THE PENNSYLVANIA STATE UNIVERSITY

IONOSPHERIC RESEARCH

Scientific Report No. 319

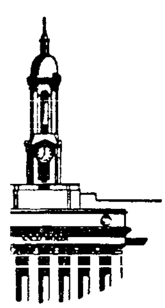
NIGHTTIME BEHAVIOR OF THE F-REGION OF THE IONOSPHERE

by

R. D. Warner

July 15, 1968

IONOSPHERE RESEARCH LABORATORY



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Scientific Report

on

"Nighttime Behavior of the F-Region of the Ionosphere"

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R. D. Warner

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Ionosphere Research Laboratory

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ABSTRACT

A study has been made of the detailed behavior of the F region at night using the incoherent scatter sounder at the Arecibo Ionospheric Observatory to determine to what extent it is compatible with current laboratory reaction rates.

It was found that if currently accepted values for the ratios of the atom ion interchange reactions between atomic oxygen and molecular nitrogen and molecular oxygen are employed with the CIRA 1965 model atmosphere, then a production source of the order of 10^9 electrons cm^{-2} sec^{-1} would be required. It is concluded that such ratios are difficult to reconcile with available production mechanisms.

The behavior if either the neutral molecular densities or the reaction rates are lowered by a factor of 3 is examined and it is shown that there is considerable detailed agreement between the calculated loss rates and the observed recombination rates. Additional production sources of the order of 10^8 cm^{-2} sec^{-1} are then required after sunset and before dawn.

Photoelectron fluxes, horizontal ion velocities combined with horizontal density gradients and horizontal velocity gradients, are examined as possible production sources.

CHAPTER I

INTRODUCTION

1.1 General Statement of the Problem

Previously, Quinn and Nisbet (1965) used data derived from reduced ionograms to investigate recombination and transport phenomena in the nighttime F-region. Their analysis was restricted due to the lack of information on the electron density profiles of the top of the layer, temperatures of electrons, ions and neutral particles, and on low-lying ionization in the lower F region at night. McCrory (1966) extended their analysis and was able to reduce their restrictions by using electron density profiles derived from radar incoherent backscatter measurements completed at the Arecibo Ionospheric Observatory. The method of analysis used by Quinn and Nisbet (1965) and McCrory (1966) was an iterative process for determining the best estimates of the recombination coefficient at 300km from which the transport velocity was calculated.

McCrory (1966) found that the electron content increased during the night and assumed the production mechanism was photoelectrons from the conjugate region. Also, McCrory suggested that large scale horizontal winds, as predicted by King and Kohl (1965) and measured by King-Hele (1964), could have a direct effect on the vertical transport velocities of the electrons and the diffusion coefficient.

The purpose of this study is to compare how modern laboratory reaction rates agree with observed F region behavior at the Arecibo Ionospheric Observatory. Also an attempt will be made to explain the nighttime distribution of electrons in the F region on the basis of horizontal winds and vertical transport.

1.2 Previous Related Studies

1.2.1 Ionospheric Wind Theory

King and Kohl (1965) considered theoretical ionospheric movements at F layer heights caused by atmospheric pressure gradients as reduced from satellite drag data. They considered the forces which would act on a moving atmosphere with velocity components, u_x, u_y, u_z along the south-to-north, west-to-east and vertical directions respectively. The driving forces due to atmospheric pressure were assumed to exhibit a diurnal variation and take the form of $\omega_o u_x$, where ω_o is the Earth's rotation. The Coriolis force, $2\omega_o \sin\varphi u_x$, where φ was the geographic latitude, was taken to be $10^{-4} u_y$ at a latitude of 45^o. Also, it was assumed that the Coriolis force along the x-direction was $10^{-4} u_x$. The ion drag term was the force which charged particles exert on the neutral atmosphere and was taken to be $N_+ \omega / N_n \sin^2 I u_x$, where I was magnetic dip, and $\nu N_+/N_n$ was the collision frequency of one atom with all ions.

Assuming $\nu/N_n = 7\text{x}10^{-10}\text{cm}^2\text{sec}^{-1}$, $N_+ = 10^6\text{cm}^{-3}$, $I = 60^o$, the ion drag term was $5.3\text{x}10^{-4}u_x$, and therefore, was the dominant force. Thus, the driving acceleration, $-\frac{1}{\rho}\frac{dP}{dx}$, where ρ is the atmospheric density and P is the atmospheric pressure, was equated to the ion drag term and upon substitution of temperature and density gradients yielded a south-north horizontal component of atmospheric wind equal to 34m sec^{-1}.

The calculation of King and Kohl (1965) neglected the viscous effects and therefore was subject to error at higher altitudes. The calculation was further restricted since it only applied at the F layer maximum and at midlatitudes. This work has been extended, Kohl and King (1967), to consider a global wind system produced by pressure gradients at different local times. Their calculation was based upon satellite drag measurements which revealed at F layer heights an atmospheric pressure dependent upon both latitude and local time, with a maximum pressure at 1400 L.M.T. and a minimum pressure at 0400 L.M.T. They considered the following forces to be of importance in their calculation.

1. ∇P = the atmospheric pressure gradient.
2. $2\rho(\bar{u}\text{x}\bar{\omega})$ = Coriolis force, where $\bar{\omega}$ = frequency of the earth's rotation, $\bar{u}$ = atmospheric wind velocity, ρ = atmospheric density.
3. $\rho\mu\ (\frac{\partial^2\bar{u}}{\partial h^2})$ = viscous force.

4. $\rho\ (\frac{\partial u}{\partial t} + (\overline{u} \cdot \nabla)\overline{u})$ = inertial forces, where

   $(\overline{u} \cdot \nabla)\overline{u}$ is neglected.

5. $\rho \nu_n (\overline{u}-\overline{u}_i) = \frac{\rho \nu_i N_i}{N_n}$ = ion drag where ν_n = the collision frequency of a neutral particle with all ions

   $\hat{t}$ = unit vector along the magnetic field line

   ν_i= the collision frequency of an ion with all neutral particles

   $\overline{u}_i$= ion velocity

   N_i= ion concentration

   N_n= neutral particle concentration

The momentum equation for the motion of the atmosphere was developed in the following form

$$\frac{\partial \overline{u}}{\partial t} - \mu \frac{\partial^2 \overline{u}}{\partial h^2} - 2(\overline{u} x \overline{\omega}) + \frac{\nu_i N_i}{N_n} (\overline{u} - (\overline{u} \circ \hat{t})\hat{t}) = - \frac{1}{\rho} \nabla P$$

This momentum equation was solved numerically by King and Kohl (1967) and the values for N_i, μ, $\frac{\nu_i}{N_n}$ and $\nabla \rho/\varphi$ were determined in the following manner.

1. The values used for the coefficient of viscosity were taken from a profile calculated by Matuura and Nagota (1962) and were extrapolated exponentially above 400km.
2. It was assumed that $N_i = N_m \exp(1-\frac{h-h_m}{H} \exp(\frac{h-h_m}{H}))$

where N_m, h, h_m, H, have their usual meaning and h_m, N_m, and H, are independent of latitude and local time.

3. The quantity ν_i/N_n was chosen to be equal to $7\times10^{-10}\mathrm{cm}^3\mathrm{sec}^{-1}$, and was assumed to be valid at all altitudes.

4. The driving force was calculated from models by Jacchia (1965) and was approximated by $-\frac{1}{\rho}\frac{\partial P}{\partial x} = A(h)\sin(\omega t)$ where A(h) is a correction profile for various altitudes.

An analysis of the calculated wind system in the northern hemisphere at 300km indicated that under maximum sunspot conditions, ($N=10^6\mathrm{cm}^{-3}$, H=80km) there was a wind speed of 45m sec^{-1} in the direction of the driving force. The reason for the wind being in the direction of the driving force was that under maximum sunspot conditions the ion drag term was dominant. Under conditions of sunspot minimum ($N = 3\times10^5\mathrm{cm}^{-3}$, H = 60km) where Coriolis and inertia forces were dominant, the average wind speed was 140m sec^{-1} and had an eastward component at high latitudes, and westward component at low latitudes. In effect, the inertia force caused a lag in phase of the velocity behind that of the driving force. It also appeared that since N_mF2 was 1.45 times greater while the wind was moving toward the west than toward the east, then the greater velocities would occur toward the east. This is in agreement with King-Hele and Scott (1967) who have observed a net eastward rotation of the upper atmosphere.

Lindzen (1966) proposed a simplified model to estimate the zonal velocity associated with the diurnal temperature oscillation in the thermosphere. His primary objective was to determine a horizontal pressure acceleration, $\frac{1}{\rho}\frac{\partial P}{\partial x}$, and to estimate the dynamic response of a fluid to its distribution when the effect of viscosity was included. For this calculation Lindzen made the following assumptions:

1. That at the equator the horizontal pressure gradient was mainly in an east-west direction.
2. That horizontal diffusion was negligible.
3. That nonlinear terms could be ignored.
4. Coriolis forces could be neglected.

Then, using the boundary conditions that the horizontal velocity, $\bar{u}_x$ was $\bar{u}_o$ at $z = 0$ and that $\frac{\partial u}{\partial z} \rightarrow 0$ as $z \rightarrow \infty$, the momentum equation was solved and yielded a horizontal velocity of the order of 136m sec^{-1} at 110km and 241m sec^{-1} at 374km. Lindzen (1967) repeated the calculation and this time included the ion drag term which necessitated the use of a numerical solution as opposed to the analytical solution in the previous calculation.

He was interested in knowing if a large velocity could occur in the presence of ion drag. He found that the inclusion of electric fields, $\overline{E}$, tended to oppose the zonal velocity of the neutral gas in giving rise to a vertical transport of ions. Since the ion drag was inversely proportional to the zonal velocity of the neutral gas and $\overline{E}$ tended to reduce ion drag, the ion drag term was over-estimated by neglecting $\overline{E}$. Therefore, if a large zonal velocity of the neutral gas was found, it would not be diminished by the electric field. Comparing the results of this calculation with Lindzen (1966) it was evident that the ion drag term was significant in determining neutral winds above 500km. The ion drag term was found to be greatly dependent upon the ion distribution. Depending on the ionization model that was used, neutral zonal velocities varied from 180m sec^{-1} to 780m sec^{-1} at 800km. However, for velocities over 240m sec^{-1} Lindzen (1967) indicated that nonlinear advection terms should have been included.

Geisler (1967) has solved the equation of motion for a given pressure distribution and describe a global wind system at the F2 layer maximum. Previously Geisler (1966) used a set of static models for the thermosphere and arrived at the series of steady-state solutions to the equations of motion as indicative of the form of a time varying solution.

Geisler (1967) wrote the equation of motion and included the pressure driven driving force, Coriolis force, viscous force, and the ion drag force as did Kohl and King (1967). The physical assumptions and atmospheric models used by Geisler (1967) paralleled those used by Kohl and King (1967) with the exception that a different ion distribution was employed. Geisler (1967) used one ion distribution for nighttime hours and another ion distribution for the daytime hours, with a linear change in ion concentration at each level for sunrise and sunset. Sunrise and sunset were centered on 0400 and 2100 hr. for the summer; 0600 and 0800 hr. for the equinox; and 0800 and 1700 hr. for the winter.

The results of Geisler's solution showed that

1. averaged over a 24 hour period, the meridional component of the wind at 45° latitude yielded a net equatorward transport of mass; and
2. the zonal component averaged over a 24 hour period was found to be westward with a mean speed of 50m sec^{-1}.

Geisler (1967) found that the time varying solution yielded velocities of larger amplitudes with the maximum velocity occurring at a later time when compared with the results for the steady state solution. Thus, Geisler's solution (1967) suggested a net westward rotation of the upper atmosphere of 50m sec^{-1} while Kohl and King's solution (1967) indicated a net eastward rotation of the upper atmosphere greater than 100m sec^{-1}. Observation of satellite drag studies by King-Hele and Scott (1967) showed that the diurnal average zonal wind at middle and low latitudes was directed toward the east at speeds greater than 100m sec^{-1}.

Volland (1966) considered a two-dimensional dynamic model of the upper atmosphere within the equatorial plane during equinox and used the following restrictions for his set of hydrodynamic and thermodynamic equations.

1. That total symmetry existed relative to the equatorial plane, i.e. $\frac{\partial P}{\partial y} = 0$.
2. That diffusive equilibrium existed at a lower boundary of 120km.
3. At the upper boundary of 800km the hydrodynamic concept was valid.
4. The only plasma effect was ion drag.
5. Non-linear terms were included.

The system of equations had five unknowns, u, w, ρ, P, T where:

u,w = the components of the wind velocity

P = atmospheric pressure

T = atmospheric temperature

ρ = atmospheric density,

but on account of diffusive equilibrium they were solved independently for each constituent of the air. The only coupling that existed between the different constituents was in the heat production term. Thus, the method used to solve the above equations was a recursion method. Volland (1966) also used a series solution in which all known and unknown values were in the general form of a Fourier series. This led to a system of ordinary differential equations in which a WKB solution was used to arrive at generalized gravity waves (i.e. included viscosity, heat conductivity, and external heat sources) with periods of one day.

Volland arrived at a solution indicating a bulk motion of eastward rotation of approximately 100m sec^{-1} which agreed both in magnitude and direction with that observed by King-Hele and Scott (1967).

1.2.2 Direct Wind Measurements

Atmospheric wind measurements in the altitude range from 70 to 115 km have been obtained by the use of chemiluminous clouds and by radio meteor observations.

Analysis of chemiluminous cloud observations have been obtained for Eglin Air Force Base, Florida by Rosenburg and Edwards (1964), Wallops Island, Virginia by Kochanski (1964), and at Barbados, West Indies by Murphy (1966). These experiments were restricted to twilight and nighttime hours and to an altitude range where T.M.A. (trimethyl aluminum) would combine with oxygen to produce chemiluminous gas trails.

Radio meteor trails at various locations have been analyzed by Robertson, Liddy, and Elford (1953), Huxley (1957), Elford (1959) and Hines (1960), to obtain wind velocities in the region from 90 to 110 km.

The instantaneous measurement of the amplitude and direction of the wind was not in general possible since it required meteor showers to give a minimum of three trails occurring at the same height and time. Thus, only wind velocities averaged over the period of an hour could be calculated.

The results of radio meteor studies and gas trail experiments were as follows:

1. Wind speeds varied between $\pm$ 100m sec^{-1} with a maximum velocity in the altitude range from 100 to 110 km. The wind vector rotated clockwise as viewed from above with a wavelength of the order of 12-15km and the interval between wind nulls increased with altitude. Downward phase velocities were present throughout the night and were of the order of one wavelength per twelve hours.
2. The diurnal variation showed morning wind speeds to be greater than evening wind speeds by 10m sec^{-1}.

Seasonal variations indicated a wind from the east to northeast in the summer and from the northwest to northeast in winter.

Measurements of both ionized and neutral winds above 115km have been observed by using T.M.A. trails, ion and neutral clouds (B_a^+, B_a, S_r, N_a) and satellite drag measurements.

The T.M.A. trail experiments were limited to a maximum altitude of 190km since T.M.A. would no longer combine with oxygen above that altitude to produce visible chemiluminous gas trails. Since a photographic triangulation technique was used to observe the gas trails, the experiments were restricted to twilight and evening hours.

Observation of ionized and neutral cloud experiments were also restricted to twilight and evening hours, but were applicable in the region from 130 to 2000km.

Wind measurements deduced from satellite drag data were greatly dependent on magnitude of changes in inclination, with the altitude and latitude range determined by the satellite's orbit.

Wind measurements obtained by these techniques for the F region indicated a marked variation in the wind direction and magnitude from sunset to sunrise. These variations along with seasonal and latitude changes have been summarized in Table 1 and Figure 1 by vector diagrams. The calculated wind system given by Kohl and King (1967) is shown in Figure 2.

1.2.3 Drift Measurements

Radio wave techniques have been used to measure the horizontal drift velocities of irregularities in the E and F regions. The most frequently used radio method makes use of radio waves transmitted from the ground and reflected by ionospheric irregularities. Spaced receivers receive the reflected signal and record variations in the amplitude pattern as a function of time. Thus, as irregularities drift across the receivers they produce a ground diffraction pattern which is related to the ionospheric irregularities in their dynamical and geometric structure. However, the amplitude pattern is anisotropic and the diffraction pattern is subject to random motions as it moves over the ground. Error introduced by the anisotropic amplitude pattern and the random motions has been handled statistically by either similar fades or correlation techniques.

Drift measurements have revealed the drift velocity to be latitude dependent and exhibit a diurnal and seasonal variation. The results of F region drift measurements by the spaced receiver technique have been

Table 1 Nighttime Horizontal Wind Measurements

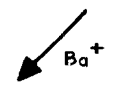
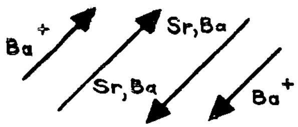
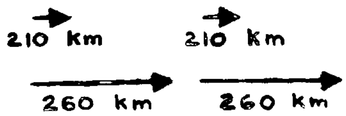
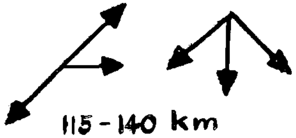
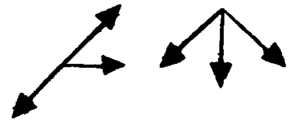
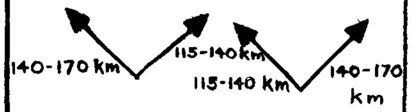
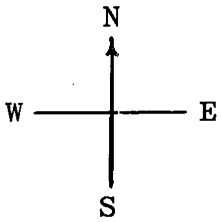
Observer	Method	Type of Motion	Location	Altitude	Sunset Sunrise
Föppl et. al (1965)	Ba^+ Clouds	Ionized Wind	(40^ON, 10^OE)	140-160km	
Haerendel et. al (1966)	Ba, Ba^+, Sr Clouds	Ionized and Neutral Wind	(40^ON, 10^OE)	140-250km	
Kochanski (1964)	T.M.A. Trails	Neutral Wind	(38^ON, 75^OW)	115-190km	Su' & Winter Su' & Winter 
King-Hele & Scott (1967)	Satellite Drag Measurements	West-to-East Atmospheric Wind	Middle Latitudes	200-260km	Net Velocity Net Velocity 
Rosenburg and Edwards (1964)	T.M.A. Trails	Neutral Wind	(30^ON, 30^OW)	115-140km	Summer Summer 

Table 1 (Cont'd)

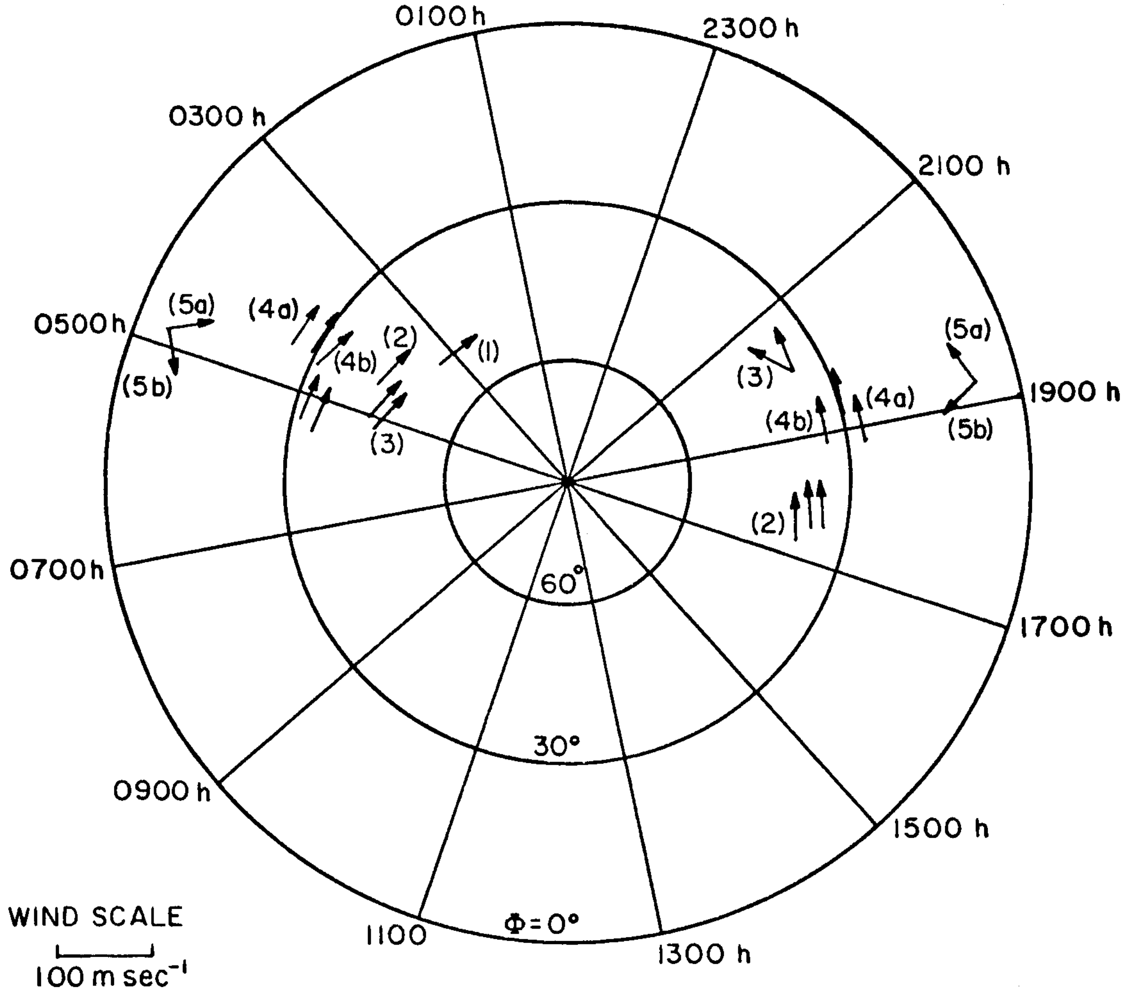
Observer	Method	Type of Motion	Location	Altitude	Sunset Sunrise
Rosenburg and Edwards (1964)	T.M.A. Trails	Neutral Wind	(30^{o}N, 30^{o}W)	115-140km	Winter Winter 
Bharsar & Rao (1966)	Na Cloud	Neutral Cloud	(8^{o}N, 76^{o}E)	115-170km	



