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A Method for the Interpretation of Ionospheric Absorption Measurements during the Sunrise Effect in the D-Region

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Summary: Results of A 3 observations in the LF range at medium latitudes before and during sunrise are described. For absorption variation during night-time and during sunrise at medium sunspot number, comparison is made between summer and winter. Generally, at constant R, the sunrise absorption increase is stronger in summer than in winter; it is very similar for propagation paths with different azimuths. At constant season, the sunrise absorption increase is stronger at $R_{\max}$ than $R_{\min}$, indicating at least at medium latitudes non-galactic high-energy particles being the principal ionization source, if there are no solar cycle aeronomic changes.

The classical O_2^--photodetachment model of the sunrise D-region is checked by calculating the electron concentration profiles which are needed to produce the observed summer sunrise absorption increase at medium sunspot number. The resulting theoretical electron concentration profiles, treated by full wave calculation, give the observed absorption variation at negative sun heights below $-4°$ ($\chi > 94°$), but they do not agree with rocket measured electron concentrations nor with the strength of at least the galactic cosmic ray ionization rate. From the differences, an additional negative ion species, not affected by light penetrating the ozone layer, should be assumed especially in the 70 to 90 km height range. Furtheron an additional free electron source is indicated by the sunrise absorption increase at negative sun heights above $-4°$ ($\chi < 94°$), possibly negative ions the electrons from which are detached by photons not penetrating the ozone layer.

Thus, for interpreting the sunrise behaviour of the D-region by electron detachment from negative ions, two ion species seem to be necessary: The first one being destroyed when visible light reaches the D-region, and causing the $\eta = -9°$ onset of sunrise effect in radio propagation whereas the electron from the second one is detached well above the ozone shadow.

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Zusammenfassung: Resultate von LF-A3-Absorptionsmessungen in mittleren Breiten vor und während des Sonnenaufgangs werden beschrieben. Die tageszeitlichen Variationen der Absorption während der Nacht und während der Dämmerung bei mittlerer Sonnenfleckenzahl werden für Sommer und Winter verglichen; es zeigt sich, daß die morgendliche Absorptionszunahme im Sommer stärker ausgeprägt ist und daß sie für Strecken verschiedener Richtung sehr ähnlich verläuft. Für die gleiche Jahreszeit ist der Dämpfungszuwachs bei Sonnenaufgang bei maximaler Sonnenfleckenrelativzahl stärker als bei minimaler. Falls aeronomische Änderungen an diesem Unterschied nicht wesentlich beteiligt sind, ist daraus zu entnehmen, daß mindestens in mittleren Breiten energiereiche Partikel, die nicht zur galaktischen kosmischen Strahlung gehören, als nächtliche Ionisationsursache dominieren.

Das klassische aeronomische Modell der D-Region (negatives Ion: O_2^-) wird geprüft durch Berechnung derjenigen Elektronenkonzentrationsprofile, die bei Annahme dieses Modells zur Deutung des morgendlichen Dämpfungsanstieges im Sommer bei mittlerer Sonnenfleckenzahl erforderlich sind. Die hierbei erhaltenen Profile geben bei der Durchrechnung nach der Methode der vollen Wellengleichungen den für negative Sonnenhöhen η ($\eta < -4°$, $\chi > 94°$) beobachteten Absorptionsanstieg richtig wieder, sie stimmen jedoch weder überein mit gemessenen Elektronenkonzentrationen, noch mit der Ionisationsrate der galaktischen kosmischen Strahlung. Auf Grund der Differenzen liegt die Annahme nahe, daß insbesondere im Höhenbereich 70—90 km ein weiteres negatives Ion existiert, dessen Elektron nur oberhalb des Ozonschattens vom Sonnenlicht abgespalten werden kann. Auch der Absorptionsanstieg für Sonnenhöhen $\eta > -4°$ deutet auf eine Quelle freier Elektronen hin, die oberhalb des Ozonschattens liegt.

Zur Deutung des Absorptionsverhaltens der D-Region bei Sonnenaufgang durch Photoelektronenabspaltung von negativen Ionen erscheinen somit zwei Arten negativer Ionen erforderlich: Ein Ion, das bereits bei Bestrahlung mit sichtbarem Licht Elektronen abgibt und den Einsatz des Absorptionsanstieges bei der Sonnenhöhe $-9°$ verursacht, und ein anderes, das erst oberhalb des Ozonschattens gespalten wird.

1. Observational results

Ionospheric A3-observations in the low-frequency range have been carried out at Kühlungsborn Ionospheric Observatory since 1948. This method has been proved to be very sensitive to many kinds of disturbances in the D- and lower E-region (Lauter et al. (1960), Lauter and Knuth (1967)), but in this paper we will examine the normal behaviour of the lowest part of the D-region during sunrise. This choice has been made with respect to the following aeronomic model considerations (section 2), which refer to negative sun heights permitting only photodetachment but no ionization by solar photons. Whilst the sunrise absorption increase is thought to be due to electron photodetachment from negative ions, the sunset decrease is not only due to electron attachment to neutrals, but also to recombining daytime ionization. Because these recombination processes are not fully understood, the sunrise is taken into consideration only.

The experimental results are mainly based on continuous steep incidence skywave-fieldstrength-measurements on 128.5 kHz in Kühlungsborn (Deccatransmitter Zeven, about 190 km west of Kühlungsborn, equivalent frequency 88 kHz, geographic coordinates of the reflection point: $\varphi = 53.7°$N; $\lambda = 10.5°$E; geomagnetic latitude $\Phi = 54.6°$N). At the receiver, the groundwave is suppressed by a loop aerial. During daytime the ionospheric skywave absorption amounts to 40 dB (winter) or 70 dB (summer). The absorption decreases with decreasing solar elevation angle η and reaches its minimum value of 14—16 dB during night.

