on October 13.

In other words, the results presented here

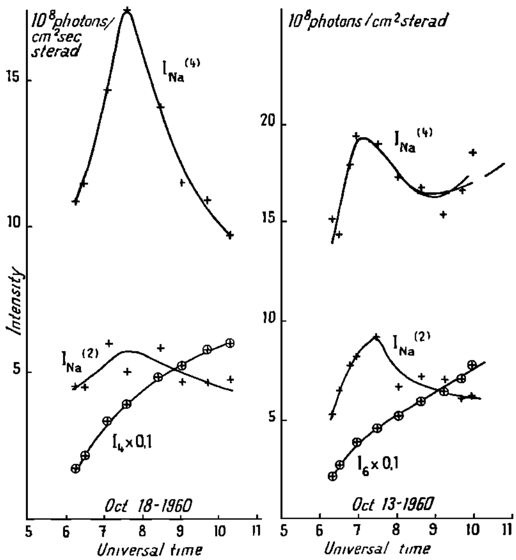

Fig. 18. Sodium dayglow intensities for zero and 2000 oersteds compared. Also total signal at 4000 oersteds.

would be identical if comparative signals at 2000 and 4000 oersteds had been considered rather than at 0 and 4000 oersteds. Therefore water vapor absorption can scarcely be responsible for our results, since it is altogether unlikely that the water vapor absorption line would so well simulate in width and in position a sodium emission at 200°.

Conclusions

1. From the fact that the ratio of intensity observed in scattered light at the bottom of the Fraunhofer D lines to that in the wings differs from that observed in direct sunlight, and from the fact that it varies during the day, we conclude that we are observing resonance-scattered light from sodium atoms in the upper atmosphere during the day.

We have shown that it is easy to extract the sodium signal from the contributions of other forms of scattering.

Support for the thesis that this is sodium dayglow is provided by the following facts: (*a*) the signal attributed to sodium dayglow is closely correlated with the intensity of the sodium twilight flash but not at all with the amount of Rayleigh and Mie scattering; (*b*) the D_2/D_1 ratio differs from that in the Fraunhofer lines and also varies during the day; (*c*) the same relationship with the twilight flash and the same diurnal variation are found if the light in what should be the wings of the atmospheric D lines is observed rather than the light in the center of the lines.

2. The dayglow signal is far stronger than would be expected relative to the twilight flash for the abundances deduced from the twilight flash, an intensity ratio of about 7/1 between day and twilight being found in place of about 2/1. We are forced to assume the presence of four times as much sodium in day as in twilight during September and early October 1960, and perhaps only about 1.5 times as much in November. Support for this assumption is provided by these facts: (*a*) the data then fit theoretical curves giving intensity as a function of solar elevation very well; (*b*) the ratio of day to twilight intensity varies as expected for a 4/1 ratio; (*c*) absorption measurements by Scrimger and Hunten also showed much more sodium in day than in twilight; (*d*) it can explain low D_2/D_1 values relative to intensity found during twilight.

3. If this is the case, however, all abundances deduced from twilight intensities and from D_2/D_1 measurements must be revaluated.

4. The altitude of the dayglow is not known but is probably between 50 and 100 km.

5. The sodium appears and disappears very rapidly—within 15 minutes when the sun is about 2° above the horizon. This small time constant is the same as found in studies of sodium clouds ejected from rockets in twilight above 100 km.

6. The hypothesis that the result is instrumental is not tenable. The possibility that it is attributable to water vapor absorption is small, especially since the variation during the day is opposite in phase to that expected from water vapor absorption. Nevertheless, considerable experimentation should be devoted to this possibility.

7. The dayglow radiation in sodium can be as strong as 30 kilorayleighs at the zenith, and the quantity of sodium as high as 40×10^9 atoms/cm^2.

Acknowledgments. We should like to express our appreciation of the help given by J. P. Schneider, Mlle M. L. Lory, and G. Charvet in obtaining much of the observational material reported here. A discussion of the absorption measurements with Professor D. M. Hunten was also most useful.

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