Wind Scale

100m sec^{-1}

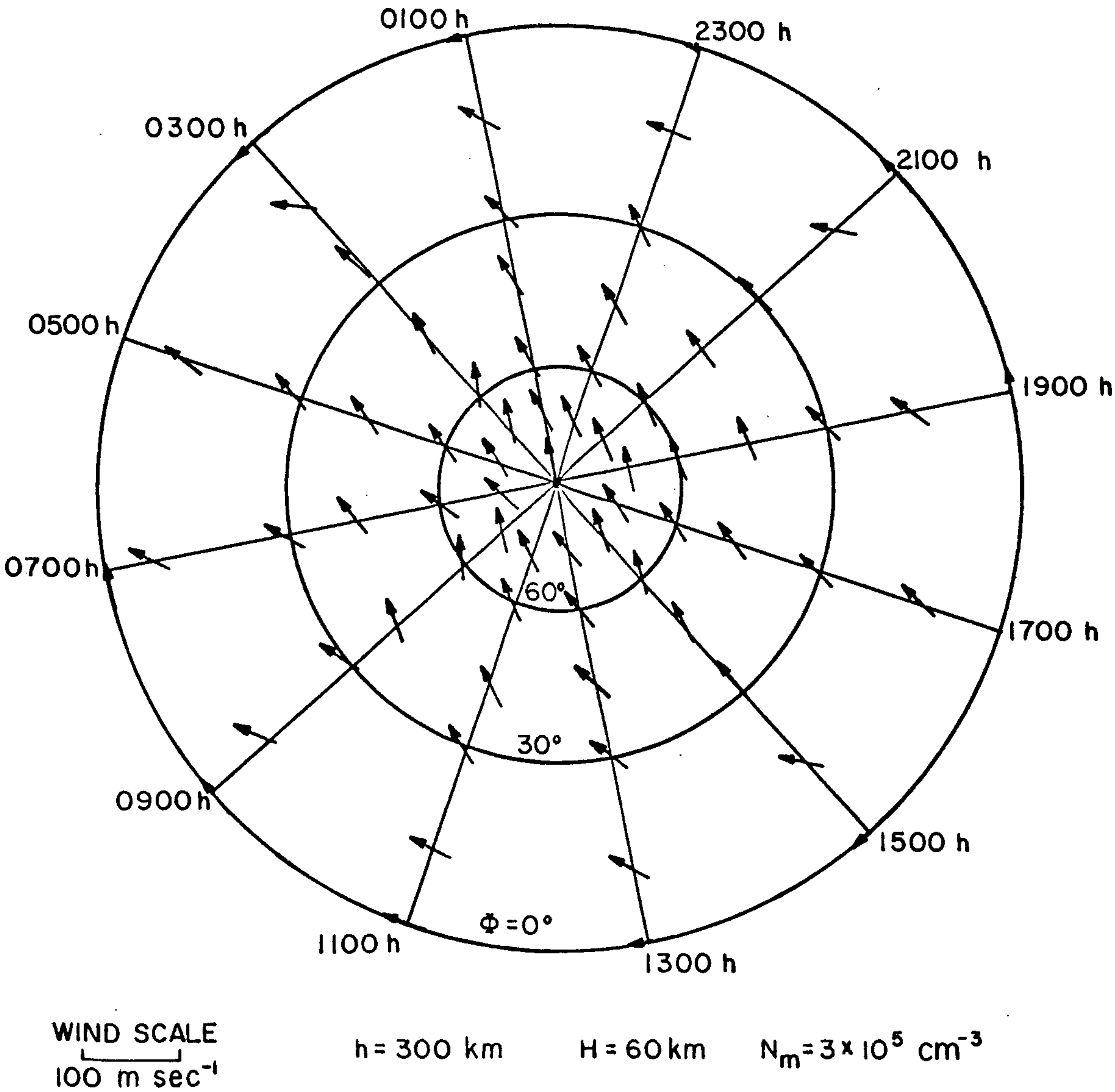
The vectors point in the direction toward which the motion occurred.



NO.	OBSERVER	LATITUDE	ALTITUDE
1	FÖPPL et. al. (1965)	40° N	140-150 km
2	HAERENDEL et. al. (1966)	40° N	190-250 km
3	KOCHANSKI (1964)	38° N	115-190 km
4a	ROSENBURG et. al. (1964)	30° N	115 km
4b	ROSENBURG et. al. (1964)	30° N	140 km
5a	BHAVSAR & RAO (1966)	8° N	115–140 km
5b	BHAVSAR & RAO (1966)	8° N	140-170 km

NIGHTTIME HORIZONTAL WIND MEASUREMENTS

FIGURE I



CALCULATED WIND SYSTEM BY KOHL AND KING (1967)

FIGURE 2

summarized in Table 2 and Figure 3 by using vector diagrams. Generally, drift velocities varied from 10-300m sec^{-1} and were toward the east near sunrise, but changed to west by evening at high latitudes with a 180^{o} reversal near the equator.

1.2.4 Recombination

An attachment-like process was postulated by Bradbury (1938) to account for the loss of ionization in the F region. He suggested that the F1 and F2 layers were formed by the same ionizing agent acting on a single ionizable constituent. Bates and Massey (1947) postulated a two-fold electron-loss process that could account for the F1 and F2 layers. The double loss process involved the charge interchange of the atomic oxygen ions with diatomic molecules in the F2 layer, at a rate proportional to the square of the electron density. The entire electron-loss process proposed by Bates and Masey (1947) is represented by the reactions:

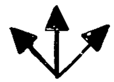
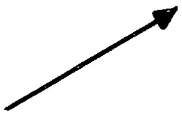
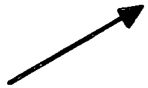
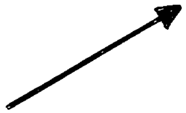
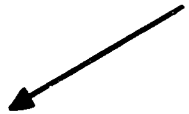
$$O^{+} + XY \rightarrow OX^{+} + Y$$

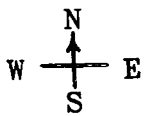
$$OX^{+} + e \rightarrow O + X$$

Table 2 F Region Horizontal Drifts by Spaced Receiver Technique

Observer	Location	Sunset	Nighttime	Sunrise
Chapman (1953)	High Latitudes	←	←	→
Becken & Maehlum (1960)	(60^ON, 11^OE)	←	←	→
Rao (1966)	(56^ON, 88^OE)	Summer ← Winter ←	Summer ← Winter ←	Summer → Winter →
Rao (1966)	(55^ON, 37^OE)	←	←	→

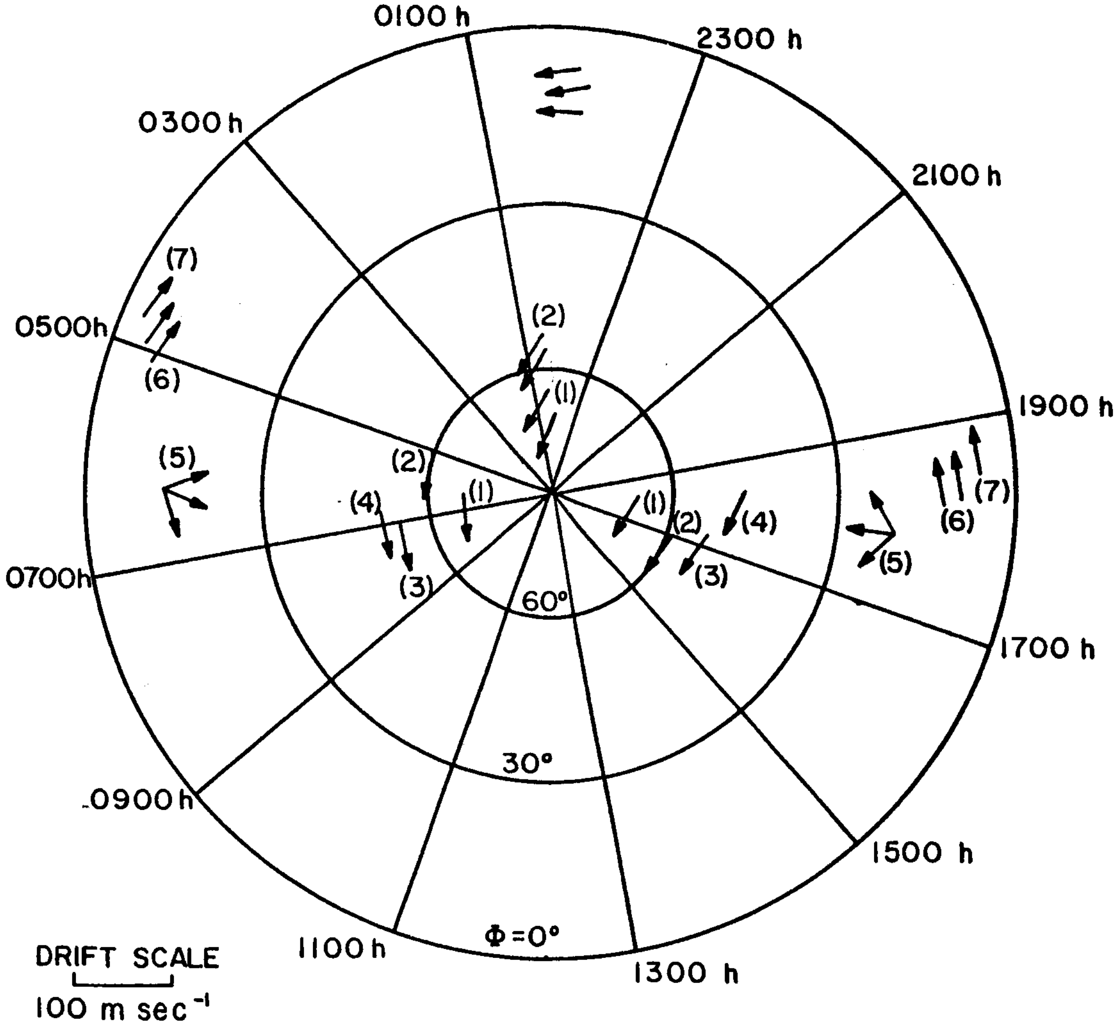
Table 2 (cont'd)

Observer	Location	Sunset	Nighttime	Sunrise
Yerg (1964)	(18°N, 67°W)	Summer and Winter 	Summer and Winter SCATTERED WIND DIRECTION 14m sec^{-1}	Summer and Winter 
Rao & Rao (1959, 1963 1964)	(17°N, 83°E)	Summer  Winter 	Summer  Winter 	Summer  Winter 
Chapman (1953)	Low Latitudes			



100m sec^{-1}

The vectors point in the direction toward which the motion occurred.



NO.	OBSERVER	LATITUDE
1	CHAPMAN (1953)	HIGH LATITUDE
2	BECHEN & MAEHLUM (1960)	60° N
3	RAO (1966)	56° N
4	RAO (1966)	55° N
5	YERG (1964)	18° N
6	RAO & RAO (1959, 1963, 1964)	17° N
7	CHAPMAN (1953)	LOW LATITUDE

F REGION HORIZONTAL DRIFTS

FIGURE 3

Ratcliffe, Schmerling, Setty, and Thomas (1956) suggested that above 150km the loss coefficient, β, at low F region altitudes was of the order of $10^{-8} n_e \sec^{-1}$, where n_e was the electron number density, and at higher altitudes β varied with the altitude, Z, as:

$$\beta \cong 10^{-4} \exp \left[\frac{300-Z}{50}\right] \sec^{-1}$$

It was later shown by Ratcliffe (1956) that when the loss coefficient varied in this way (Ratcliffe, Schmerling, Setty, and Thomas 1956) and a double loss process was assumed, the formation of the F1 and F2 layers could be explained. Although Ratcliffe et. al. (1956) realized that diffusion and drift could be important in determining the morphology of the F region, they minimized these effects in their analysis to determine the recombination coefficient.

Martyn (1956) postulated that transport in the nighttime F region could arise from either atmospheric motions, electric fields or diffusion under gravity. He concluded that at night the F region layer moved downward due to gravity, but the undersurface was depleted by an increase in the linear recombination coefficient. The combination of diffusion and recombination yielded the height of maximum density at 360km for a Chapman region, which was in good agreement with experimental results.

Dungey (1956) has studied the effects of ambipolar diffusion on the nighttime F layer. He assumed that the diffusion velocity was inversely proportional to the neutral dneisty, and that the loss varied as βe^{-kz} where β and k were constant. He neglected horizontal variations in all quantities and assumed that the drift velocities were vertical and uniform. Dungey (1956) imposed the shape-preserving restriction that

$$\frac{\partial n}{\partial t} = -\lambda n$$

where λ was a constant, and found the layer shape had the same general form as a Chapman layer. With the layer shape determined by this restriction Dungey (1956) was able to solve the electron continuity equation. He used electron density profiles taken at Slough, England, and with a value of 0.15 per hour for λ, concluded that β was $0.22 \times 10^{-4} sec^{-1}$ at 370 km. By assuming the neutral molecular constituent to be O_2, he was able to deduce a value for β at 300 km of $1.6 \times 10^{-4} sec^{-1}$. However, he pointed out that due to the parabolic approximations used in the calculation large errors would result unless accurate profiles were obtained from the ionogram data.

Van Zandt, Norton, and Stonehocker (1960) used electron density profiles reduced from ionograms taken at Danger Island in the central Pacific, during the October 12, 1958 eclipse, to calculate the linear recombination coefficient. It was assumed that the changes in the electron density were due to loss by recombination and production by photoionization, while the effects of transport were neglected. A linear loss process was assumed, and only the constituents O and N_2 were used for photoionization and loss respectively. These assumptions allowed Van Zandt, Norton, and Stonehocker to solve the continuity equation by a graphical technique. The results indicated that the recombination coefficient, β, was of the form

$$\beta = 6.8 \times 10^{-4} \exp\left(\frac{300-Z}{103}\right) \sec^{-1}$$

where Z = the altitude.

It was noted by the authors that this value for the recombination coefficient was larger than previously reported estimates and was too large for the nighttime F region.

Nisbet and Quinn (1963) calculated the recombination coefficient for the nighttime F region by integrating the continuity equation. The authors considered the decrease of atomic oxygen ions in a tube of force bounded by the earth's magnetic field lines which extended from the bottom of the layer to the geomagnetic equator. This method enabled Nisbet and Quinn (1963) to neglect flux terms in the integrated continuity equation.

The bottomside of the layer was determined from electron density profiles taken at Puerto Rico, that were corrected for low-lying ionization. Above the F2-peak a Chapman distribution was used to represent the layer to 500km, and an equilibrium distribution for O^+, He^+, and H^+ ions was used from 500km to the geomagnetic equator.

They showed that the recombination coefficient was temperature dependent and varied by a factor of 3 diurnally and by a factor of 30 to 40 over the solar cycle. This temperature dependence was expected since β was dependent on the densities of O_2 and N_2. Values of β at 300km varied from $1.5 \times 10^{-5} sec^{-1}$ at $700^o k$ to $1.9 \times 10^{-4} sec^{-1}$ at $1300^o k$. The importance of drift and diffusion in the nighttime F region was made clear in their results. It showed that sixty percent of the ionization recombining below the peak had diffused downward from above the peak.

Swider (1965) has calculated reaction rates of importance in the nighttime ionosphere from ionospheric data. He has considered the reactions:

$O^+ + N_2 \rightarrow NO^+ + N$ (rate γ_1)

$O^+ + O_2 \rightarrow O_2^+ + O$ (rate γ_2)

$e + NO^+ \rightarrow N + O$ (rate α_1)

$e + O_2^+ \rightarrow O + O$ (rate α_2)

and used decay models for a stationary ionosphere to obtain the corresponding reaction rates. Swider used values for the recombination coefficient as given by Ratcliffe et. al. (1956), thermosphere temperatures from Nicolet (1963), and molecular oxygen and nitrogen densities from Nicolet (1961). He found that the ratio α_2/α_1 was 1.5 ± 0.5, with a standard deviation of two, which led to the deduction that the ratio $\gamma_2/\gamma_1 = 0.1$, with a standard deviation of two. Absolute values for the reaction rates γ_1 and γ_2 were bounded by

$$10^{-12} cm^3 sec^{-1} \geq \gamma_1 \geq 10^{-13} cm^3 sec^{-1}$$

$$10^{-11} cm^3 sec^{-1} \geq \gamma_2 \geq 10^{-12} cm^3 sec^{-1}$$

with no significant temperature dependence. A value of $(1.7 \pm 1) \times 10^{-7} cm^3 sec^{-1}$ at $300^o k$ was deduced for α_2 and since dissociative recombination rates for electron-molecular ion processes were not significantly different regardless of the ion species, α_1 was assumed to be in the same range. It was suggested that the mean dissociative recombination rate followed a temperature dependence of $T_e^{-1.0\pm0.5}$ where T_e was the electron temperature, which was in good agreement with recent laboratory measurements.

Quinn and Nisbet (1965) again used mean monthly electron density profiles, but extended their analysis to include drift and diffusion. They obtained values for the recombination coefficient at 300km, β_{300}, by setting the quadratic loss coefficient equal to $0.5 \times 10^{-8} cm^3 sec^{-1}$, and using electron density profile corrections as given by Nisbet and Quinn (1963). The authors found β_{300} to be strongly temperature dependent varying from $10^{-5} sec^{-1}$ at $700^o k$ to $3 \times 10^{-4} sec^{-1}$ at $1300^o k$ with winter values being smaller than summer values. The seasonal anomaly could only be explained in terms of a seasonal variation in the relative densities of molecular oxygen and the molecular constituents responsible for recombination. The results showed no latitude variation in β_{300}. β_{300} was found to be relatively independent of the shape of the top profile, but was dependent on low lying ionization and increased when the correction for low lying ionization was omitted. Also, during the winter Quinn and Nisbet (1965) found small negative values for β_{300}. These negative values were assumed to be due to either a more rapidly decreasing layer thickness than was accounted for or production of atomic oxygen ions produced by charge interchange with protons.

McCrory (1966) extended Quinn and Nisbet's work (1965) and found the integrated electron content increased during the winter night, but was not able to explain this entirely on the basis of recombination. Thus, McCrory (1966) made an estimate of the amount of ion flux into the region necessary to explain this observed behavior. He found that photoelectrons from the conjugate region would have sufficient energy to ionize atomic oxygen. However, McCrory pointed out that it wouldn't be possible to continually supply electrons during the night from one end of a field line to the other without producing an equalizing current flow, or building up an electric field.

Mitra, Rao, and Mahajan (1967) solved the continuity equation simultaneously for the recombination coefficient and vertical transport velocity. Their solution was applicable for the nighttime F region when there was no production, and it included both the electrodynamical drift and diffusion. Mitra et. al. (1967) used electron density profiles reduced from ionograms that were corrected for low lying ionization. It was assumed that the recombination coefficient and vertical transport velocity varied exponentially with altitude. Also, it was assumed that the recombination coefficient, vertical transport velocity, and the velocity gradient remained constant over the involved time interval. The continuity equation was solved by a graphical technique and showed the recombination coefficient at 300km, β_{300}, to vary from 23 x $10^{-5}sec^{-1}$ to 28 x 10^{-5} sec^{-1} at Delhi (dip 42.3°N) and from 11 x $10^{-5}sec^{-1}$ at Huancayo (dip 2°N). The altitude variation for the recombination coefficient, β, was of the form

$$\beta = (2.0 \pm 0.5) \times 10^{-4} \exp\left[\frac{300-Z}{32\pm 2}\right] sec^{-1}$$

for both Delhi and Huancayo since there was such a small latitude variation in β_{300}. Mitra, Rao, and Mahajan (1967) compared β_{300} with the value calculated from the recent laboratory reaction rates given by Fehsenfeld et. al. (1965a). The laboratory value for β_{300} was 23.1 x $10^{-4}sec^{-1}$ which was an order of magnitude larger than β_{300} as deduced from ionospheric data. However, the authors showed that when the laboratory reaction rates were subjected to a $T^{-1.5}$ law, that ionospheric values for β as a function of altitude were in close agreement with β's calculated from laboratory reaction rates.

Laboratory measurements of positive ion-molecular reaction rates did not exist until the last decade. Early reaction rate measurements were subject to errors in identification of ion species coupled with errors in the excitation of the vibrational levels of diatomic molecules. Paulson (1964) has reviewed the laboratory measurements of positive ion-molecular reaction rates prior to 1963. He has reported laboratory reaction rates for $O^+ + N_2 \rightarrow NO^+ + N$ and $O^+ + O_2 \rightarrow O_2^+ + O$ ranging from 10^{-8} to $10^{-13} cm^3 sec^{-1}$. Paulson (1964) concluded that on the basis of ionospheric behavior, reaction rates greater than $3 \times 10^{-11} cm^3 sec^{-1}$ were invalid. Since Paulson's review, laboratory measurements of positive ion reaction rates have become more consistent due to refinements in afterglow experiments.

Fehsenfeld, Schmeltekopf, and Ferguson (1965a) used an afterglow technique to measure the thermal ion-molecular reaction rate for $O^+ + N_2 \rightarrow NO^+ + N$. The authors found this reaction to proceed at a rate of $3 \times 10^{-12} cm^3 sec^{-1}$ at a reference temperature of $300^o k$. Concurrently, Fehsenfeld, Golden, Schmeltekopf, and Ferguson (1965b) using the afterglow technique found $O^+ + O_2 \rightarrow O_2^+ + O$ proceeding at a rate of $(4 \pm 1) x 10^{-11} cm^3 sec^{-1}$ at $300^o k$.

Gunton and Shaw (1965) have studied the recombination of electrons with nitric-oxide in a nitric-oxide-neon gas mixture. They used a pulsed hydrogen lamp with a lithium-fluoride window which produced the ultra-violet radiation, but did not excite the neon gas. Following the ionizing pulse the decay of electron density was measured by a microwave-cavity reflection technique. The results indicated a reaction rate value of

6×10^{-7} to $12 \times 10^{-7} cm^3 sec^{-1}$ at $196^o k$ and 3.0×10^{-7} to $3.7 \times 10^{-7} cm^3 sec^{-1}$ at $358^o k$ for the reaction $e + NO^+ \rightarrow N + O$.