1.1 Night time variation of absorption

In Fig. 1, the diurnal variation of absorption at great solar zenith angles is shown, plotted in the same way as by E. A. Lauter (1966). During summer at negative sun heights below — 10°, an absorption decrease is found, which changes abruptly into a relatively quick increase when at the path midpoint the sun height passes through about — 10° before ground sunrise. This early onset of absorption increase should be ascribed to photodetachment by sun light, because ionizing radiation can not penetrate into D-region at those sun heights. During winter, the picture is more complicated.

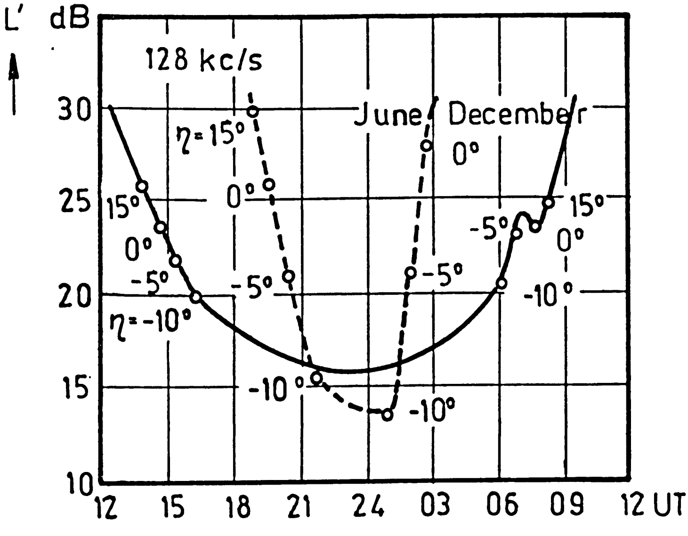

Fig. 1: Diurnal absorption variation at great zenith angles and during night; $f = 128,5$ kHz.

An absorption increase is found soon after midnight, when no direct sun light can reach the D- and lower E-region. During winter night there is more time for recombination, and perhaps the absorption increase after midnight may be caused by the beginning penetration of the radio waves into the lower E-region, or some yet unknown small ionization source (perhaps scattered Ly α or Ly β from the night sky). At $\eta \approx -10°$, the absorption increase becomes remarkably faster due to the ionospheric sunrise effect. A secondary minimum of absorption is found near ground sunrise, which is not present during summer.

1.2 Sunrise effects at medium sunspot number

Fig. 2 shows the mean behaviour of ionospheric absorption at sunrise on 128.5 kHz for all twelve months and medium sunspot number (mean from 1959—1963) from sunheight $\eta = -10°$ to $+10°$. For clearly separating the amount of sunrise effect in absorption itself, from all absorption values the $\eta = -10°$ value has been subtracted. It was supposed, that for $\eta < -10°$ the D-region is not affected by the sun in any way. Obviously the LF-sunrise effect is a very regular phenomenon. In the months April—November three distinct steps of absorption increase can be found, one at about $\eta = -8°$, the second at $\eta = -4° \ldots -3°$ and the third at $\eta = +3° \ldots +4°$. But in the months December—March only the first and third step occur. Obviously the third absorption increase at positive sunheights is due to increasing ionization under the influence of Lyman-Alpha and X-rays 1—10 A. This is in good accordance

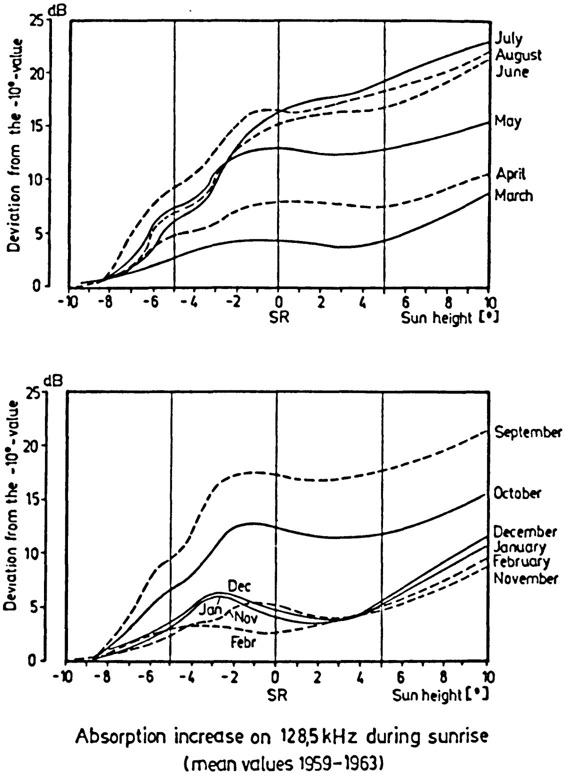

Fig. 2: Absorption increase on 128,5 kHz during sunrise (mean values 1959—1963). For the measuring path see Fig. 3. For clearly separating the sunrise effect, the — 10° value has been subtracted.