Copsey, Smith, and Sayers (1966) have used an after-glow technique and found the reaction rates for $O^+ + O_2 \rightarrow O_2^+ + O$ at 2.7×10^{-11} to $3.4 \times 10^{-11} cm^3 sec^{-1}$ and $O^+ + N_2 \rightarrow NO^+ + N$ at $(2.4 \pm 0.4) \times 10^{-12} cm^3 sec^{-1}$. The authors compared their rates with those obtained from ionospheric data and found their reaction rates to be an order of magnitude larger than those obtained by Swider (1965). Copsey et. al. (1966) concluded that this discrepancy indicated a strong temperature dependence for these reaction rates in order to reduce their values at ionospheric temperatures.

Rishbeth (1966) has used recent laboratory reaction rates as given by Ferguson et. al. (1965) and Copsey, Smith, and Sayers (1966) to calculate the linear recombination coefficient at low sunspot activity for the F2 layer. The loss rate of F2 layer ionization was taken to be proportional to the electron density with a rate coefficient β given by

$$\beta = \beta(N_2) + \beta(O_2) = \gamma(N_2) \cdot [N_2] + \gamma(O_2) \cdot [O_2]$$

where the square brackets denoted gas concentrations and γ was the rate coefficient.

Rishbeth (1966), used these reaction rate values along with six different neutral atmospheric models to obtain a recombination coefficient, ß, of the order of 1 to 2 x $10^{-4}sec^{-1}$ for middle latitudes at the F2 peak under minimum sunspot conditions.

Donahue (1966) has attempted to obtain a set of laboratory reaction rates that were consistent with recent mass spectrometric determinations of the content of ionic species in the ionosphere between 120 and 220km. The author concluded that when the following reaction rates were used:

$O^+ + N_2 \rightarrow NO^+ + N$	at 4 x $10^{-12}cm^3sec^{-1}$	(γ_1)
$O^+ + O_2 \rightarrow O_2^+ + O$	at 4 x $10^{-11}cm^3sec^{-1}$	(γ_2)
$e + NO^+ \rightarrow N + O$	at 5.2 x $10^{-7}cm^3sec^{-1}$	(α_1)
$e + O_2^+ \rightarrow O + O$	at 1.2 x $10^{-7}cm^3sec^{-1}$	(α_2)

and α_1 decreased with electron temperature as $T_e^{-1.4 \pm 0.1}$ and α_2 as T_e^{-1}, then the nighttime ionosphere (120 to 220km) could be explained. However, this was valid only if weak ionization sources were present with ionization rates of 5 to 10 ion pairs/cm^3sec above 180km and 10 ion pairs/cm^3sec near 130km. Also, Donahue neglected transport and as was shown by Nisbet and Quinn (1963) this could produce large errors in the results.

A temperature dependence for the $O^+ + O_2 \rightarrow O_2^+ + O$ reaction rate has been given by Smith et. al. (1966) to be $T^{-1/2}$ in the temperature range from 200 - 600K

Schmeltekopf, Fehsenfeld, Gilman, and Ferguson (1967) have shown that the reaction rate for $O^+ + N_2 \rightarrow NO^+ + N$ was increased when N_2 was vibrationally excited. They used a rotational temperature of 300K in all their experiments, but studied the increase in the reaction rate when the vibrational temperature was varied from 300 - 600K. Schmeltekopf et. al. used an afterglow technique and found that for a Boltzman distribution of the vibrational energy states of N_2 with a vibrational temperature of 400K, there was an increase of twenty in the reaction rate over that of the ground state reaction rate. The authors concluded that large laboratory reaction rates for $O^+ + N_2 \rightarrow NO^+ + N$ have been due to the excitation of the vibrational levels of molecular nitrogen. Also, disturbed conditions in the atmosphere could excite the vibrational levels of molecular nitrogen and thus account for a decrease in the electron density.

1.2.5 Transport Velocities

Martyn (1947) introduced the concept of transport phenomena to account for the morphology of the F2 region. He considered the transport velocity, $\overline{v}$, of the electrons (and ions) and wrote the continuity equation as

$$\frac{\partial n}{\partial t} = q - \beta n - \operatorname{div}(n\overline{v})$$

where q, β, and N have their usual meaning.

Later, Martyn (1956) showed that the transport of ionization was an important parameter in the nighttime F region and suggested that it might arise from atmospheric motions, electric currents and diffusion under gravity.

Chandra, Gibbons, and Schmerling (1960) considered the vertical transport of electrons in the F region. They developed a method which enabled them to solve the continuity equation from experimental data. They assumed there was no distinction between the F1 and F2 layers and that electron production and loss were the controlling factors with the vertical transport of electrons acting as a perturbation.

The recombination coefficient, β, above 250km used was

$$\beta(z) = 2.2 \times 10^{-5} + 0.25\exp(-Z/37) ,$$

with no diurnal variation. Below 250km an effective $\beta(z)$ was calculated from the relationship $\beta = \alpha N^2$, where $\alpha = 4 \times 10^{-9} \mathrm{sec}^{-1}$ at 100km and N was the number density of electrons.

A study of electron density profiles indicated that horizontal density gradients were negligible when compared with the vertical gradient, and therefore, only the divergence of the flux in the vertical direction was considered.

Integration of the continuity equation yielded values of the vertical velocity at various altitudes in terms of an arbitrary velocity at a lower or initial altitude. The initial velocity was taken to be $\pm$ 20m sec^{-1} at 100km with the corresponding velocity profiles converging with increasing altitude. Vertical velocity profiles were calculated for Huancayo, Talara, Peru, Panama, Canal Zone, and Washington, D.C. The diurnal variation of the vertical velocity profiles indicated an upward velocity during the day for both summer and winter. However, the transport velocity at Washington, D.C. was negative in winter during the day, which indicated a phase reversal at middle-latitude stations.

Garriot and Thomas (1962) have used electron density profiles reduced from ionograms taken at Slough ($I=67^{o}$), San Francisco ($I=62^{o}$), Puerto Rico ($I=52^{o}$), Bogota ($I=33^{o}$) and Chimbote ($I=7^{o}$) to obtain vertical drift velocities from the electron continuity equation. The total drift velocity included both electromagnetic drift and diffusion. Their results were highly dependent upon the assumed value for the recombination coefficient, the neutral atmospheric model, a constant positive scale height gradient, and the assumed diffusion coefficient. Their solution was not valid near the bottom of the layer nor at one scale height higher, but for the region between these boundaries they obtained drift velocities for Puerto Rico at night of the order of 30m sec^{-1} for quiet conditions, and 80m sec^{-1} for the disturbed conditions. A marked latitude dependence was noticed with smaller drift velocities occurring near the equator.

Quinn and Nisbet (1965) extended their analysis on recombination (Nisbet and Quinn 1963) to include vertical transport in the nighttime F region. They integrated the electron continuity equation along a tube of volume bounded by lines of the earth's magnetic field. Electron density profiles were deduced from ionograms taken at six different stations varying in latitude from 19° to 52°N. The authors were able to separate the diffusion velocity due to gravity from the total transport velocity, and thus, were able to calculate the drift velocity with the assumption that the drift component was independent of altitude. The results showed that for Puerto Rico the drift velocities from 23:00 to 01:00 were less than 10m sec^{-1} and generally decreased in magnitude during the night. No seasonal dependence was noticed.

Hanson (1966) pointed out that diffusion coefficients obtained by Quinn and Nisbet (1965) were lower than previously reported values. He attributed this discrepancy as a result of the corrections applied to the lower portion of the profile. However, Quinn and Nisbet (1966) suggested that neutral atmospheric winds present on the night side of the earth could influence both the diffusion coefficient and the assumed uniform drift velocity more than the correction for low lying ionization.

Shimazaki (1966) has used a least squares method to simultaneously obtain the temporal variations in temperatures and drift velocities at Puerto Rico from the continuity equation. The method he employed involved the use of electron density profiles reduced from ionograms, various diffusion and neutral atmospheric models. He found that for slow diffusion models the drift was generally downward throughout the night and never exceeded 40m sec^{-1}. These results were in good agreement with those deduced from geomagnetic variations by Maeda (1962).

Mitra, Rao, and Mahajan (1967) calculated the vertical transport velocity at Delhi (dip: 425^{o}N) and Huancayo (dip: 2^{o}N) from electron density profiles as reduced from ionograms. They solved the continuity equation by a graphical technique and assumed that both the recombination coefficient and vertical transport velocity varied exponentially with altitude. No attempt was made to separate the electrodynamical drift velocity from diffusion velocity, but at Huancayo the transport velocity was mostly due to electrodynamical drift since vertical diffusion is almost zero at the geomagnetic equator.

Mitra et. al. (1967) found that at Delhi the transport velocity was downward from 00:00 - 03:00 hours at 6-7m sec^{-1} with a velocity gradient of 3 x 10^{-5} sec^{-1}. The results were in good agreement with those obtained by Chandra et. al. (1960), but indicated larger vertical velocities at the equatorial station than at the middle latitude station.

1.3 Specific Statement of the Problem

The summary of preceding studies on F region processes indicated that horizontal winds, vertical transport of electrons and recombination determine the structure of the F region. It is the purpose of this investigation to examine these mechanisms and to determine their influence on F region behavior.

1.3.1 Detailed Comparison of Recombination Rates and Theoretical Loss Rates

Previous studies by Quinn and Nisbet (1965) and McCrory (1966) involved the study of the recombination of the nighttime F layer and its relations to the loss rates that would have to be used to explain the behavior of the layer. These studies were somewhat hampered by the necessity of using ionograms to determine the profiles for the Quinn and Nisbet study and to normalize the incoherent scatter measurements in the McCrory study. High resolution electron content measurements are now being made at Arecibo using the ATS-3 satellite which allows an improvement of about one order of magnitude in the measurement of the recombination rate for a 45 minute period. It is the purpose of this present study to compare in detail the loss rate and recombination rate throughout the night using these data and to investigate what additional information can be obtained by these detailed comparisons.

1.3.2 Comparison of Laboratory Rates for the Recombination Reactions Effective in the F Layer with Observed Behavior

Recent measurements of the laboratory rates for the atom ion interchange and dissociative recombination reactions effective in the F layer are believed to be much more accurate than those available previously. Neutral atmospheric models are still largely based on the satellite orbital decay measurements which in turn depend on the neutral atomic oxygen density. Recombination in the F layer is, however, mainly controlled by the molecular nitrogen and molecular oxygen densities.

The behavior of the recombination in the nighttime F layer is dependent on the product of the loss rates and the neutral densities. It is one of the aims of this study to determine to what extent these rates and models can be used to explain the nighttime behavior of the F layer.

1.3.3 Differences Between Summer and Winter Loss Rates

Quinn and Nisbet (1965) found that the effective loss rate calculated neglecting all production sources was lower in winter than in summer McCrory (1966) attempted to study the production necessary to maintain the winter nighttime F layer assuming that the rates for the atom ion recombination in the night were the same as those effective during the day. By studying the early morning behavior and the daytime equilibrium layer he was able to make estimates for the value of the atom ion recombination rates effective during the day and to relate them to the nighttime loss rates. Recent measurements by Schmeltekopf, et. al. (1967) have shown that the rates for the atom-ion reaction are quite sensitive to the vibrational excitation of the neutral molecules and that consequently the daytime and nighttime rates may differ considerably. It is one of the aims of this study to determine the effect of these findings on the behavior of the layer and the necessary production. In particular it is of interest to determine whether the differences are due to a nighttime production source which is greater in winter than in summer or to seasonably modified loss rates due to changes in the molecular densities or reaction rates.

1.3.4 Effect of Photoelectron Fluxes on the Nighttime F Layer in Winter

Carlson and Nisbet (1966) showed that photoelectrons produced in the conjugate ionosphere were effective in heating the F layer during the night. Theoretical estimates of the fluxes effective at Arecibo have been made by Nisbet (1968) and Kwei and Nisbet (1968). It is one of the aims of this study to determine to what extent such fluxes contribute to the production of electrons in the nighttime F region.

1.3.5 Effect of Ion Drift Velocities on the Nighttime F Layer

Ion drift velocities of the order of 100 m/second have been observed in the F region at sunset by Haerendel et. al. (1966). Neutral winds have been estimated theoretically by Kohl and King (1967), Volland (1966) and Geisler (1967). Satellite orbital decay measurements by King-Hele et. al. (1967) have been interpreted as showing large horizontal winds. It is one of the aims of this study to determine to what extent horizontal ion motions can be used to explain discrepancies between the observed behavior of the nighttime F layer and that which is predictable on the basis of a one dimensional model of the region.

CHAPTER II

DETAILS OF THE EXPERIMENT

2.1 The Experimental Apparatus and Procedure

The data used for this analysis were obtained from incoherent backscatter radar measurements taken at the Arecibo Ionospheric Observatory, Arecibo, Puerto Rico. The radar facilities consist of an incoherent scatter sounder operating at frequency of 430 Mc/s. The experimental data were taken at pulse lengths of either 40μs or 100μs with alternate 500μs pulse lengths. The data for the 40μs and 100μs pulse lengths were averaged over a 10 minute time interval and over a 15 minute time interval for the 500μs pulse lengths. The electron density profiles obtained for the 40μs or 100μs and alternately 500μs runs were then normalized to the peak electron density as determined from ionosonde measurements. When the ionograms were unavailable or unuseable, for example, due to spread F, then the electron density profiles could be calculated by using power density profiles which were calibrated using a noise pulse. The transmitted power was measured by a bolometer via a directional coupler and a knowledge of the antenna gain. When this was done however the accuracy of the electron density measurement decreased considerably. This was not of great importance when the measurements of density themselves were used, but when the difference in the density measurements made 45 minutes apart was used to determine recombination rates the error became much more serious. The 40μs, 100μs, and 500μs profiles had an altitude resolution of 6 Km, 15 Km and 75 Km respectively. The 40μs or 100μs profiles were combined with the alternate 500μs profiles in order to extend the profile above the peak to 1000 Km.

The electron and ion temperatures were determined from the 500μs runs by using a least squares fitting technique to determine the minimum error between the observed autocorrelation functions and theoretical autocorrelation functions. It was estimated that the temperatures determined by this technique were correct to approximately ± 50K throughout the night.

For the winter 1967 experiments we were fortunate to obtain measurements made by the Stanford University of the Faraday rotation of 137.35 Mc/s signal in the ionosphere to the satellite ATS-3 at an altitude of approximately 35,780 km, and at an elevation angle of 22^{o}.

The incoherent measurements were made in the vertical direction and this would correspond to an approximately 154 km horizontal separation between the two measurements at 400 Km.

2.2 Experimental Data

Temperatures and electron density profiles were obtained from eight experiments performed at the

Arecibo Ionospheric Observatory in Arecibo, Puerto Rico (18^{o}N, 67^{o}W). The parameters for the solar and geomagnetic activity during these experiments were obtained from the Solar-Geophysical data of the Space Disturbances Laboratory, U.S. Department of Commerce, Environmental Scientific Services Administration and are listed in Table 3. The solar and geomagnetic parameters listed in Table 3 are:

$S_{10.7}$ = Daily Solar Flux at 2800 Mc/s.

$\overline{S_{10.7}}$ = 52 Day Running Average Solar Flux.

A_p = Geomagnetic Indices.

K_p = Planetary Geomagnetic Indices.

Neutral atmospheric densities were taken from the Harris and Priester model atmospheres (CIRA, 1965). The model atmospheres were chosen to correspond with the appropriate solar and geomagnetic indices present during the experiments.

Table 3 The Solar and Geophysical Indices during the Experiments

Dates of Experiments	Start Time (60°W)	Stop Time (60°W)	$S_{10.7}$	$\overline{S_{10.7}}$	A_p	3 Hour Range Indices of K_p
July 29, 1966	17:19:14	21:10:55	128.9	101.3	5	2 2 2
30			124.2	101.8	6	1 2 1 1 1 1 2 2
August 16, 1966	16:58:42	20:06:28	92.8	104.0	4	0 0 1
17			94.4	103.9	2	1 1 0 0 1 1 1 0
December 20, 1966	11:25:10	10:58:52	111.2	119.4	7	0 0 0 0 1
21			110.0	119.6	12	0 1 1 3 2 1
23	00:33:33	08:18:13	114.4	120.2	8	0 0 0 1 0 1 1 3
24			114.3	120.5	12	2 1
25	09:01:46	05:00:56	115.4	120.9	14	2 1 1 1 4 3
26			114.7	121.3	24	2 2
December 11, 1967	14:30:56	15:29:00	141.0	144.3	3	0 0 0 2
12			143.6	144.5	6	2 1 1 1 2
18	16:41:53	19:58:05	219.4	148.6	19	4 3 2 2
19			212.2	149.2	30	4 2 3 4 4 5 6
26	16:14:03	04:06:33	171.0	153.6	7	2 1 3 1
27			183.1	154.7	9	2 2 3 3 1 1 1 1
28			190.4	156.1	5	1

CHAPTER III

METHOD OF ANALYSIS

3.1 The Rate of Recombination

3.1.1 The Electron Continuity Equation

The electron density continuity equation as discussed in Section 1.2.5 is

$$\frac{\partial n}{\partial t} = q - L - \mathrm{div}(n\overline{v}) \tag{3-1}$$

where

n = the electron density

L = the loss of electrons

$\overline{v}$ = the transport velocity

q = production by ionization

Equation 3-1 may be integrated and by choosing the lower limit of integration to be in a region where the density is sufficiently small the n, v, term can be neglected. Thus, integration of the electron continuity equation yields

$$\frac{\partial}{\partial t}\int_{z_1}^{z_2} n dz = -\int_{z_1}^{z_2} L dz + \int_{z_1}^{z_2} q dz - n_2 V_2 \tag{3-2}$$

3.1.2 Calculation of the Loss of Ionization

As discussed in Section 1.2.4 the ions of importance in the F region are O^+, NO^+ and O_2^+ and it is upon the recombination rates for these ions that the electron loss rates depend. Modern laboratory measurements of these reaction rates as summarized by Donahue (1966) and Ferguson (1967) are given in Table 4.

The reaction rates involving O^+, NO^+, $O_2{}^+$ are temperature dependent as discussed in section 1.2.4. The laboratory reaction rates were corrected for a temperature of 900K with γ_2 varying as $T_i^{-1/2}$, α_1 as $Te^{-1.5}$ and α_2 as Te^{-1}. Then the set of reaction rates used in this study were related to the laboratory reaction rates by a set of constants K and C such that

$$\gamma_1 = K(1.15 \times 10^{-12} cm^3 sec^{-1})$$
$$\gamma_2 = K(1.15 \times 10^{-11} cm^4 sec^{-1})$$
$$\alpha_1 = C(1.00 \times 10^{-7} cm^3 sec^{-1})$$
$$\alpha_2 = C(3.96 \times 10^{-8} cm^3 sec^{-1})$$

Under conditions of equilibrium the electron loss rate L, can be shown to be

$$L = \frac{\partial n}{\partial t} = \frac{K\left[\gamma_1 \; n(N_2) + \gamma_2 \; n(O_2)\right] n^2}{n + C\left[\frac{\gamma_1}{\alpha_1} \; n(N_2) + \frac{\gamma_2}{\alpha_2} \; n(O_2)\right]} \tag{3-3}$$

Table 4 Reaction Rates after Donahue (1966) and Ferguson (1967) at 300K

F Region Reactions	Laboratory Reaction Rates at 300K ($cm^3 sec^{-1}$)		Reference value assumed at 300K ($cm^3 sec^{-1}$)
$O^+ + N_2 \rightarrow NO^+ + N$	1.5×10^{-12}	Paulson et. al., 1967	2.0×10^{-12}
(Rate γ_1)	2.4×10^{-12}	Copsey et. al., 1966	
	3.0×10^{-12}	Fehsenfeld et. al., 1965a	
	$(5.0 \pm 3) \times 10^{-12}$	Aquilanti & Volpi 1966	
$O^+ + O_2 \rightarrow O_2^+ + O$	2.0×10^{-11}	Copsey et. al., 1966	2.0×10^{-11}
(Rate γ_2)	2.0×10^{-11}	Warneck 1967	
	2.6×10^{-11}	Schmeltekopf et. al. unpublished results	
	4.0×10^{-11}	Fehsenfeld et. al., 1965b	
$NO^+ + e \rightarrow N + O$ (Rate α_1)	5.2×10^{-7}	Gunton and Shaw, 1965	5.2×10^{-7}
$O_2^+ + e \rightarrow O + O$ (Rate α_2)	1.2×10^{-7}	Kasner and Bondi, 1966	1.2×10^{-7}

Using Equation 3-3, the reference rates, and the measured electron density profiles, the loss term and loss profiles could be calculated for various values of K and C. The loss term was programmed for computation on an I.B.M./360 digital computer. Then, the loss profiles were integrated from the base of the layer to 1000 km to obtain the integrated loss.

3.1.3 The Total Electron Content

The total electron content for the summer and winter of 1966 experiments was obtained by integrating the corrected electron density profiles from the base of the layer to 1000 km. It was estimated that the total electron content could only be determined to within ($\pm$ 3) x 10^{11} el cm^{-2} when spread F was present. This corresponded to an accuracy of approximately $\pm$ 1.1 x 10^{8} el $cm^{-2} sec^{-1}$ for the rate of change in the electron content over a 45 minute interval.

For the winter 1967 experiments, Faraday rotation measurements were supplied by Stanford University from the synchronous satellite ATS-3 located at 94.8°W, 0.46°N. The Faraday rotation angle, θ, is related to the total electron content

by

$$\theta = \frac{K}{f^2} \int_z n \, B_L \sec \phi \, dz$$

where

n = the electron density

ϕ = the zenith angle of the ray path

f = satellite transmission frequency in c/s

B_L = the longitudinal component of the earth's magnetic field along the ray from the satellite to the receiver

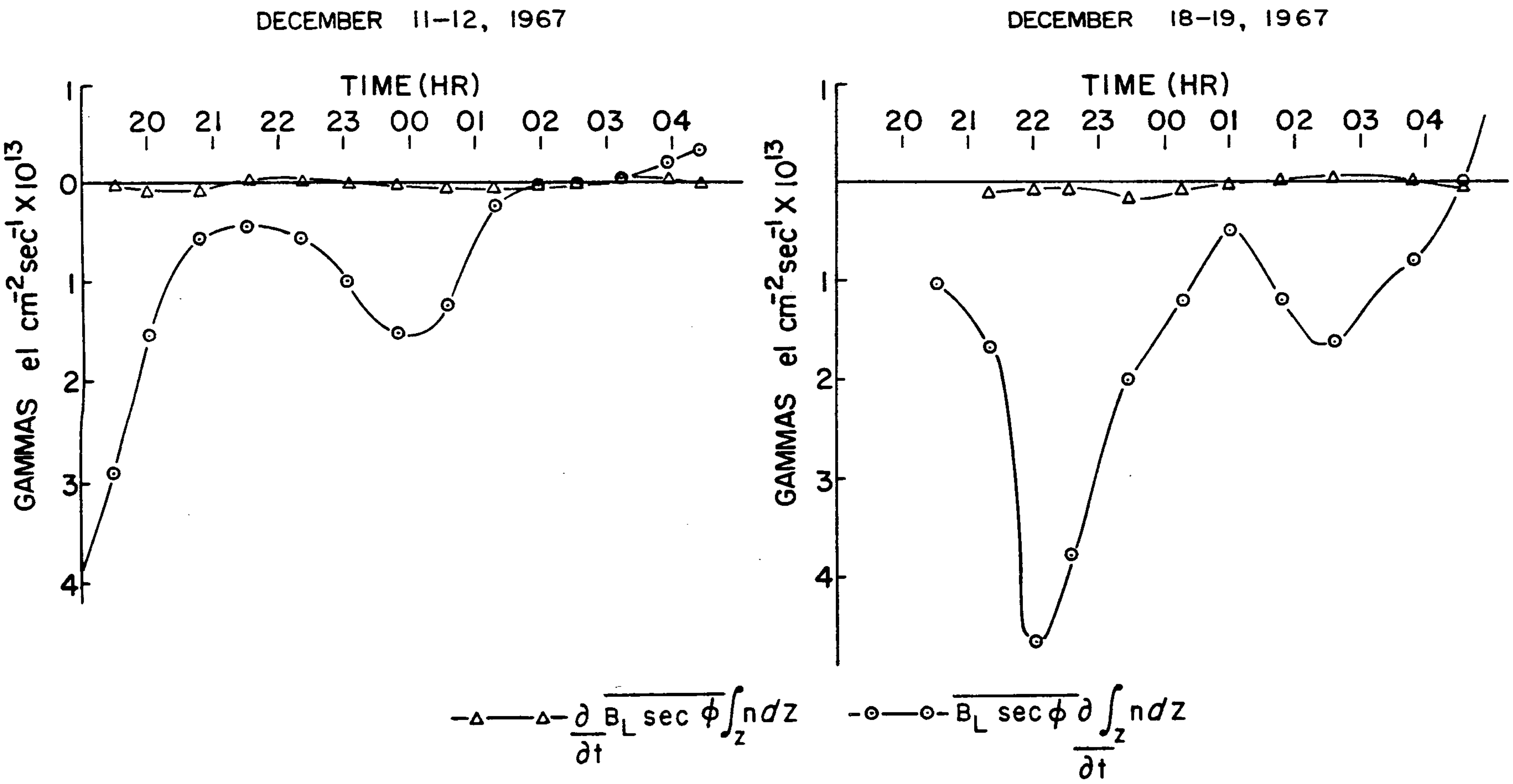
$K = 2.36 \times 10^4$ rationalized MKS units

The rate of change in the total electron content is related to the Faraday rotation angle, θ by

$$\frac{d\theta}{dt} = K < B_L \sec\phi > \frac{\partial}{\partial t} \int_z ndz + K \int_z ndz \frac{\partial}{\partial t} < B_L \sec\phi >$$

where $< BL \sec\phi >$ denotes the average value of $BL \sec\phi$. The contribution to $d\theta/dt$ by these two terms for the experiment on December 11/12, 1967 and December 18/19, 1967 is shown in Figure 4. The contribution of the $\partial/\partial t < BL \sec\phi >$ term to the rate of change in the electron content was applied when necessary.

The Faraday rotation measurements had a resolution of approximately $\pm 1^o$ corresponding to a rate of change in electron content of approximately $\pm 2 \times 10^7$ el cm^{-2}sec^{-1} over a 45 minute time interval. The Faraday rotation measurements were made along the ray path toward the satellite, ATS-3, while backscatter measurements were in the vertical direction.



CONTRIBUTION TO THE CHANGE IN THE FARADAY ROTATION ANGLE

FIGURE 4

CHAPTER IV

RESULTS OF THE EXPERIMENT

4.1 Assumption That the Production is Zero

The simplest assumption that can be made is that the production and flux at the upper boundary are both zero. This was the initial assumption used by Quinn and Nisbet (1965). It is therefore of interest to compare results obtained with the present high resolution data extending well above the maximum of the layer with the more extensive but much less accurate data used in the previous study.

With the above assumption

$$\int_{z_1}^{z_2} \frac{\partial n}{dt}\, dz = -\int_{z_1}^{z_2} L dz$$

In the present analysis the upper and lower altitudes used were 174 km and 1000 km.

In order to make a comparison with the previous work the parameters K which control β_{300} and C which control $\bar{\alpha}$ were varied

$$K = \frac{\gamma_1}{1.15 \times 10^{-12}\ cm^3 sec^{-1}} = \frac{\gamma_2}{1.15 \times 10^{-11} cm^3 sec^{-1}}$$

$$C = \frac{\alpha_1}{1.00 \times 10^{-7}\ cm^3 sec^{-1}} = \frac{\alpha_2}{3.99 \times 10^{-7}\ cm^3 sec^{-1}} \qquad (4\text{-}1)$$

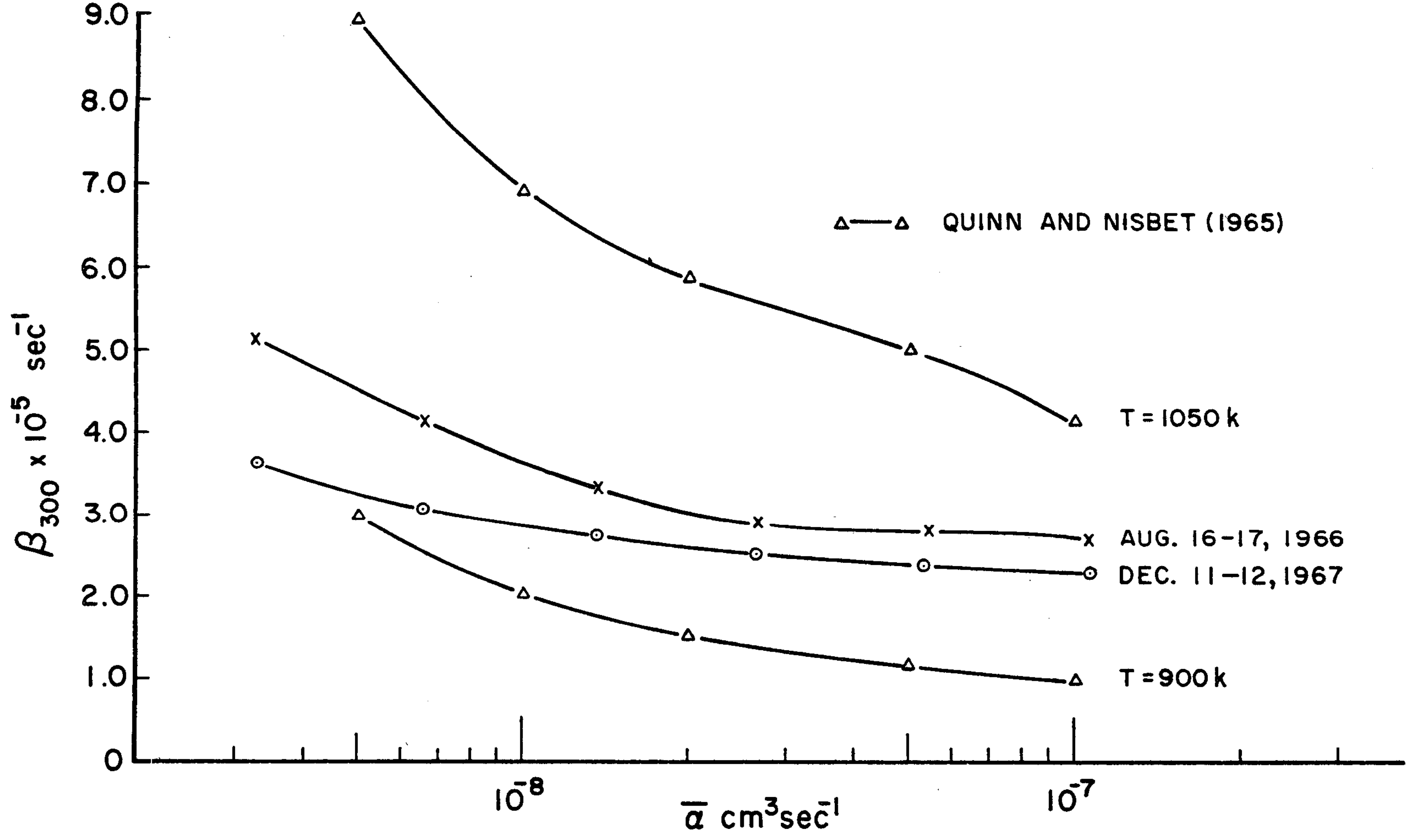
$$\beta_{300} = \gamma_1 \, n\,(O_2) + \gamma_2 \, n(N_2) \qquad (4\text{-}2)$$

$$\overline{\alpha} = \frac{\gamma_1 \, n(N_2) + \gamma_2 \, n(O_2)}{\dfrac{\gamma_1 \, n(N_2)}{\alpha_1} + \dfrac{\gamma_2 \, n(O_2)}{\alpha_2}} \qquad (4\text{-}3)$$

For any given value of K and hence β_{300} the value of $\overline{\alpha}$ was selected which gave the smallest variance in the function, ϵ, throughout the night.

$$\int_{z_1}^{z_2} \frac{\partial n}{\partial t} \, dz + \int_{z_1}^{z_2} L \, dz = \epsilon$$

These results are shown in Figure 5. It is apparent that there is general agreement with results previously obtained by Quinn and Nisbet (1965). Values of β_{300} calculated in this way are larger in the summer than in the winter as was found in the previous study and the values of β_{300} are in general agreement with those obtained previously for the neutral atmospheric temperatures effective at the time these measurements were made. The values of β_{300} calculated in the present study are not quite as dependent on the values of $\overline{\alpha}$ as was found in the previous study. This may be due to the considerably larger number of measurements of the two integrals in the present study. This allowed the detailed shape of the time variation to be studied when previously almost all that could be measured was the recombination



VARIATION OF β_{300} WITH THE QUADRATIC LOSS TERM $\bar{\alpha}$ WITH NO PRODUCTION

FIGURE 5

over a period of several hours. In this study as in the past, increases in the electron content were observed in the early hours of the morning in winter under low sunspot conditions, an observation inconsistent with the basic assumption of the method of analysis.

It should be noted that the values for β_{300} and $\overline{\alpha}$ indicate much smaller losses than are typical of the rates calculated from laboratory measurements. For a value of $\overline{\alpha}$ of 6.25×10^{-8} cm^3sec^{-1} corresponding to C = 1 a value of K = 0.18 is obtained in the summer and K = 0.10 in the winter. These would correspond to the rates

Summer Rates	Winter Rates
$\alpha_1 = 1.00 \times 10^{-7}$ cm^3sec^{-1}	$\alpha_1 = 1.00 \times 10^{-7}$ cm^3sec^{-1}
$\alpha_2 = 3.96 \times 10^{-8}$ cm^3sec^{-1}	$\alpha_2 = 3.96 \times 10^{-8}$ cm^3sec^{-1}
$\gamma_1 = 2.07 \times 10^{-13}$ cm^3sec^{-1}	$\gamma_1 = 1.15 \times 10^{-13}$ cm^3sec^{-1}
$\gamma_2 = 2.07 \times 10^{-2}$ cm^3sec^{-1}	$\gamma_2 = 1.15 \times 10^{-12}$ cm^3sec^{-1}

The calculated rates would be expected to be smaller than the laboratory rates if production sources are present during the night as such sources have been neglected in the above analysis.

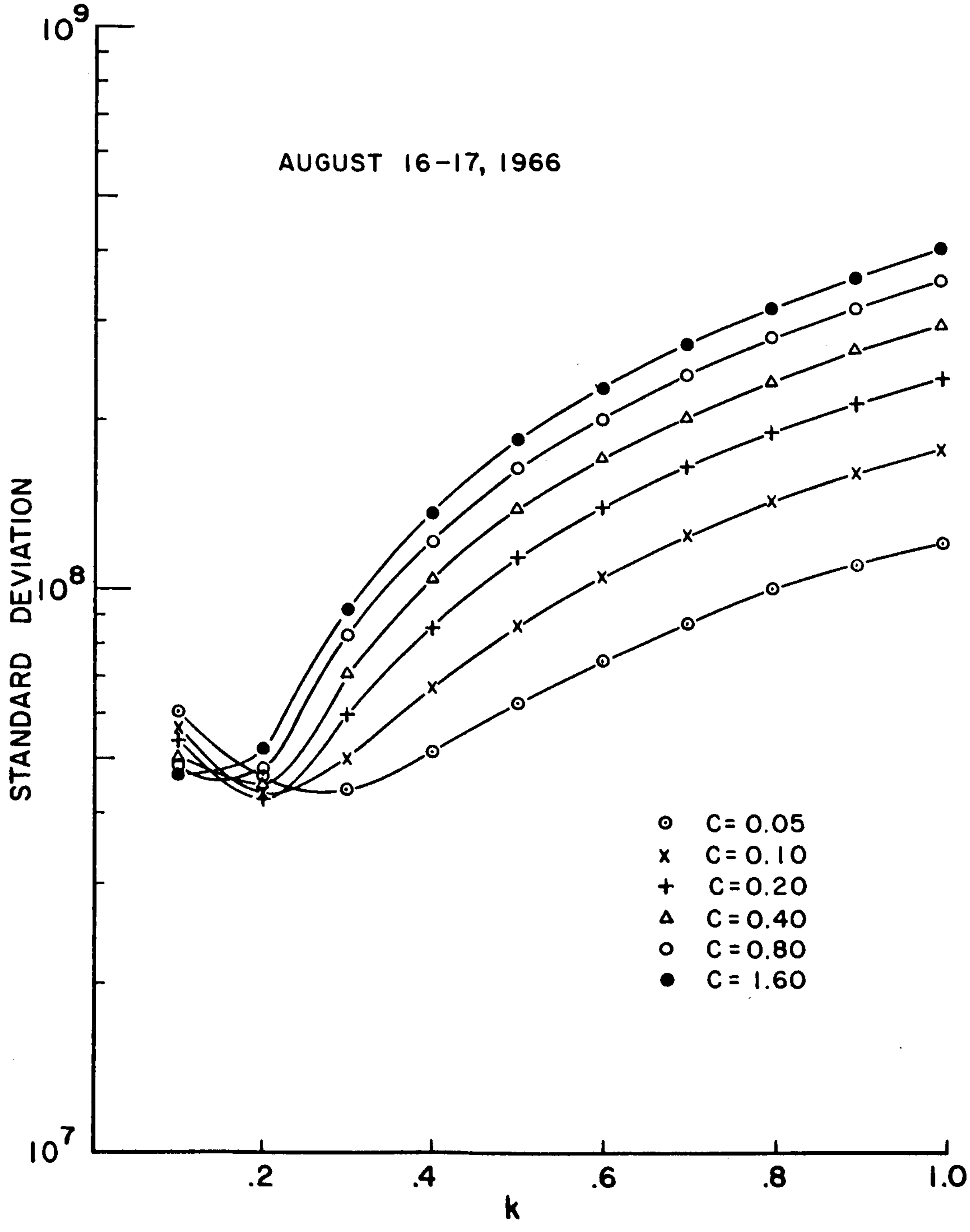
4.2 Constant Production

There is evidence in the increase in electron content during the winter that production sources are occasionally present during the night. By production sources in this content is meant any mechanism such as a downward flux at the upper boundary, a horizontal drift in the presence of a horizontal density gradient or an influx of ionizing particles such as high energy photoelectrons. The first approximation including such a term has been made by assuming a constant production throughout the night and solving a least squares technique for optimum values of K and C to give the best fit to the nighttime behavior.

The variance of the function

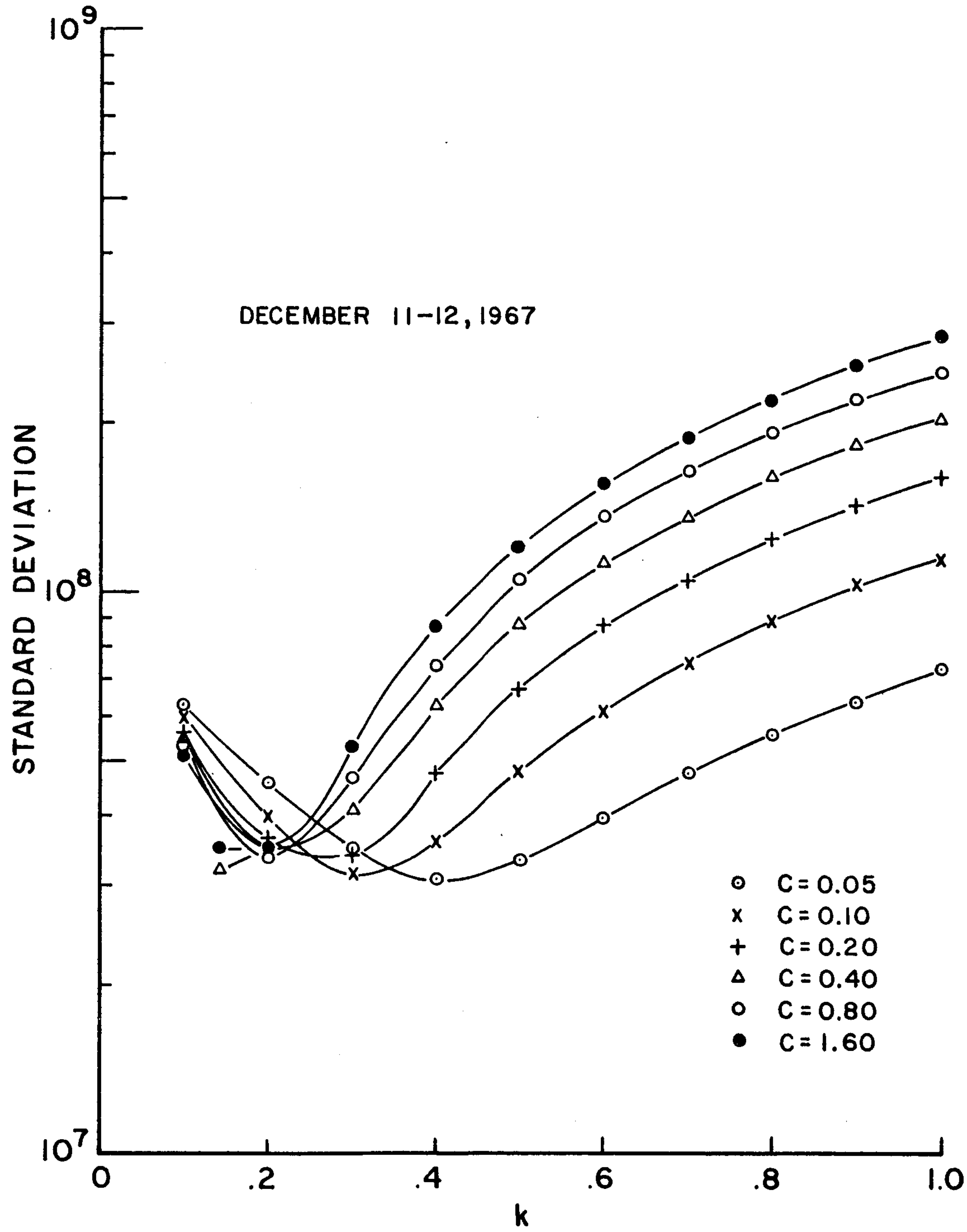
$$\epsilon = \int_{z_1}^{z_2} \frac{\partial n}{\partial t}\, dz + \int_{z_1}^{z_2} L\, dz - \int_{z_1}^{z_2} q\, dz$$

with q chosen to be that fixed value which would minimize $\bar{\epsilon}^2$ is shown in Figures 6 and 7 for the August 16/17, 1966 and December 11/12, 1967 experiments. It is apparent that for the given values of C, the best fit is obtained for values of K ranging from 0.1 to 0.4. This implies that under the conditions of a constant production the best least squares fit is obtained by choosing values of β_{300} which would be between one half and one order of magnitude less than the laboratory reference reaction rates. The variation of β_{300} with $\bar{\alpha}$ was calculated using Equations 4-2 and 4-3 for the optimum values of K and C and is shown in Figure 8. It is