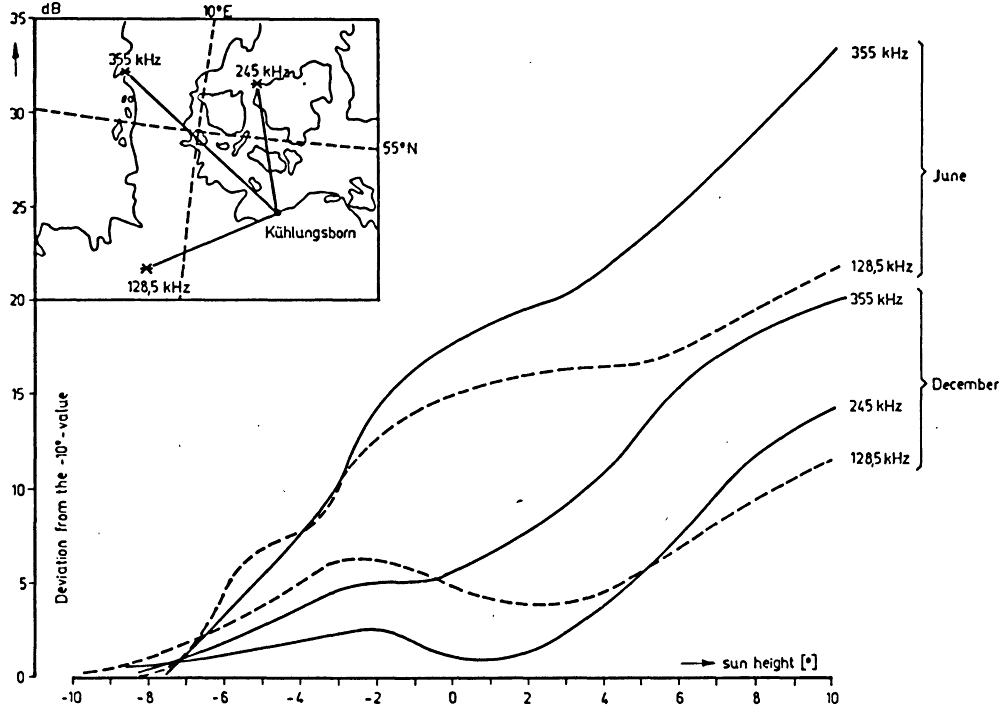

Fig. 3: Sunrise absorption increase on different frequencies and measuring paths. In spite of different path directions, the sunrise effects and their summer—winter differences are quite similar (the 245 kHz transmitter is off during sunrise in summer).

with the observations of sunrise effects by the SOLRAD-satellite, which indicate an effective shadow height for Lyman α of 80 km, that means it will be effective in the lower D-region only when $\eta > 0°$. The first and second absorption increases are not in the same way monotonically rising with η, but they reach saturation levels. Since it is highly improbable that these absorption increases are caused by a variation of the collision frequency, it has to be assumed that there is a change of electron density.

To exclude the possibility that these sunrise effects are a particular behaviour of a certain propagation path, Fig. 3 shows the sunrise absorption increases on the frequencies 128,5, 245 and 355 kHz. The geometry of the propagation paths is indicated. It can be seen that, in spite of the different propagation paths, the sunrise effects are very similar in general; the differing absolute absorption values are certainly due to the different equivalent frequencies. On 245 kHz the transmitter is off during sunrise in summer.

1.3 Comparison between sunrise effects at sunspot maximum and minimum

The sunrise absorption increases at $R_{\max}$ and $R_{\min}$ are shown in Fig. 4. Generally, the sunrise absorption increase is stronger at $R_{\max}$. Thus, at least at our latitude, high-energy particles from the magnetosphere may be a more effective primary ionization source than galactic cosmic rays, because the latter show the opposite variation with R. As can be seen from Fig. 4, the mean behaviour of LF sunrise effect during winter (December, January, February) and early summer (May, June, July) is very similar at $R_{\max}$ (November 1958—October 1960, $\bar{R} \approx 138$) and $R_{\min}$ (July 1963 to June 1965, $\bar{R} \approx 15$). But in both cases the absorption values of the first step in $R_{\min}$ reach only half the values of $R_{\max}$.

Perhaps the first absorption increase occurs a little later during $R_{\min}$, but this statement is not significant. The other months in Fig. 4 show clear differences between $R_{\max}$ and $R_{\min}$ apart from the above mentioned differences of absorption values. The second absorption increase at about $-4°$ sunheight from April to November is clearly marked only in the years with higher sunspot number; in $R_{\min}$ a second step is present only in May, June and July.

2. Aeronomic considerations

2.1 Introduction

Because the sunrise effects on long wave radio propagation occur at negative sunheights when no ionizing solar radiation can penetrate into the D-region those effects are conveniently ascribed to electron detachment from negative ions by low energy solar photons. It the two distinct steps of absorption increase are due to photodetachment from two different negative ion species, then the negative ion corresponding to the second step should be destroyed later, i. e. when photons with higher energy and