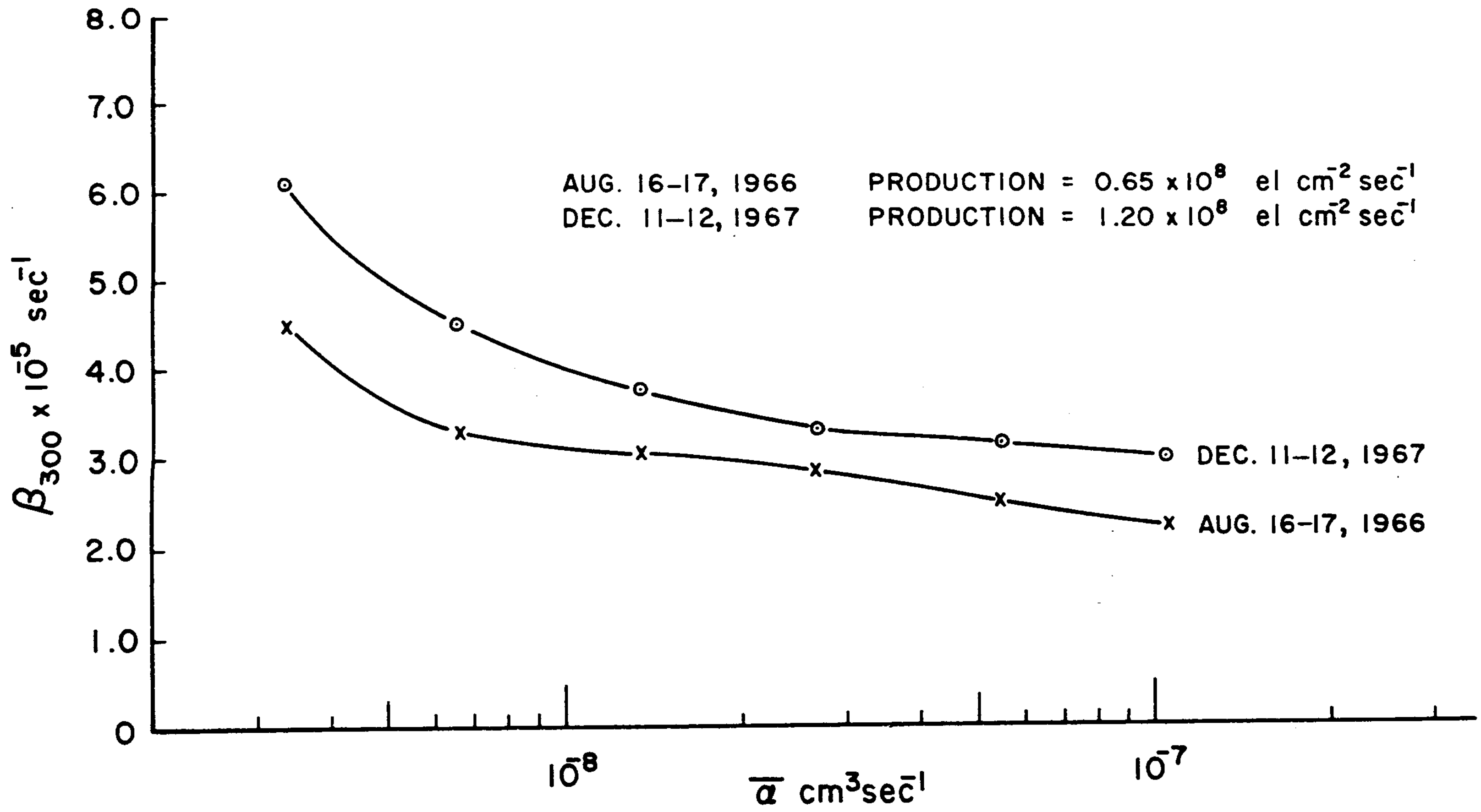
STANDARD DEVIATION BETWEEN THE OBSERVED RATE OF CHANGE IN ELECTRON CONTENT AND THE OBSERVED INTEGRATED LOSS VS k

FIGURE 6



STANDARD DEVIATION BETWEEN THE OBSERVED RATE OF CHANGE IN ELECTRON CONTENT AND THE OBSERVED INTEGRATED LOSS VS k

FIGURE 7



VARIATION OF β_{300} WITH THE QUADRATIC LOSS TERM $\overline{\alpha}$ FOR A CONSTANT PRODUCTION

FIGURE 8

obvious that the winter values for β_{300} are now higher than the summer values which is just the reverse of the results obtained when the production term was neglected. It would thus appear that the values of β_{300} which best fit the data using optimum values of $\overline{\alpha}$ indicate that if an additional production source is included the higher recombination rate in winter is due to an increase in the production term and not to an increase in the loss rates.

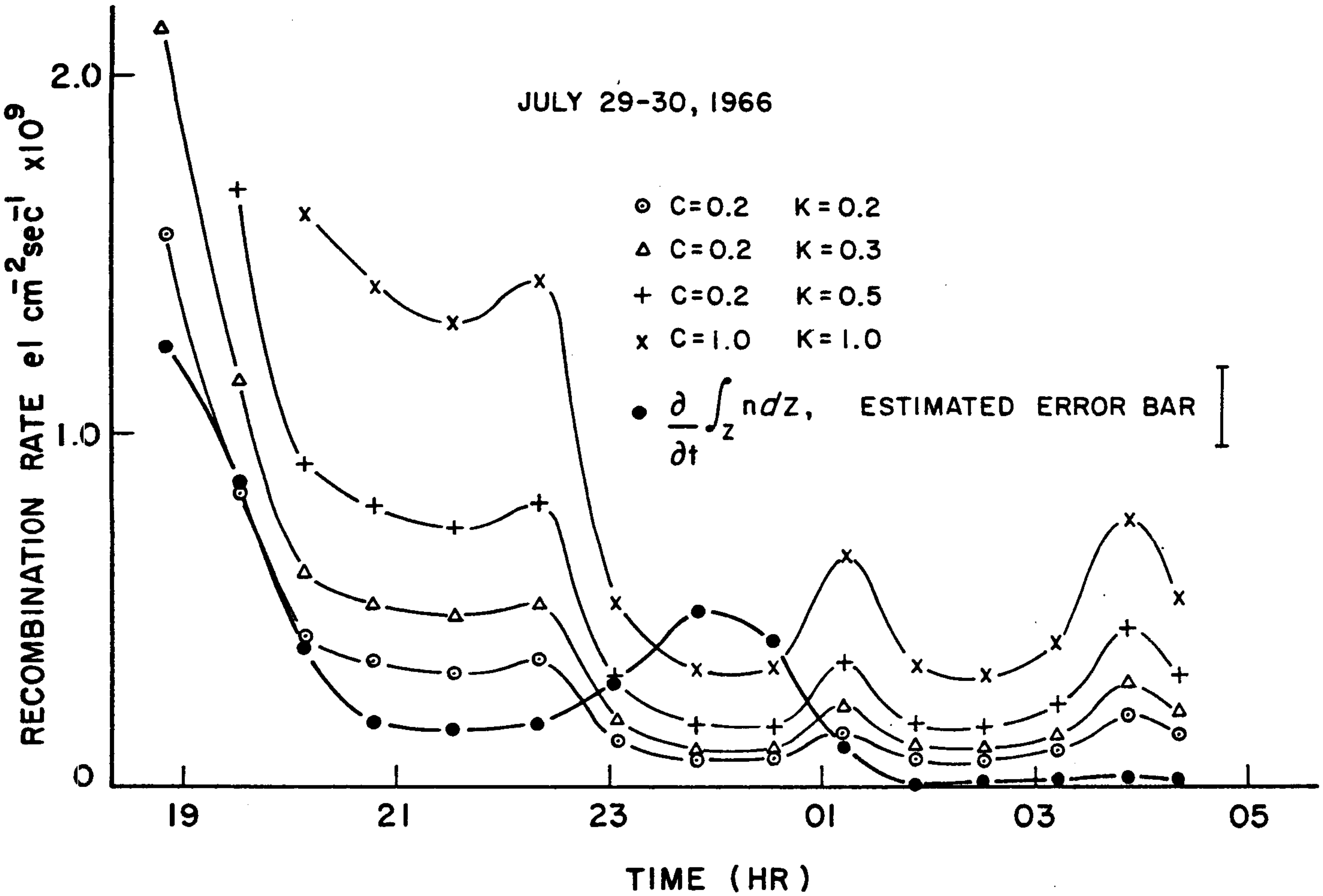
This conclusion should be accepted with some caution, however, for there is convincing evidence that the production does not remain constant during the night, for example, in the case of the predawn photoelectric flux, Carlson and Nisbet (1966), Carlson (1966), Nisbet (1968), Nisbet and Kwei (1968). The relation between the recombination rate and the assumed value of $\overline{\alpha}$ will depend on the shape of the electron density profile and $\overline{\alpha}$ will presumably have the most effect in the early evening when the F 1 layer is recombining. Thus, offsetting systematic errors may be made by assuming the production to be constant and adjusting the recombination parameters to obtain a best fit to the data. In particular, it should be noted that the best fit data correspond to values of $\overline{\alpha}$ which would be very difficult to reconcile with laboratory measurements.

4.3 Difference Between the Loss and Recombination Rates

The most general form of the electron continuity equation includes recombination, production and a downward flux from the top of the layer. Thus, if the reaction rates are assumed to be known it is possible to determine the production necessary to explain the observed changes in the electron content. The difficulty in using this technique is that the neutral atmosphere densities are uncertain to at least a factor of 2. There is also an uncertainty in the laboratory rates and their temperature coefficients.

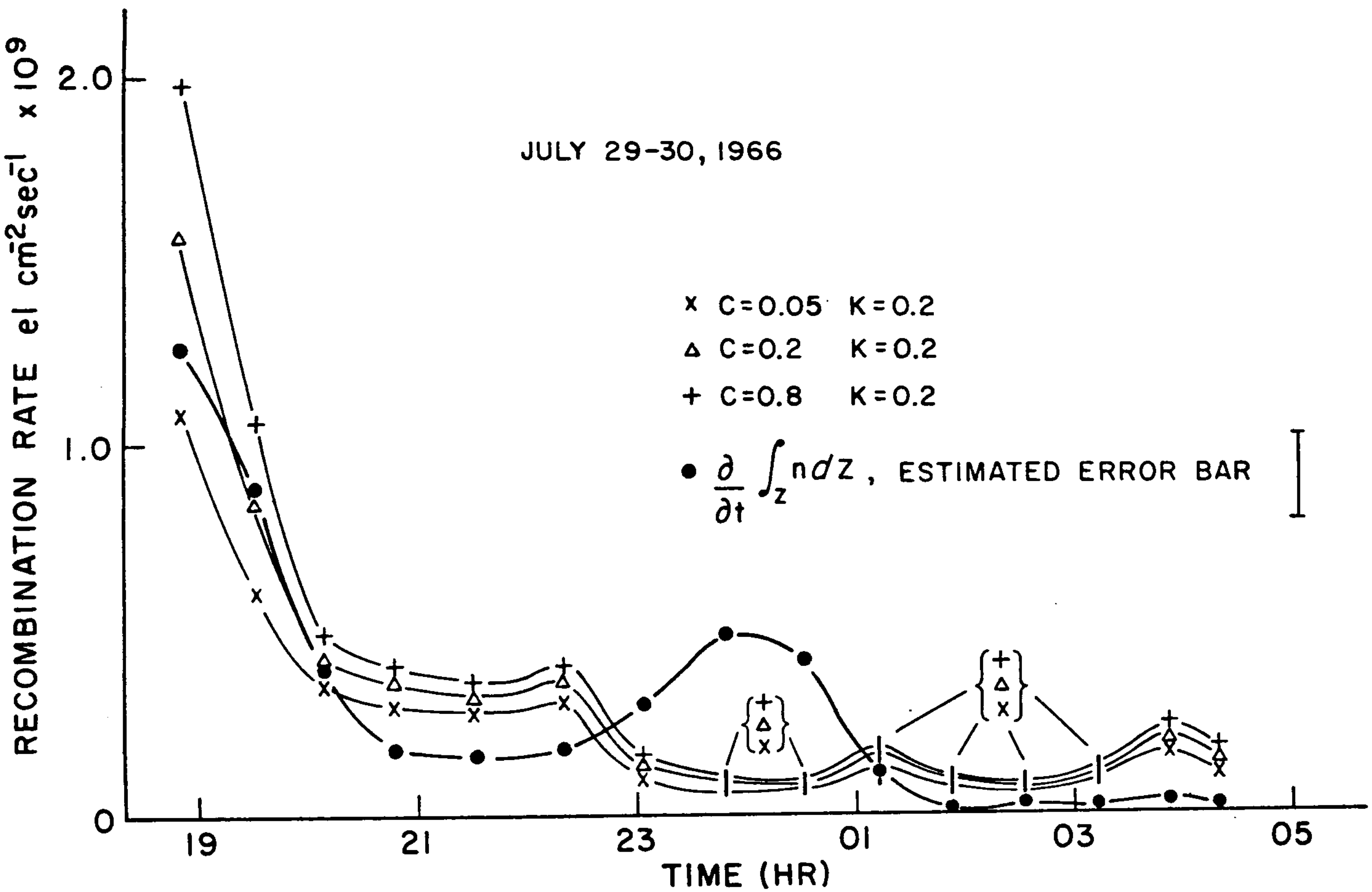
4.3.1 Production Required if Reference Rates are Assumed to be Correct

If it is assumed that K and C are unity, that is, the neutral atmospheres are correct in regards to the molecular nitrogen and oxygen densities and that the reference rates for the atom ion interchange and dissociative reaction rates are correct, then the recombination rate and the loss rates can be compared. It is apparent from Figures 9 through 24 that there is a general agreement between the behavior of the loss and of the recombination. For fluctuations with periods longer than four hours, the loss rate increases when the recombination rate increases. During the early part of the night both decay together. The loss rates remain



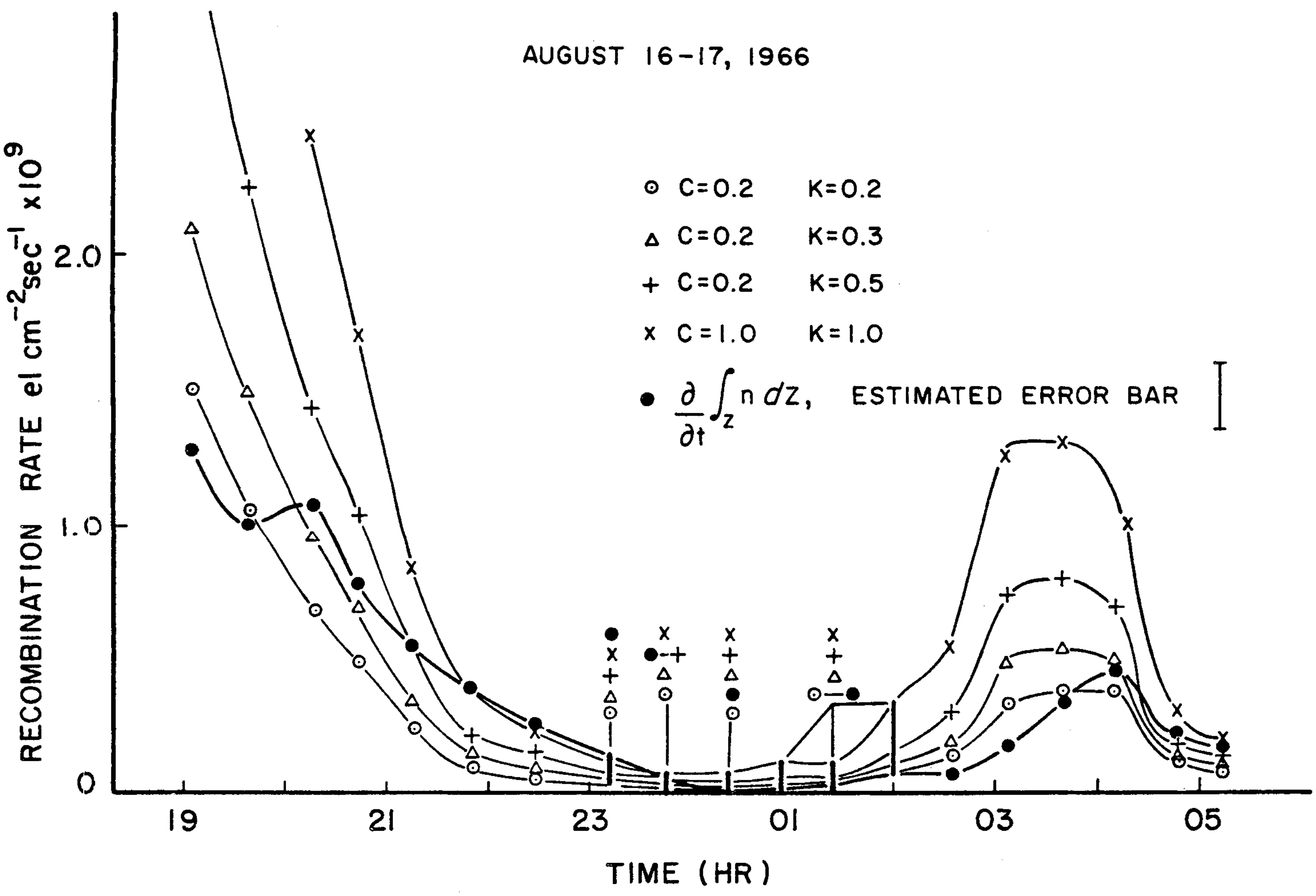
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 9



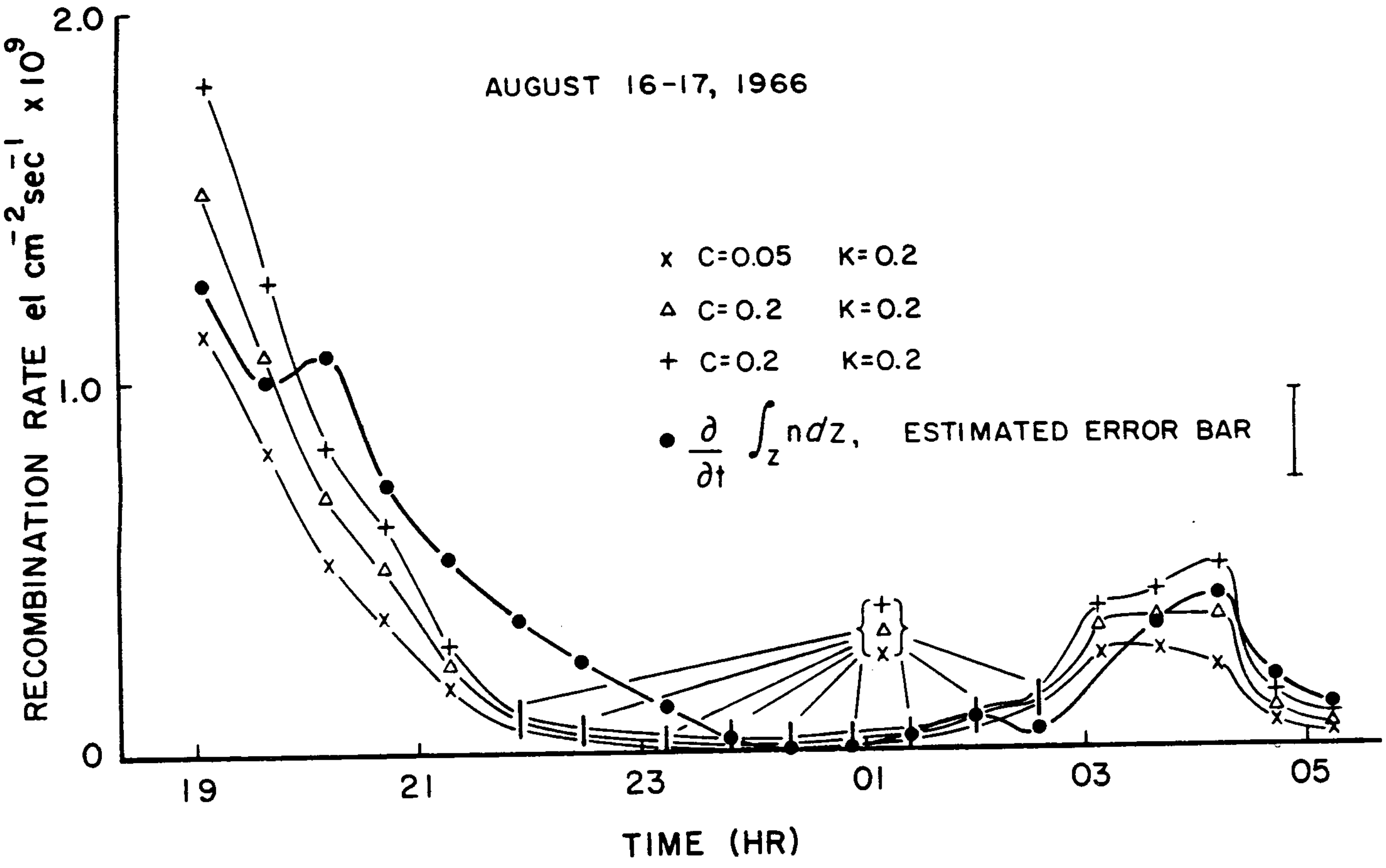
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 10