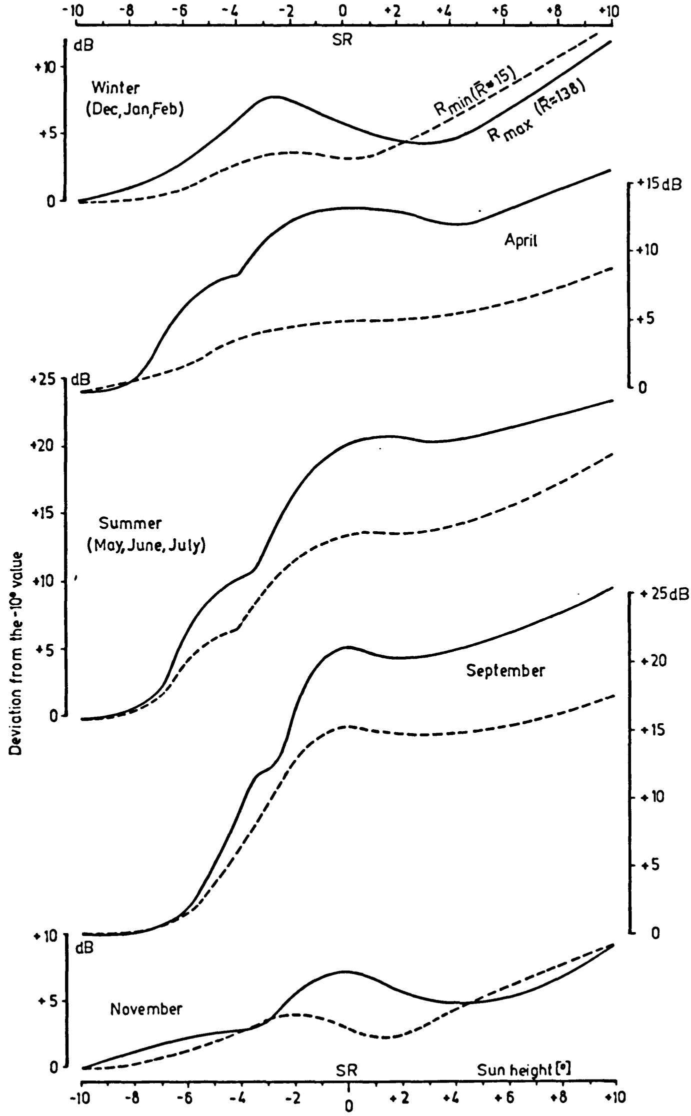

Fig. 4: LF-sunrise-effects (128,5 kHz) in years with high and low solar activity ($R_{\max}$ ———, $R_{\min}$ - - - - - -).

higher absorption coefficient in ozone penetrate into the D-region. According to the smaller amount of the sunrise absorption increase during winter, the negative ion concentration at the end of the night should be smaller than during summer. Here, the longer duration of the winter night, providing more time for recombination, might be regarded as a cause, but also true aeronomical changes are assumed to be present, because there is a remarkable time lag between season and amount of sunrise absorption increase (cf. Fig. 2).

In the following sections, the classical O_2^-, e^--model of the sunrise D-region will be checked by calculating the electron concentrations which have to be assumed if this model should explain the first step of absorption increase as observed during summer at medium sunspot number. The summer sunrise has been chosen because the absorption behaviour prior to the sunrise effect seems to be clearer during summer than during winter (cf. section 1.1 and Fig. 1). During winter, besides the sunrise effect, a different mechanism producing a small absorption increase is present soon after midnight. In summer, the sunrise seems to begin before this complicated situation could develop.

2.2 Basic model assumptions

a) Upper border of electron concentration versus height profile.

An intensity change of the sky wave may be produced by changing the electron concentration in the D-region as well as by changing the steepness of the electron concentration gradient at the lower border of the E-region. Now, distinct steps of absorption increase are found before ground sunrise, which are thought to be caused by electron-photodetachment. In order to find the electron concentrations which would have to be assumed if the whole sunrise effect should be explained by electron photodetachment in the D-region, at the lower border of the E-region a constant steep concentration gradient was assumed.

b) Negative ion species.

As to the D-region, the investigations carried out so far lead to the conclusion that in the D-Region the negative ions O_2, NO_2^- and, perhaps, O_3^- or CO_3^- may be present.

As a first attempt, the classical model assuming that the negative ion of the molecular oxygen O_2^- is the only negative ion existing in the D-region, has been considered. This ion was chiefly selected because of the approximate knowledge of the temporal change of the photodetachment and the numerous reaction coefficients measured in the laboratories.

Furtheron, the small electron affinity of O_2 enables visible light to detach electrons from O_2^-. Thus, ionospheric effects can be accounted for, which occur when the solid Earth's shadow passes through the upper D-region just below the lower border of the

E-region. E. g., at sunheight $\eta = -9°$, the height of the solid Earth's shadow would be about 80 km (without atmospheric refraction), whilst the shadow height of a 30 km thick ozonosphere would be ca. 110 km. Because at about $\eta = -9°$ generally a first small amount of absorption increase can be found (cf. Fig. 2), a negative ion species appears suitable, the electron of which can be detached by light penetrating the ozonosphere.

As to sunrise effects on radio propagation at negative sun heights, there is additional evidence from VLF observations. J. Rieker (1963) analyzed sunrise and sunset effects on long wave propagation over great distances, namely, Rugby-Neuchatel (GBR 16 kHz, 832 km) and Balboa-Neuchatel (NBA 18 kHz, 9000 km). Corresponding to each reflection point of these propagation paths, he observed a distinct step of phase advance during sunrise. For Rugby-Neuchatel (one-hop path) that step started, when $\eta = -8{,}33°$ at the reflection point, for Balboa-Neuchatel (five-hop path), the steps started when at their corresponding reflection points η was between $-10{,}7°$ and $-16{,}8°$. H. Volland (1964) investigated diurnal phase variations of the GBR (Rugby) signal as received at Berlin (16 kHz, 980 km). The amplitude and phase effects (sunrise) began when $\eta = -9°$ at the midpoint of the propagation path. This behaviour is found very regularly, the angle $\eta = -9°$ has been taken from monthly mean curves. (June and December 1962).

Sunrise effects at such great solar zenith distances have also been reported for special paths which were nearly parallel to the sunrise terminator, so that nearly a unique sun height applies to the whole path.

E. A. Lewis and J. E. Rasmussen (1962) observed the variation of the phase difference between receiver outputs at Derry N. H. and Hogback Mountain, Vt., the transmitter being NBA (Balboa, 18 kHz). Both propagation paths are about 4000 km long and are nearly parallel to the sunrise line in late October. In the example given, 22. 10. 1960, the sunrise phase transient began nearly at the time, at which the first sun rays reached an altitude of 80 km above Derry (this corresponds to a shadow height of the Ozonosphere of about 110 km).

G. B. Carpenter and A. L. Whitson (1965) report on observations of the NPG Signal (24 kHz, transmitter at Jim Creek, Washington) at Tracy, California (path length 1169 km). At 13. 3. 1964, the sunrise terminator was parallel to the propagation path. Sunrise effects started as much as 10 minutes before the shadow of the ozonosphere, the height of which was assumed to be 30 km, would have passed through a height of 90 km.

Generally, to explain the observations, one could think of e. g. sunrise effects in the D-region caused by visible light which can penetrete the ozone layer, or of propagation parameters being influenced by ionospheric effects occuring distant from the great circle path or reflection point. As to the latter case, this has been done e. g. by E. A. Lauter and K. H. Schmelovsky (1958) for VLF propagation at oblique incidence in relation to sunrise effects at negative sun-heights for the path Rugby (16 kHz)—Kühlungsborn as well as for atmospheric noise intensity.

As mentioned above, for explaining the LF steep incidence observations, our model has been based upon the first assumption, and as a first attempt the electron concentrations have been checked which would result if our first step of LF-absorption increase is due to photodetachment by visible sunlight only.

Thus the tentative aeronomic model has to take into consideration three components: the electrons (density n_e), the positive ions (density n_+) and the negative ion O_2 (density n_-). A model has been used taking into account the night-time ionization rate, three-body- and radiative attachment processes, the photodetachment process, the collision detachment process, the ion-ion recombination, and the electron-ion recombination process (for the special processes and rate coefficients see below).

c) Starting values of charged particle concentrations.

For solving the reaction kinetic differential equations, one must know the starting values of the concentrations before sunrise in the lower ionosphere. Here, a simplification is introduced, assuming that during night-time especially around sun height $\eta = -10°$ an equilibrium state is reached between electrons, positive and negative ions i. e.

$$\left(\frac{dn_e}{dt}\right)_{\text{night}} = 0, \quad \left(\frac{dn_+}{dt}\right)_{\text{night}} = 0, \quad \left(\frac{dn_-}{dt}\right)_{\text{night}} = 0 \tag{1}$$

2.3 Reaction kinetic equations

After sunrise this equilibrium is disturbed by the incidence of electromagnetic radiation from the visible and infrared spectral range. Thus a new process—the photodetachment process—adds to the loss-processes which diminish the number of negative ions. Since the energy and the flux of the radiation increases with increasing sun height, the photodetachment-rate also changes with time. By the photodetachment process the number of electrons increases, that of the negative ions decreases. The density of positive ions adapts itself to the new conditions. Taking into consideration the processes mentioned above, the electron density and the ion densities are governed by the equations

$$\frac{dn_e}{dt} = q(\text{night}) + (\zeta_{O_2} \cdot n_{O_2} + \zeta_{N_2} \cdot n_{N_2} + \varkappa) \cdot n_- - \omega_{O_2} \cdot n_{O_2}^2 \cdot n_e - \omega_{N_2} \cdot n_{N_2} \cdot n_{O_2} \cdot n_e$$
$$- \alpha_{O_2} \cdot n_{O_2} \cdot n_e - \iota_e \cdot n_+ \cdot n_e \tag{2a}$$

$$\frac{dn_-}{dt} = \alpha_{O_2} \cdot n_{O_2} \cdot n_e + \omega_{O_2} \cdot n_{O_2}^2 \cdot n_e + \omega_{N_2} \cdot n_{N_2} \cdot n_{O_2} \cdot n_e$$
$$- (\zeta_{O_2} \cdot n_{O_2} + \zeta_{N_2} \cdot n_{N_2} + \varkappa) \cdot n_- - \iota_- \cdot n_+ \cdot n_- \tag{2b}$$

$$\frac{dn_+}{dt} = q(\text{night}) - \iota_e \cdot n_+ \cdot n_e - \iota_- \cdot n_+ \cdot n_- \tag{2c}$$

and the condition

$$n_+ = n_e + n_- \tag{3}$$

The meaning of the symbols can be taken from Table 1.

The task is now to find from these equations those solutions $n_e(z, t)$ for which the calculated absorption values in dependence on time are in good agreement with the observed ones.

As mentioned above the photodetachment rate increases with time during the sunrise interval. A rough approximation for this dependence on time has been received in the following way. REID (1961) has calculated the photodetachment rate of O_2^- in dependence on a parameter h_0. The connection between this parameter, the height h, and the solar elevation angle η is given by

$$\cos\eta = \frac{R_e + h_0}{R_e + h}.$$

It is possible to transform the sunheights into local time-values for the special days considered here. Along this way the dependence of the photodetachment rate on local time can be calculated. REID has performed his calculations on the basis of a day-time photodetachment rate $\varkappa = 0.44\ s^{-1}$. Supposing the same qualitative form for the dependence of $\varkappa$ on time a rough approximative curve has been obtained for a daytime value $\varkappa = 0.1\ s^{-1}$.

For the solution of the equation (2) one needs the individual reaction coefficients. Many of them are not very well known. A review about the magnitude of the individual reaction coefficients has been given by NICOLET, SWIDER (1963) and WAGNER (1966). The calculations have been performed with some different combinations of reaction coefficients. One example is given in Table 1.

Table 1.