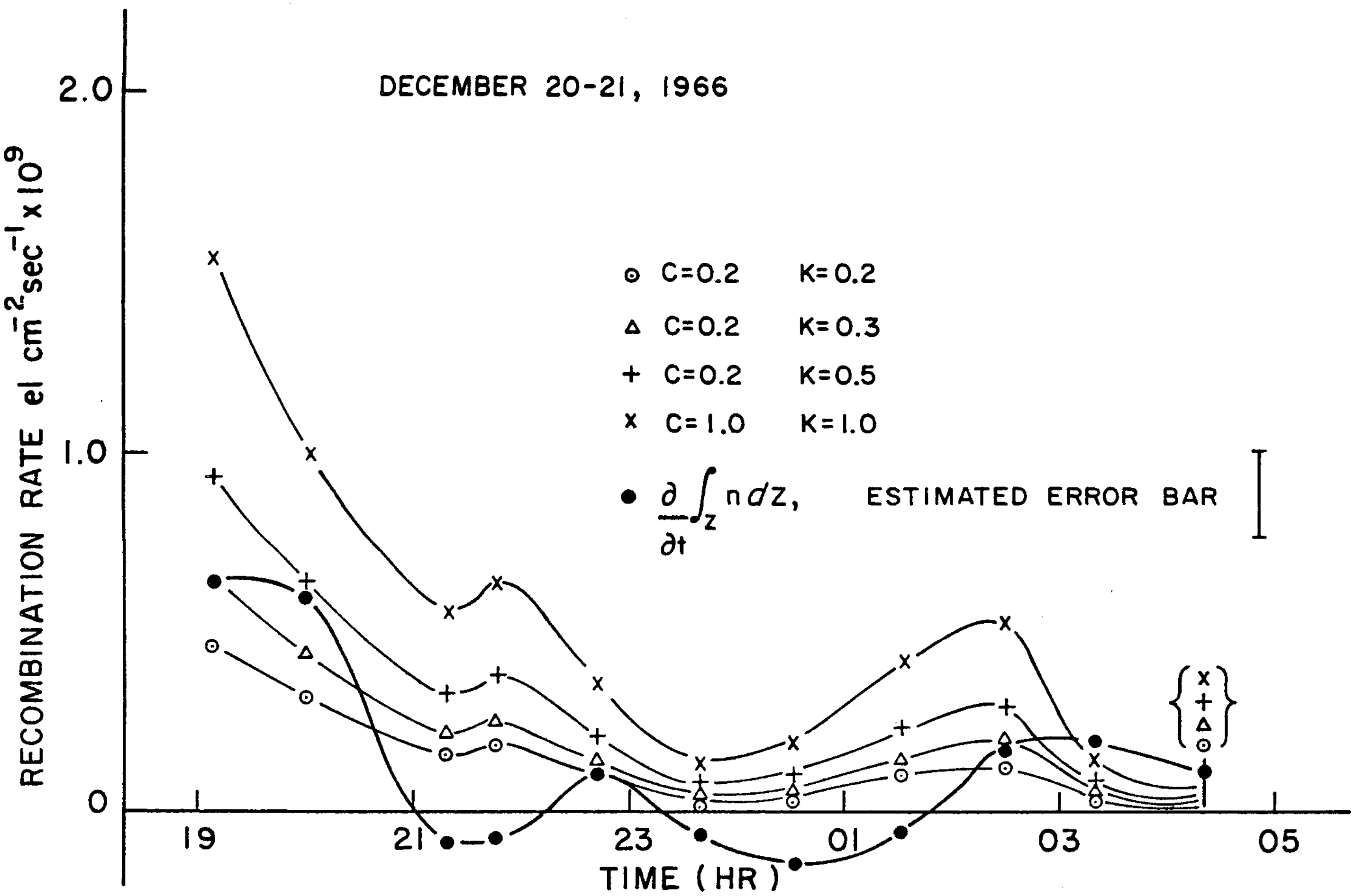
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 11



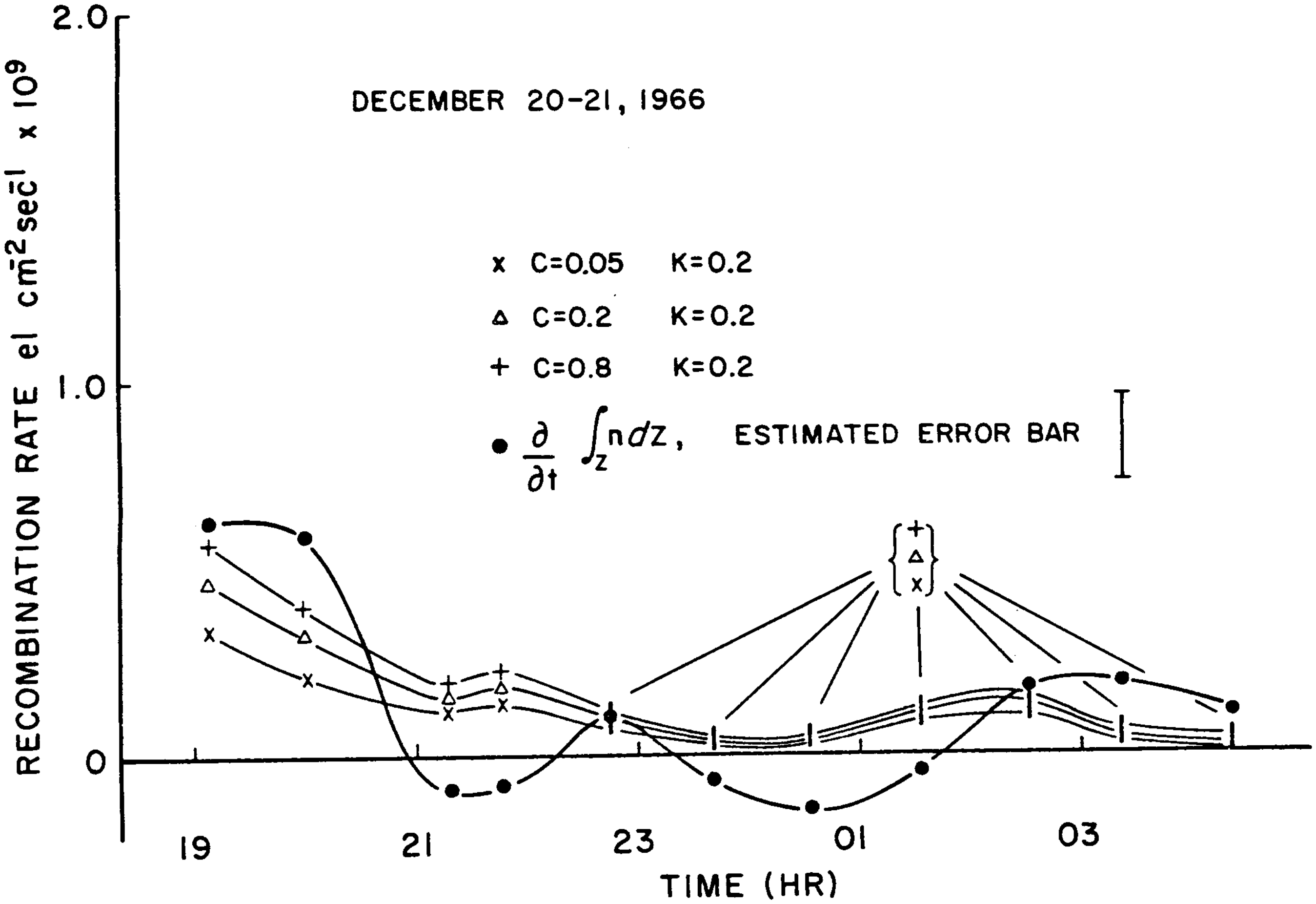
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 12



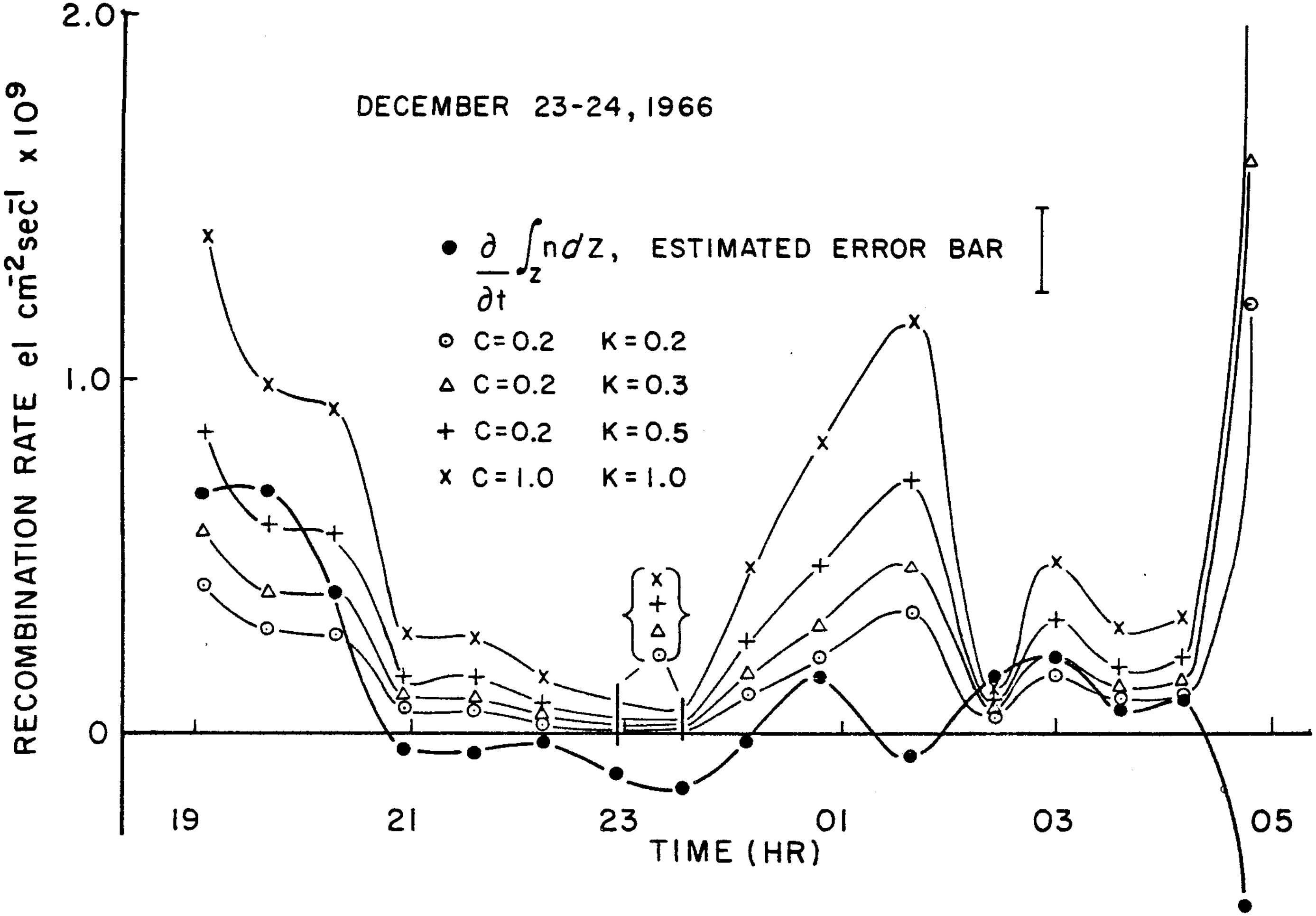
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 13



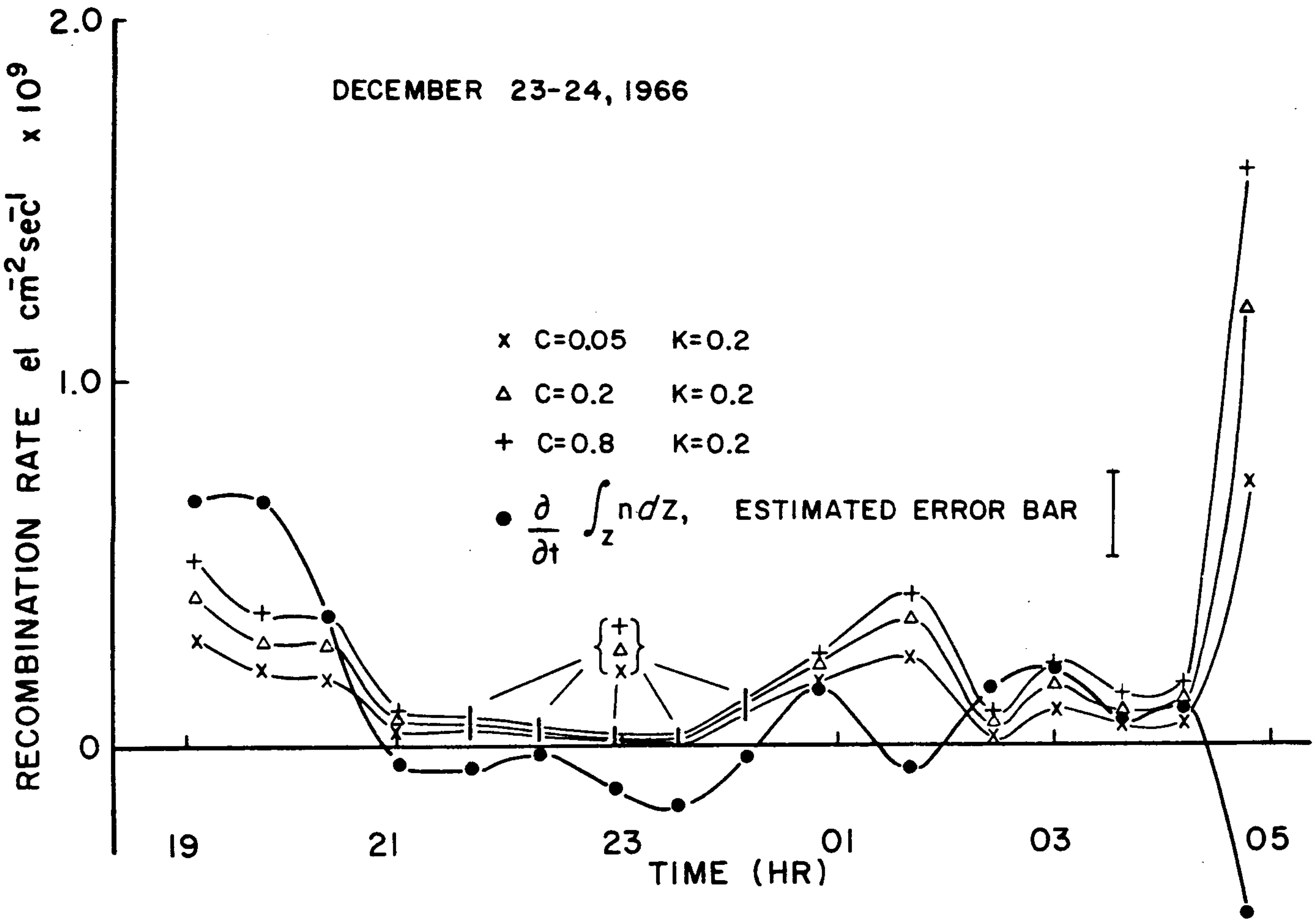
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 14



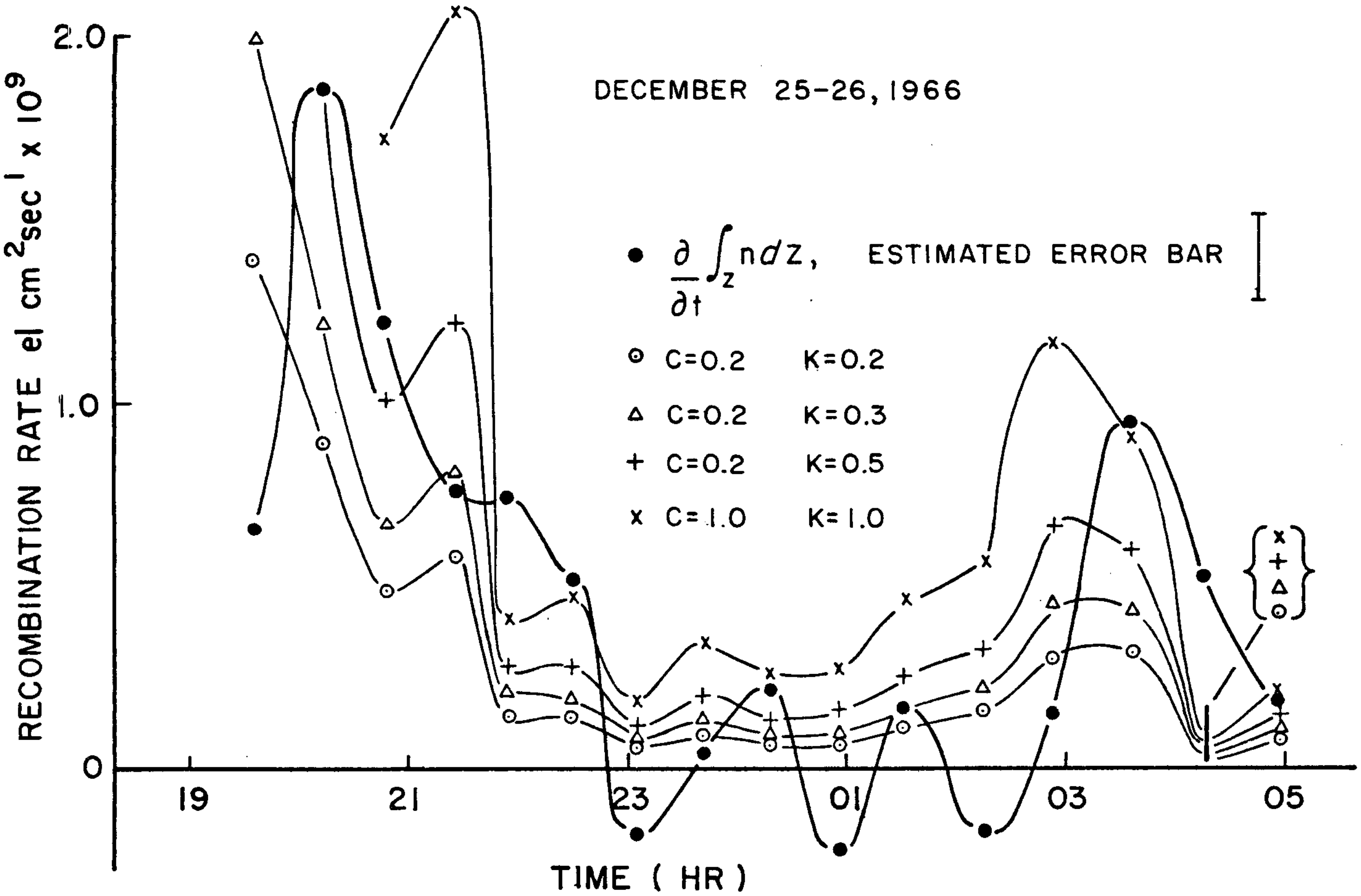
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 15



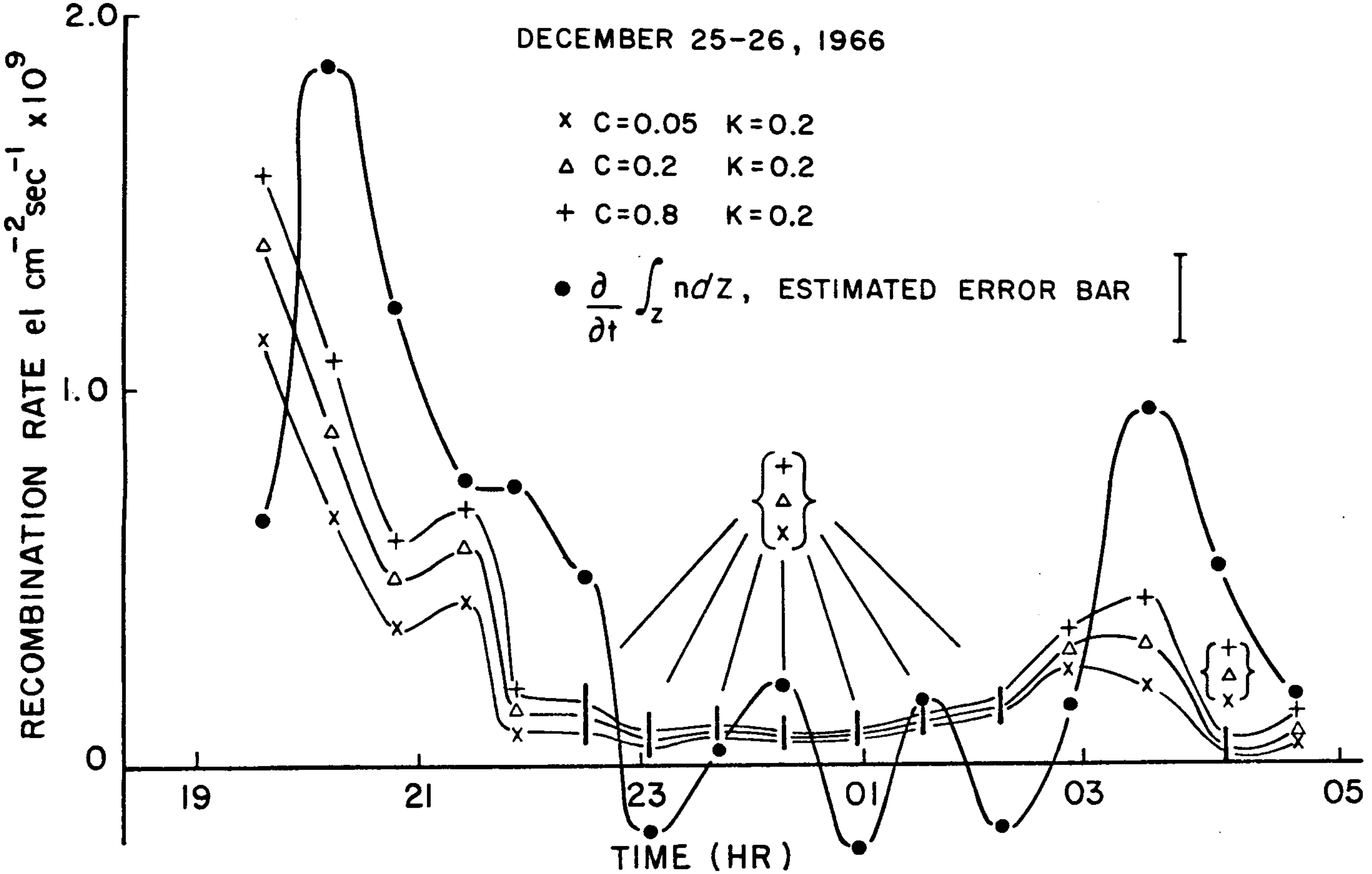
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 16