Reaction	Coefficient Symbol; Value		Reference
$O_2 + O_2 + e \Rightarrow O_2^- + O_2$	ω_{O_2};	$2 \cdot 10^{-30}\ cm^6/s$	VAN LINT, WYATT (1963) CHANIN et al. (1962)
$O_2 + N_2 + e \Rightarrow O_2^- + N_2$	ω_{N_2};	$1 \cdot 10^{-31}\ cm^6/s$	VAN LINT, WYATT (1963) CHANIN et al. (1962)
$O_2 + e \Rightarrow O_2^- + h\nu$	α_{O_2};	$2 \cdot 10^{-18}\ cm^3/s$	WAGNER (1966)
$O_2^- + O_2 \Rightarrow O_2 + O_2 + e$	ζ_{O_2};	$4 \cdot 10^{-17}\ cm^3/s$	NICOLET, AIKIN (1960) BAILY (1959)
$O_2^- + N_2 \Rightarrow O_2 + N_2 + e$	ζ_{N_2};	$10^{-18}\ cm^3/s$	WAGNER (1966)
$O_2^- + h\nu \Rightarrow O_2 + e$	$\varkappa$;	$0.1\ s^{-1}$ (daytime)	POPPOFF, WHITTEN (1963)
$O_2^- + A^+ \Rightarrow O_2^* + A^*$1)	ι_-;	$10^{-8}\ cm^3/s$	WHITTEN, POPPOFF (1964)
$A^+ + e \Rightarrow A^*$1)	ι_e;	$3 \cdot 10^{-7}\ cm^3/s$	WAGNER (1966)

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1) A may be a molecule or atom, A* may be an excited atom or molecule or a molecule just before dissociation.

The equations (2) with (3) have been solved assuming that the real ionisation rate q is known. This solution has been performed taking into consideration the facts that n_+ varies slowly, and that the ratio of negative ions to electrons $\lambda = n_-/n_e$ reaches the equilibrium values within a few seconds. For this reason an equation for λ has been used instead of (2b) as the third equation.

In order to solve the equations, it is necessary to know the real ionisation rate q. Since no radiation, which is able to ionize neutral particles, can penetrate into the D-region during the whole time from sunrise in 100 km to sunrise at ground, the real ionisation rate q is supposed to remain the same as it is during night-time. The night-time ionisation was first supposed to be equal to the ionisation rate by cosmic radiation as given by NICOLET (1958). With this assumption, however, it was not possible to explain the night-time absorption and, above all, the sunrise effects. Therefore, first of all, one has to determine the ionisation rate q (night) from a suitable night-time electron density distribution e. g. from the electron density distribution $n_e(z)$ for $\eta = -10°$. Assuming that during night-time the ionosphere has reached an equilibrium i. e. taking into consideration equ. (1) and (3) it is possible to determine q (night) from the formulae

$$\begin{aligned}\lambda = \frac{n_-}{n_e} = & -\frac{\zeta_{O_2}\cdot n_{O_2} + \zeta_{N_2}\cdot n_{N_2} + \iota_-\cdot n_e}{2\cdot\iota_-\cdot n_e} \\ & + \left\{\left(\frac{\zeta_{O_2}\cdot n_{O_2} + \zeta_{N_2}\cdot n_{N_2} + \iota_-\cdot n_e}{2\cdot\iota_-\cdot n_e}\right)^2 \right. \\ & \left. + \frac{\alpha_{O_2}\cdot n_{O_2} + \omega_{O_2}\cdot n_{O_2}^2 + \omega_{N_2}\cdot n_{N_2}\cdot n_{O_2}}{\iota_-\cdot n_e}\right\}^{1/2} \end{aligned} \tag{4a}$$

$$q\,(\text{night}) = (1+\lambda)(\iota_e + \iota_-\cdot\lambda)\cdot n_e^2 \tag{4b}$$

In the following investigations the determination of a suitable night-time electron density profile proved to be the major problem. Starting from this profile, electron density distribution $n_e(z, t)$ can be calculated in dependence on time. With these $n_e(z, t)$-profiles absorption curves $L(t)$ must be computed and compared with the observed ones in Fig. 1.

2.4 Full wave absorption calculations

The absorption calculation has been done by solving the four coupled linear differential equations for the four horizontal electric and magnetic field components as given by K. G. BUDDEN (1961):

$$\frac{d}{dz}e = -ik_0\,T(z)\,e \tag{5}$$

Here, e is a complex four-vector consisting of the four horizontal electric resp. magnetic components of the electromagnetic wave field, whereas $T(z)$ is a complex 4-4-matrix, depending on the height z. Two linear independent solutions of (5) have to be calculated starting with pure upgoing waves at a sufficiently high starting altitude.

To avoid "swamping" of the linear independent solutions by the non-penetrating upgoing wave, Pitteway's (1965) method of reorthogonalization has been used. From the solutions in the free space below the ionosphere, the ionospheric reflection matrix R is calculated.

$$R = \begin{pmatrix} R_{\parallel\parallel} & R_{\perp\parallel} \\ R_{\parallel\perp} & R_{\perp\perp} \end{pmatrix} \tag{6}$$

In the four components of R, the first resp. second index indicates the polarization of the upgoing resp. downgoing wave with respect to the plane of incidence. For the measuring path Zeven-Kühlungsborn, the transmitted upgoing wave is polarized parallelly to the plane of incidence. At the receiver, the groundwave is suppressed by a loop aerial system, the normal axis of which points to the transmitter, Thus, only that component of the downcoming wave is received, which is polarized vertically to the plane of incidence:

$$L_{\text{observed}} = -20 \log R_{\parallel\perp}(t) . \tag{7}$$

The task is to find such electron concentration profiles $n_e(z, t)$ which obey the reaction kinetic differential equations and give the observed $R_{\parallel\perp}(t)$ by full wave calculation. Besides the electron concentration $n_e(z, t)$ the electron collision frequency $\nu(z)$ is needed for calculating T. ν was firstly supposed to be independent on electron velocity (classical magnetoionic approach). For

$$\nu < \frac{\omega}{3}, \qquad \nu_{\text{eff}} = \frac{5}{2} \nu_M$$

was used, and for

$$\nu > 3\omega, \qquad \nu_{\text{eff}} = \frac{3}{2} \nu_M$$

was used to calculate T, ν_M being the collision frequency for mono-energetic electrons of energy kT. Lateron, the calculations were performed with velocity-dependent electron collisional frequencies (Sen-Wyller-theory). The change in absorption values found is within 10% (ca. 1 dB), which is meaningless with respect to the other uncertainties involved in the model. $\nu_M(z)$ was taken from Deeks (1966) and extrapolated parallelly to the curves of Hall and Fooks (1965) above 90 km. Since the full-wave theory deals with plane electromagnetic waves, an angle of incidence must be chosen. In the particular case of the sunrise D-region, reflection at the lower border of the E-layer has been assumed. The angle of incidence was therefore calculated from reflection height, which is supposed to be 95 km in this case, and transmitter-receiver distance, and checked by full-wave phase calculations.

2.5 $n_e(z)$ profile construction by trial- and error method

From the night-time electron concentration profiles $n_e(z, t_0)$, one gets the time-dependent profile $n_e(z, t)$ during sunrise by solving the reaction kinetic differential equations. From $n_e(z, t)$, the absorption $L(t)$ is calculated by the full-wave-theory. Both $n_e(z, t)$ and $L(t)$ were calculated by aid of computers. A first profile $n_{e,0}(z, t)$ was constructed using a simplified set of reaction kinetic equations (suppressing the recombination terms) as well as a simplified absorption calculation basing on the APPLETON-HARTREE-Formula. This $n_{e,0}(z, t)$ was adjusted to give the observed absorption variation $L(t)$ by applying the more sophisticated reaction kinetics including recombination, which are described in section 2.3 and the full wave absorption calculations discussed above. Since the concentration $n_e(z, t)$ turned out to be nearly proportional to $n_e(z, t_0)$ in spite of the non-linear recombination terms, and the absorption ΔL of an ionospheric slab was nearly proportional to n_e and the slab thickness Δz, the modification of $n_{e,0}(z, t)$ reduced to a linear procedure which could easily be accomplished using a desk-calculator.

3. Results and discussion

The resulting summer profiles (medium latitude, medium sunspot number) are shown in Fig. 5; observed and calculated absorption is compared in Fig. 6. As may be seen, the O_2-model can only interpret the first step of absorption increase between sun heights $\eta = -10°$ and $-4°$. For the second increase a free electron source may be responsible, which needs photons with higher energy and larger atmospheric absorption coefficients. As to the $n_e(z, t)$ profiles at $\eta = -4°$, a maximum is found near 65 km, similar to results found at $\eta = 0°$ by D. G. DEEKS (1966). In both cases the maxima remain nearly constant after sunrise, a feature which is to be expected in the medium latitude D-region. The special shape of the profiles near 55 km corresponds to the last part of the first step of absorption increase, if it is to be explained by electron photodetachment from O_2. The minimum around 85 km seems very deep. Eventually, other negative ions with higher electron affinities may be important in this region, giving other electron concentrations and producing by photodetachment the further absorption increase at negative sun heights above $-4°$, which is found regularly during summer. The photons producing the photodetachment of electrons from this second kind of negative ions do not seem to penetrate into these altitudes as long as the radiation must cross the ozone layer. That means: The second increase step in the absorption measurements may be due to photodetachment of electrons from negative

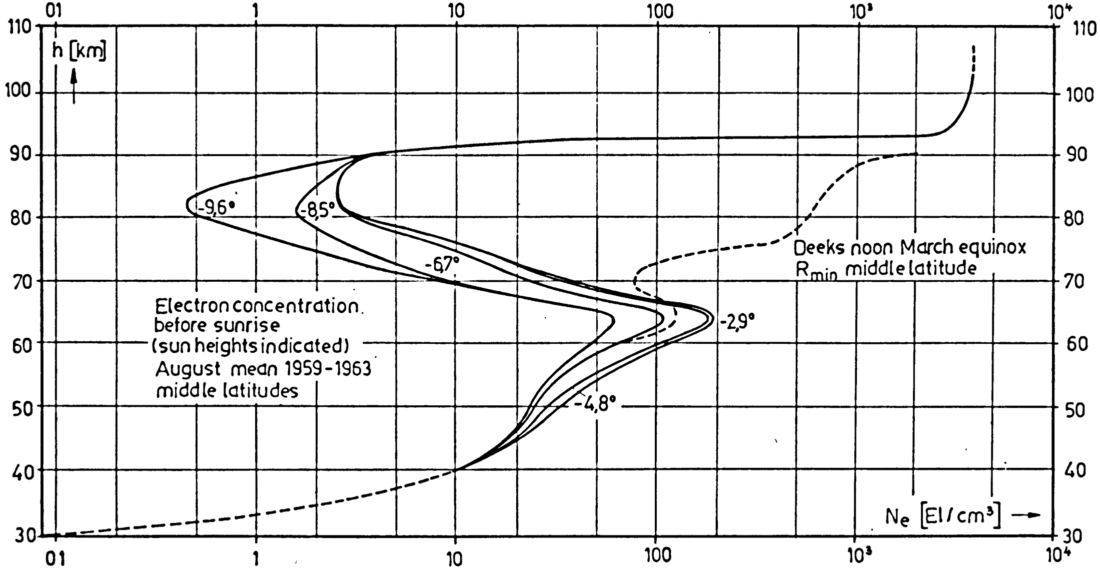

Fig. 5: Theoretical sunrise electron concentration profiles. These profiles result, if the observed sunrise absorption increase during summer (cf. Fig. 2, 128,5 kHz) for negative sunheights below —4° is to be explained by electron photodetachment from O_2^- (the upper part of the $n_e(z)$ profile having been kept constant).