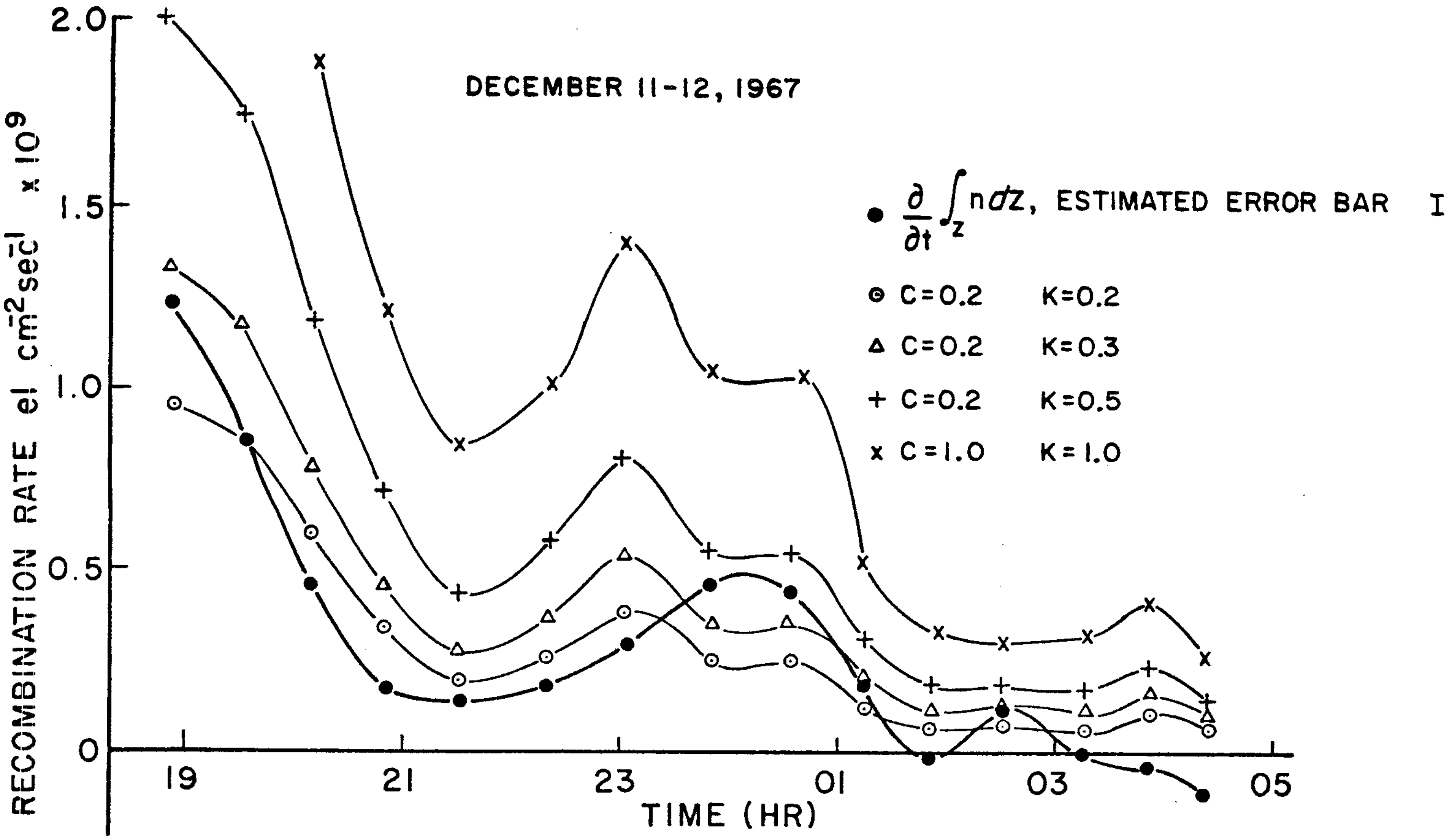
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 17



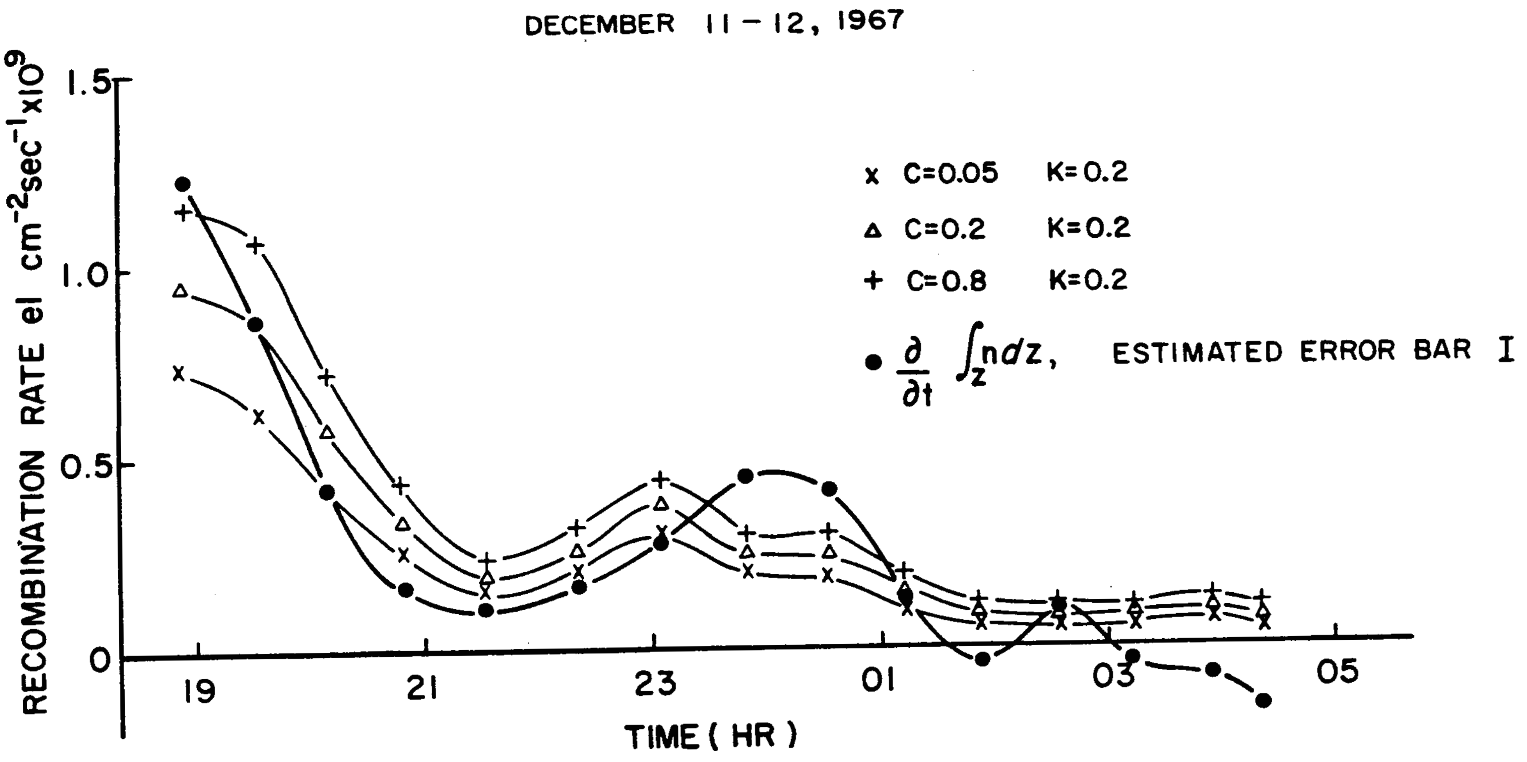
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 18



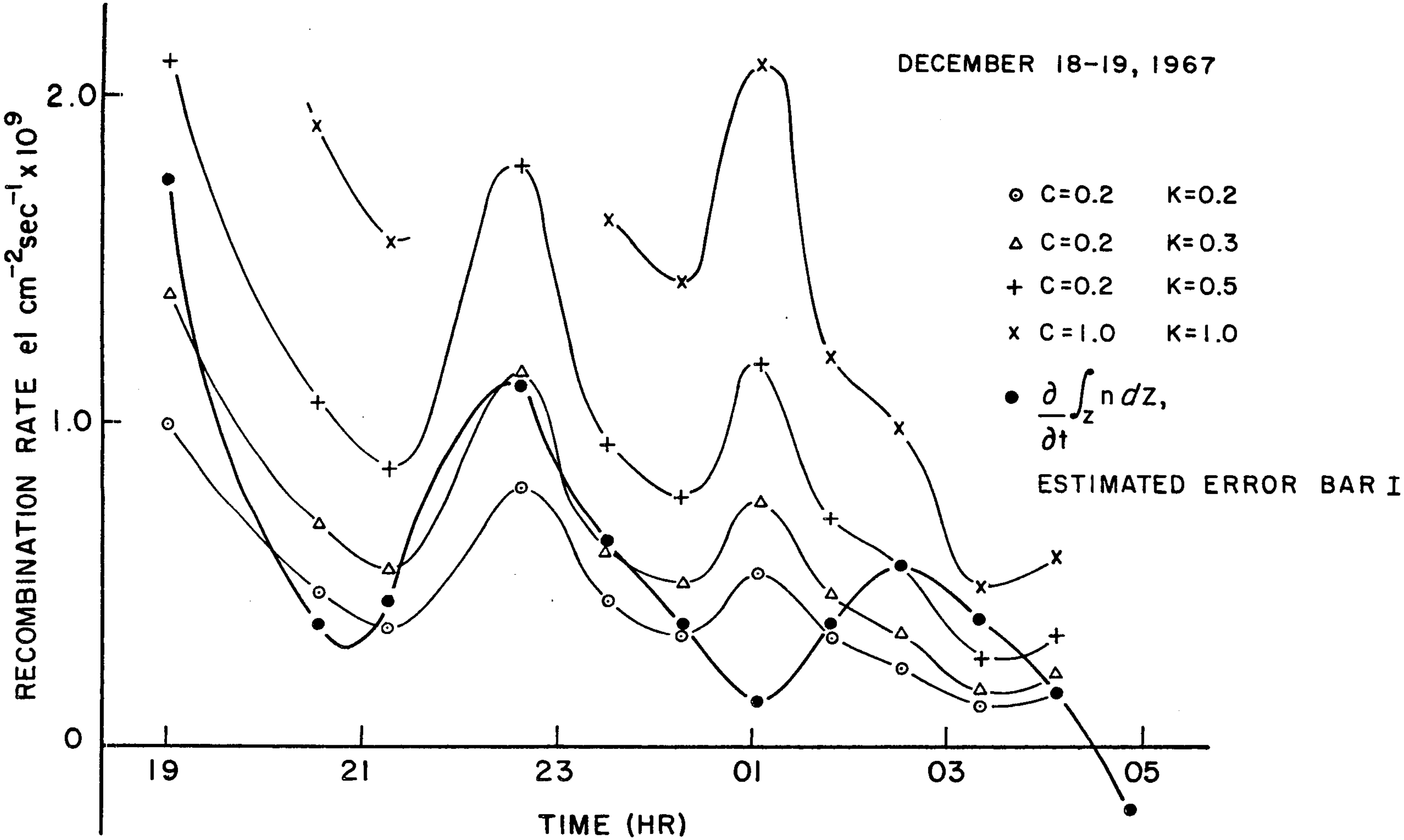
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 19



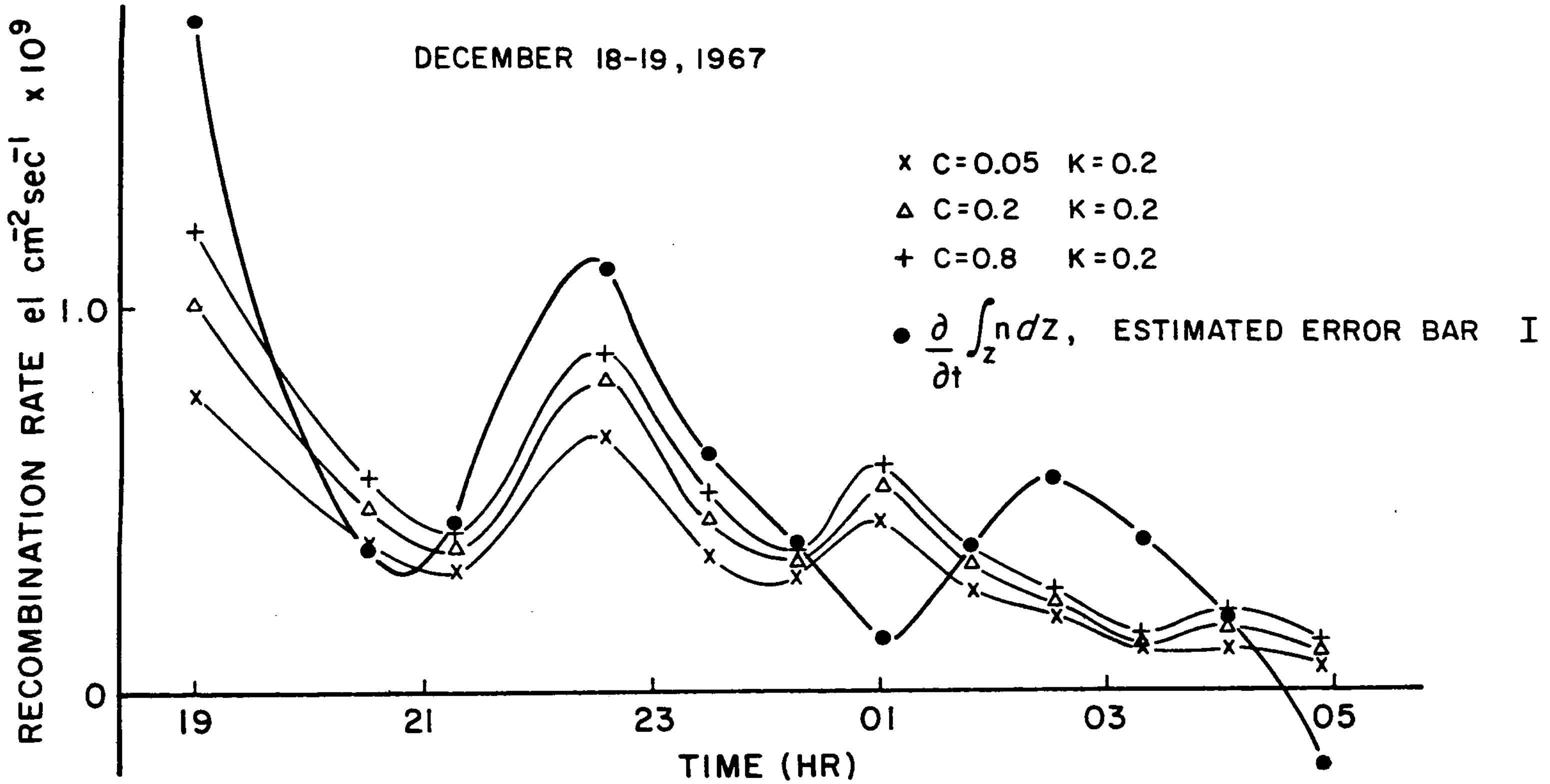
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 20



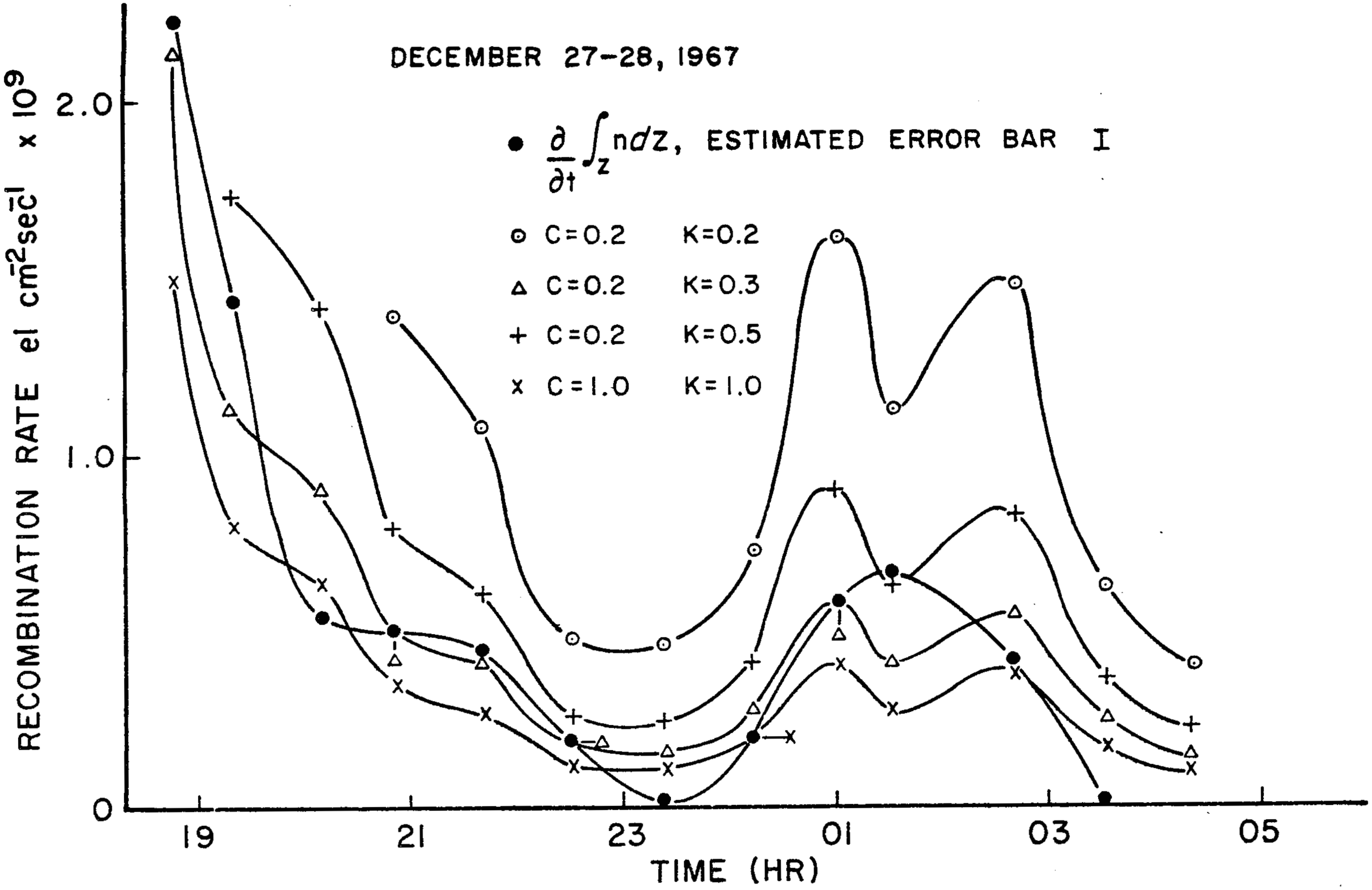
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 21



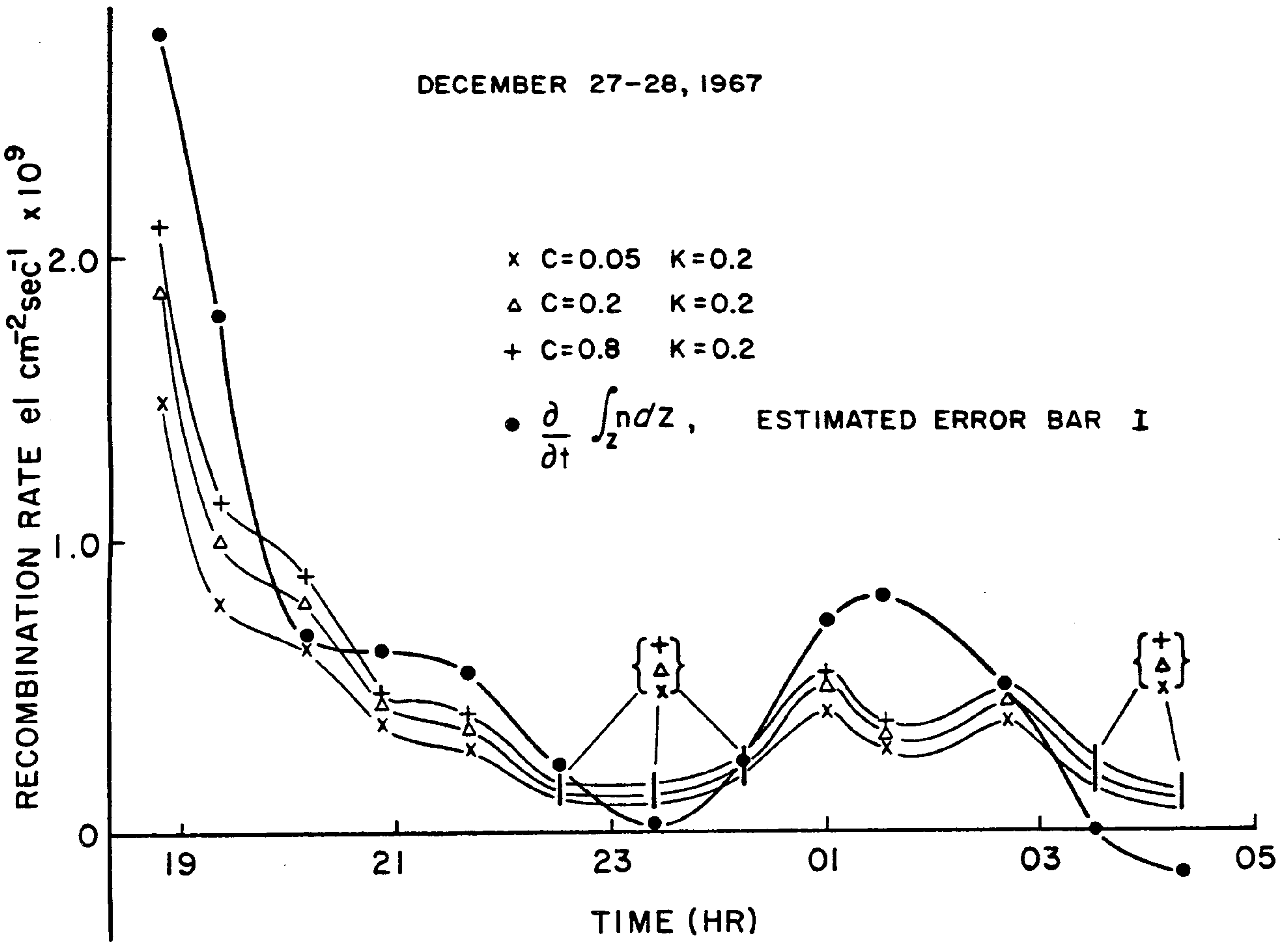
RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 22



RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 23



RATE OF CHANGE IN THE TOTAL ELECTRON CONTENT COMPARED WITH THE INTEGRATED LOSS

FIGURE 24

rather consistently higher by about a half order of magnitude than the recombination rates. This behavior is shown rather well in Figures 11 and 19 for example.