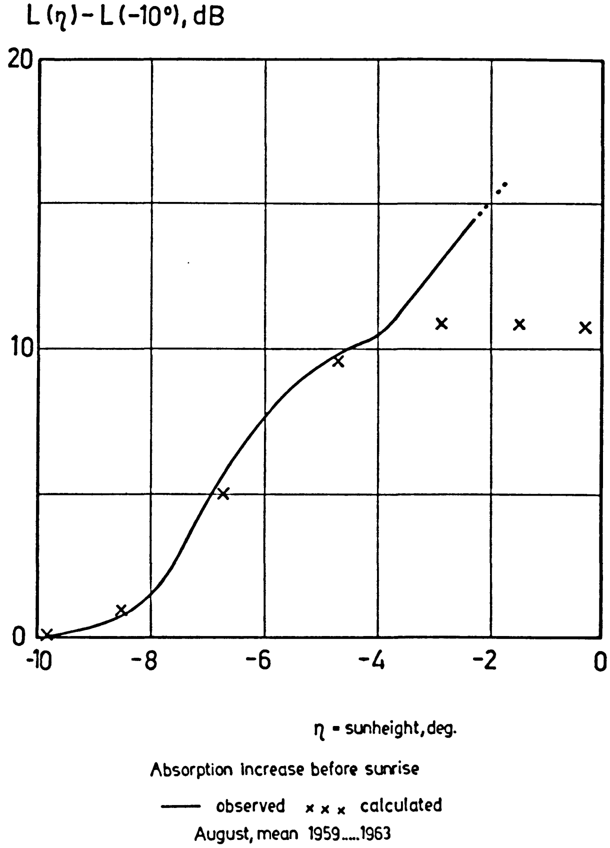

Fig. 6: Comparison of the observed sunrise absorption increase (128,5 kHz; summer; cf. Fig. 2) and the increase which results from the theoretical profiles of Fig. 5 (basing upon electron photodetachment from O_2^-). For discussion see text.

ions with higher electron affinity by photons from the UV-range which had been absorbed before in the ozone layer. Therefore negative ions with electron affinity above 3 eV would have to be assumed e. g. NO_2^-. The absence of the second absorption increase during the winter months (see Fig. 2) seems to indicate a seasonal change of negative ion composition in the D-region.

As it has already been mentioned, there was no possibility of explaining the necessary night-time n_e, n_- profiles by the cosmic ray ionization $q_{CR}(z)$. Calculating $q(z)$ from the reaction kinetic loss terms (equilibrium at sun height $\eta = -10°$ assumed), the difference against $q_{CR}(z)$ is most serious in the height region between 70 and 90 km where q shows a deep minimum. This result again indicates the presence of further negative ions in this height region which would require also a higher ionization rate, so that the minimum can be removed.

Recently, MECHTLY and BOWHILL (1968) and SECHRIST (1968) have published rocket results of D-region electron concentration during sunrise; VLF absorption at steep incidence has been measured simultaneously. At those days, for which rocket results are given, the VLF absorption increase started at solar zenith angles not greater than 98°. The electron density profiles are completely different from those presented in Fig. 5, showing concentrations of about 10^2 cm^{-3} at 85 km and steep gradients between 70 and 82 km; below 70 km, the electron concentrations are very small ($< 0{,}1$ cm^{-3}). According to the height at which the steep gradients occur, from solar zenith angle and UV absorption in the ozonosphere, minimum photodetachment energies are calculated as 3,9...4,6 eV. For photons with such high energy, the ozone shadow is effective, preventing sunrise effects in the D-region at $\eta \approx -9°$. As described above (section 2.2), there is some evidence for such effects (also Sechrist mentiones an observation of VLF amplitude decrease at $\eta = -9°$, which occurs, however, only infrequently). Thus from observational evidence, there seems to be a need for a free electron source depending on low energy photons which can penetrate the ozone layer¹). From the above presented results, it is seen, that the classical O_2^--model, which gives the early beginning of absorption increase, may not explain the rocket-measured electron concentrations and the *CR* ionization rate.

Thus for explaining the *LF* sunrise observations by electron photodetachment, two free-electron sources have to be assumed, the first of them being effective below the ozone shadow and consisting of negative ions with low detachment energy, and the other one containing negative ions with higher detachment energy and producing free electrons above the ozone shadow. In both cases, there is urgent need for laboratory measured reaction kinetic coefficients as a reliable basis for aeronomic calculations.

During night, the electron concentration in the lower D-region corresponding to the classical model is markedly greater than rocket measured values. Enlarging the day to night ratio of the electron detachment rate, could remove the discrepancy, because the same electron concentration incerase is then produced starting from a smaller night time value. The associative detachment

$$O_2^- + O \rightarrow O_3 + e$$

may act in that direction, for it depends upon the O concentration, which increases during sunrise.

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¹) Otherwise, if the O_3 shadow should be effective only, ionospheric effects are to be expected at $\eta \geq -8°$ (O_3 shadow height $\leq$ 90 km). The first small absorption increase ($\eta = -9°$ at path midpoint) should then be caused by U. V. sunrise at a point, which is located 1° east, i. e. ca. 100 km distant, from path midpoint.

Note added in proof

G. C. Reid (1968) has published PCA-results which indicate the importance of the reaction $O_2^- + O \Rightarrow O_3 + e^-$ in the sunlit D-region below 75 km. By this reaction, a greater day/night ratio of the electron detachment rate than that of the above described model may be caused, giving the same electron concentration increase at smaller initial values. Thus, the unexpectedly high electron concentrations during night (Fig. 5) might be reduced. S. A. Bowhill (1969) considering the present stage of D- and E-region chemistry, reviews observations which indicate that other negative ions than O_2^- must be present during sunrise in the D-region, and states the difficulty of explaining the VLF observations without free electron production by visible sunlight.

Thus, the necessity of further direct aeronomic measurements as a basis for interpreting the radio propagation results by the aid of improved aeronomic models is underlined once more.

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