If the reference rates and the neutral atmosphere models are correct then it is apparent that a production mechanism must exist throughout the night which is of the same order of magnitude as the loss rates. This production must be well correlated with both the recombination rate and the loss rate. Taking the night of December 11/12, 1967 as an example, a production of 1.5×10^9 electrons $cm^{-2}sec^{-1}$ would be required at 19 hours and a production of about 10^9 electrons $cm^{-2}sec^{-1}$ would be required at 23 hours. Production sources of this order of magnitude are very difficult to explain. If it is assumed that they are due to a particle influx, then changes in the electron temperature would be expected, but during this period the T_e/T_i ratio remains close to unity within the limits of accuracy of the measurement. If it is assumed that the production is due to horizontal transport in a density gradient then with the order of magnitude of the gradients effective during this part of the night, 5×10^3 electron cm^{-3}, a production of 10^9 $cm^{-2}sec^{-1}$ would require a horizontal ion transport velocity of 2000 meters per second which is quite unreasonably large. It thus seems that if the reference rates are indeed effective for the night in question the entire nighttime F region theory must be completely re-examined.

4.3.2 Rates Lower than Reference Rates

Figure 12 shows the effect of varying the rates of the dissociative recombination reactions. It is apparent that providing the ratio of the rates for these reactions is not reduced below about 0.2 of the reference rates the recombination is little affected by the actual value chosen. Values for the rates of the dissociative recombination reactions can be made arbitrarily large without materially affecting the conclusions of this section.

As mentioned in Section 2.1.1 the accuracy in determining the recombination was dependent upon how accurately the peak electron density could be determined from the ionograms. When ionograms were unavailable or unuseable it was necessary to rely upon the power density profiles which introduced error in the evaluation of the recombination over 45 minute time intervals. When the ionograms were not available or showed spread F, then only conclusions could be made concerning the general variations over the entire night in question. The recombination for the winter 1967 experiments was obtained from Faraday rotation measurements and were very much more accurate. With these measurements there did remain the difference of about 140 km in the horizontal separation of the ionospheric regions sampled by the electron content and recombination measurements.

For the December 11/12, 1967 experiments the ionosphere remained relatively quiet with 3 hourly k_p indices of 0, 2, 2, 1 from 18 hours to 3 hours and only occasional spread F. The recombination and loss for the December 11/12, 1967 experiments were in general agreement, with the best fit obtained for K = 0.3 or K = 0.2. For K = 0.3 there was the need for an additional production of the order of 10^8 el $cm^{-2}sec^{-1}$ from 19 to 21 hours. For K = 0.2 the assumed loss was within the error bars from 19 to 21 hours, but an additional production of the order of 10^8 was needed from 3 to 4 hours for either K = 0.2 or K = 0.3.

The ionosphere was disturbed during the night of December 18/19, 1967 as indicated by the 3 hourly k_p indices of 2, 2, 4, 2 from 10 hours to 3 hours and there was evidence of spread F from 3 hours until 4 hours. It is interesting to note that for the December 18/19, 1967 experiments there were large fluctuations in both the recombination and the assumed loss. The best fit from 19 hours to midnight was obtained for K = 0.3. It was noticed that for K = 0.2

the loss was generally less than the recombination. Fluctuations in the loss and the recombination were opposite in phase between 1 and 3 hours. For K = 0.2 an additional production of 2×10^8 el $cm^{-2}sec^{-1}$ was needed at 1 hour, but an excess loss of 2×10^8 el $cm^{-2}sec^{-1}$ was needed at approximately 2:30.

The ionosphere on the night of December 27/28, 1967 was quiet with 3 hourly K_p indices of 1, 1, 1, 1 from 18 hours until 3 hours and a small amount of spread F. The recombination and assumed loss were in good agreement for this December 27/28, 1967 night. The best fit was obtained for K = 0.3 from 19 hours to approximately 3 hours. A production of the order of 10^8 el $cm^{-2}sec^{-1}$ was required from 3:30 to 4 hours for K = 0.3.

For the night of July 29/30, 1966 the ionosphere was disturbed as shown by the 3 hourly K_p indices of 2, 2, 1, 2 from 18 hours until 3 hours and by spread F at midnight and from 23 hours until 3 hours. As these profiles were normalized using the ionosonde, large errors in the recombination rates may be expected at these times. The results indicated a large recombination around midnight which was not reflected in the loss rates. With an assumed K of 0.2 there was the need for an extra loss of approximately 4×10^8 el $cm^{-2}sec^{-1}$ at midnight. In general, the best fit for the night in question was obtained for K = 0.2 with a required flux of approximately 1.8×10^8 from 21 hours to 22:30 and 0.8×10^8 from 2 hours to 4 hours.

For the night of August 16/17, 1966 the 3 hourly K_p indices were 0, 1, 1, 1 from 18 hours to 3 hours, but there were no readable ionograms from 19 hours to 20 hours with spread F present from 23 hours to 2 hours and from 4 hours until 5 hours. For the August 16/17, 1966 experiments it was noted that for $K = 0.5$ a large production of approximately 2×10^9 el $cm^{-2}sec^{-1}$ would be required at 19 hours. For $K = 0.3$, a production of 10^9 el $cm^{-2}sec^{-1}$ was required at 19 hours and for $K = 0.2$ the loss was within the order of error with only a slight production required prior to 20 hours and an extra loss from 20 hours to midnight. The peak recombination observed between 2 and 5 hours was within the error bars for $K = 0.2$ or $K = 0.3$ with a slight production required for $K = 0.3$.

The 3 hourly K_p indices for the night of December 20/21, 1966 were 0, 1, 0, 1 from 18 hours to 3 hours, but spread F was present from 23 hours to midnight and no readable ionograms were available from 4 hours to 5 hours. The December 20/21, 1966 experiments showed fluctuations in both the recombination and the loss. The best fit was obtained for $K = 0.2$ or $K = 0.3$ with a required production of the order of 10^8 el $cm^{-2}sec^{-1}$ from 21 to 1 hours.

There was spread F present throughout the entire night of December 23/24, 1966 with 3 hourly K_p indices of 1, 3, 2, 1 from 18 hours until 3 hours. Thus, the large disagreement observed between the recombination and the loss for the night in question can be attributed to the large errors involved in determining the recombination from the density profiles. The December 23/24, 1966 experiments indicated very low recombination rates. The best fit from 21 hours to midnight was obtained for a value of K = 0.5 with a required production of the order of 10^8 el $cm^{-2}sec^{-1}$. The best fit from midnight to 2 hours was for K = 0.2 with a required production of the order of 10^8 el $cm^{-2}sec^{-1}$. From 4 hours until 5 hours there is an extremely large production required of the order of 2.5×10^9 el $cm^{-2}sec^{-1}$ for K = 0.2.

The ionograms for the night of December 25/26, 1966 indicated some spread F from 23 hours until midnight and increasing after midnight until 3 hours. The 3 hourly K_p indices were 4, 3, 2, 2 from 18 hours until 3 hours which indicated the presence of a magnetic disturbance. The recombination for the December 25/26, 1966 experiment indicated large flucutations with a period of about 1 1/2 hours from 23 to 3 hours. The best fit was obtained for K = 0.5 but the sudden fluctuations in the recombination were not reflected in the loss rates.

This large disagreement could be due to horizontal gradients produced by the magnetic disturbance or to the error introduced by spread F in determining the peak electron density from the electron density profiles.

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Comparison of the Theoretical loss Rates and the Observed Recombination

The previous studies by Quinn and Nisbet (1965) and McCrory (1966) indicated that if there were no production sources present during the night, then the recombination coefficient at 300 Km, β_{300}, was smaller in winter than in summer. The detailed study made of the recombination coefficient, β_{300}, with the high resolution data for the present analysis indicated that β_{300} was again smaller in winter than in summer. Also, the variation of β_{300} with $\overline{\alpha}$, the dissociative recombination rate, for this study was in good agreement with results of the previous study. It was found that the best fit between the theoretical loss rates and the observed recombination was obtained when the atom ion interchange reaction rates were reduced by a factor of 2 to 5 from current laboratory values.

5.2 Comparison of the Laboratory Reaction Rates with the Observed Behavior

It was observed that by choosing a dissociative recombination rate that was within an order of magnitude of the laboratory reaction rates that the results were quite independent of the value chosen. This means that our experiments are rather insensitive to the value of the dissociative reaction rates and provide little information about them.

If it is assumed that both the neutral molecular densities and the laboratory rates are correct then a production of the order of 10^9 electrons $cm^{-2}sec^{-1}$ would be required from 20 hours to 23 hours and smaller but comparable production rates would be required thereafter. To account for a production of this magnitude by incoming photoelectrons or higher energy particles would require much larger fluxes than are predicted theoretically or are observed, and would result in electron heating which would be readily observable. If as an alternative it is assumed that the source is the protonosphere, then these rates would result in draining the entire protonospheric electron content in one and a half hours. If it is proposed to account for the rates on the basis of horizontal ion transport then with the observed gradients a horizontal velocity of the order of 2000 meters per second would be required. It was therefore concluded that either the molecular densities are lower than given by the CIRA 1965 models or that the rates for atom-ion interchange are smaller than current laboratory values would suggest.

When values for the atom-ion interchange rates, or the molecular densities were reduced to 1/5 of the laboratory values it was found that the observed recombination rate was higher than the calculated loss rate in the early part of the night and an additional production was usually required between 2 hours and 4 hours. There are good reasons for believing that the loss rates should be higher than the recombination rates in the period prior to about 22 hours and it was concluded that the rates were higher than 1/5 of the laboratory rates.

When the values were reduced to 0.3 of the laboratory values a reasonable correlation between the detailed behavior of the recombination rate and the loss rate was observed throughout the night. A net production of the order of 10^8 electrons $cm^{-2}sec^{-1}$ was required prior to 23 hours and between 2 hours and 4 hours. As was shown, such sources of production are quite reasonable. It was concluded that for the present series of measurements the best agreement between the experimental results and the calculated loss of ionization could be obtained by reducing the product of the molecular densities (CIRA atmospheric models) and the laboratory atom-ion interchange reaction rates by about a factor of 3.

5.3 Differences Between the Summer and Winter Loss Rates

A major feature of the analysis of nighttime F region by Quinn and Nisbet (1965) was the large difference between the summer and winter loss rates under quiet solar conditions when the production term was assumed to be zero throughout the night. When the present data were analyzed with the assumption of zero nighttime production the results also showed lower rates for winter than for summer.

A second analysis in which it was assumed that the production was constant was made and a least squares technique was used to determine the best fit values for the reaction rates and the constant production term. This analysis showed that with these assumptions the loss rates were lower in summer than in winter, the reverse of the zero production result, but that the required production was larger in the winter. This conclusion must be accepted with caution since it is based on a constant production and there are good reasons for believing that this is not the case.

An examination of the detailed shape of the loss and recombination rates indicated that both the summer and winter rates were quite comparable within the limits of error and it appeared that the major differences lay in the required production from 19 hours to 23 hours and from 2 hours to 4 hours.

5.4 The Effect of Photoelectrons on the Nighttime F Layer

During the winter photoelectrons are continuously being produced in the conjugate ionosphere and it has been shown by Carlson and Nisbet (1966) and Carlson (1966) to be effective in heating the ionosphere above Arecibo.

Estimates of the fluxes and their energy distribution have been given by Nisbet (1968) and Kwei and Nisbet (1968). McCrory (1965) suggested that they might be effective in providing the production necessary to explain the increase in the electron content between 2 hours and 4 hours.

It is apparent that the photoelectron flux itself does not provide a production mechanism because any entry of charged electrons will produce a corresponding flux of thermal electrons along the field line in the opposite direction. Photoelectrons with energies above 20 ev are capable of producing secondary ionization. It is estimated that at 02.30 hours at the winter solstice under low sunspot conditions the flux of electrons having energies greater than 20 ev would be of the order of 7×10^7 el cm^{-2}.

As discussed in Section 5.2 this is lower then the production rates necessary to explain the behavior of the layer between 19 hours and 23 hours and between 2 hours and 4 hours in winter. It does seem adequate to explain the differences between summer and winter loss rates providing it is assumed that the rates of the atom ion interchange reactions multiplied by the neutral atmosphere molecular densities are lower by about a factor of 3 than the reference values adopted in this study.

5.5 Horizontal Ion Transport in the Nighttime F Region

Ionized Barium trail measurements by Haerendel et. al. (1966), described in Section 1.2.2, show at times around sunset, horizontal ion velocities in the direction of the night side of the earth of the order of 50 meters per second or about one half of the neutral wind velocity. If these motions are maintained for several hours after sunset as appears probable then they would appear to provide a quasi-production mechanism. In the period from 19 hours to 22 hours the gradient in the electron content in the east west direction is of the order of 2×10^4 electrons cm^{-3}. With a 50 meter per second drift this would produce an effective production of 10^8 electron $cm^{-2} sec^{-1}$. This is comparable with the production rates required in the summer to explain the differences between the recombination and loss with the laboratory rates for the atom ion interchange reactions reduced by a factor of 3.

As was discussed in Section 5.3 an additional production source appears to be required between 2 and 4 hours particularly in winter. As at this time of night the horizontal gradients are generally small the above mechanism cannot be very effective. One possible solution is that the ion wind system is convergent under these conditions. No measurements of the horizontal ion velocity have been obtained unless it is assumed that F region fading measurements correspond to true ion motions. It is possible, however, to make some assumptions about the divergence of the neutral wind system about this time. One way of doing this is to study the behavior of the negative temperature. It is now generally held that the "second heat source" effective in maintaining the nighttime F region is the horizontal motion from the day side to the night side of the earth. If this is indeed the case then to account for an observed heat input of Q erg $cm^{-2}sec^{-1}$ above an altitude z, it would require a divergence of the wind velocity of

$$\text{div}\ \bar{v}_{zo} = \frac{Q_o}{\int_{z_o}^{\infty} P dz}$$

where

v = the horizontal wind velocity (assumed constant) with altitude

Q = the downward heat conduction through altitudes z_o in the steady state

P = the pressure

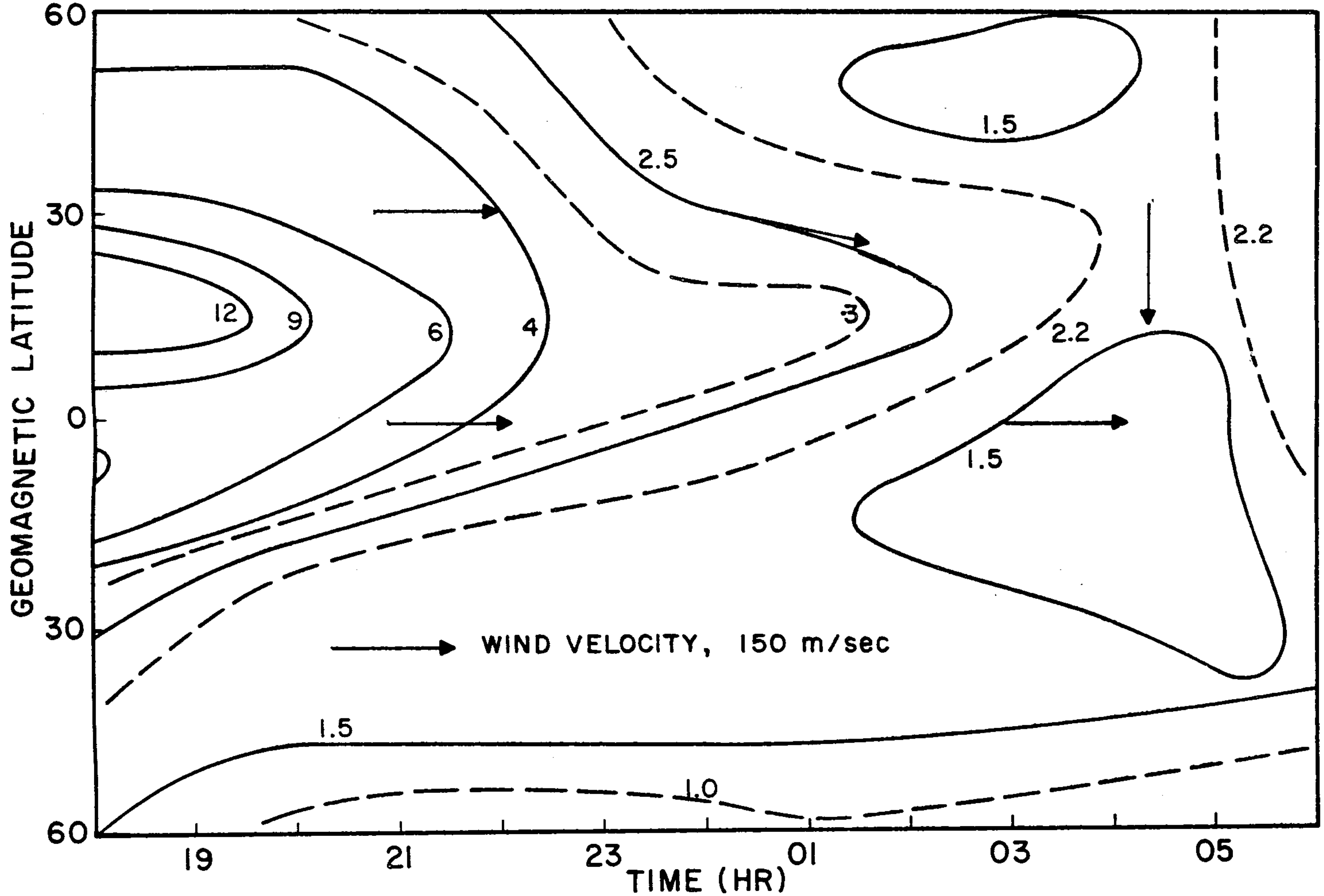
With an assumed heat flux of 1 erg $cm^{-2}sec^{-1}$ above 120 km then the divergence of the wind velocity would be 2.2×10^{-5} sec^{-1} for the neutral atmosphere models used for the preceding analysis. If it is now assumed that during this period the ion velocity divergence is equal to the above value then with an electron content of 2.5×10^{-5} electrons cm^{-2} an effective production of 0.57×10^{8} electrons $cm^{-2}sec^{-1}$ would result.

A second method of making a similar calculation is to use the neutral velocities calculated by Kohl and King (1967). These have been superimposed on a map showing the distribution of the electron content as a function of geomagnetic latitude and local time shown in Figure 25. Using the divergence theorem and considering an element from 23 hours to 3 hours and from 15^{o} to 45^{o} longitude it was calculated that the divergence of the flux was of the order of 1.2×10^{8} electrons $cm^{-2}sec^{-1}$ assuming the neutral and ion horizontal velocities to be equal.

It would therefore seem that if horizontal ion velocities are important in the period after midnight then their magnitude must be comparable with the current estimates of the neutral wind velocities.

5.6 Suggestions for Further Research

Obviously more research needs to be done using the high resolution data as provided by Faraday rotation



ELECTRON CONTENT AT NORTHERN SOLSTICE $\times 10^{12}$ el cm^{-2}

FIGURE 25

measurement. It is only when accurately determined values for the recombination coefficient are available that it will be possible to make detailed comparisons between the loss rates and the recombination concerning their detailed behavior.

Also, when more information becomes available on the ion velocities and ion velocity divergences more accurate determinations can be made on the amount of ionization available from horizontal transport.

BIBLIOGRAPHY

Aquilanti, V. and G. G. Volpi, "Some Sonic Processes of Interest in the Upper Atmosphere", Ric. Sci., 36, 359, 1966.

Bates, D. R. and H. S. W. Massey, "The Basic Reaction in the Ionized Layers", Proc. Roy. Soc., A192, 1947.

Bechen, J. and B. Maehlum, "Drift Measurements at Kjeller on the Ionospheric F Region", J. Geophys. Res., 65, 1485, 1960.

Bhavsar, H. and R. Rao, "Rocket and Balloon Studies", Presented at the Ninth COSPAR Meeting in Vienna, May 10-19, 1966.

Bradbury, N. E., "Ionization, Negative Ion Formation and Recombination in the Ionosphere", Terr. Magn. Atmos. Elect., 43, 55, 1938.

Carlson, H. C., "Ionospheric Heating by Magnetic Conjugate-Point Photoelectrons", J. Geophys. Res., 71, 195, 1966.

Carlson, H. C. and J. S. Nisbet, "Electron Densities and Temperatures in the F Region from Backscatter Measurements at Arecibo", in Electron Density Profiles in Ionosphere and Exosphere, ed. by J. Frihagen, North Holland Pub. Co., Amsterdam, 1966.

Chandra, S., J. J. Gibbons, and E. A. Schmerling, "Vertical Transport of Electrons in the F Region", J. Geophys. Res., 65, 1159, 1960.

Chapman, J. H., "A Study of Winds in the Ionosphere by Radio Methods", Can. J. Phys., 31, 120, 1953.

Copsey, M. J., D. Smith, and J. Sayers, "Laboratory Afterglow Studies of O^+ Ions on Helium-Oxygen and Helium-Oxygen-Nitrogen Mixtures", Planet. Space Sci., 14, 1047, 1966.

Cospar International Reference Atmosphere 1965, North Holland Pub. Co., Amsterdam, 1965.

Donahue, T. M., "Ionospheric Reaction Rates in Light of Recent Measurements in the Ionosphere and Laboratory", Planet. Space Sci., 14, 33, 1966.

Dungey, J. W., "The Effect of Ambipolar Diffusions in the Nighttime F Layer", J. Atmos. Terr. Phys., 9, 90, 1956.

Elford, W. C., "A Study of Winds Between 80 and 100 Kilometers in Medium Latitudes", Planet. Space Sci. 1, 94, 1959.

Fehsenfeld, F. C., A. F. Schmeltekopf, and E. E. Ferguson, "Some Measured Rates for Oxygen and Nitrogen Ion-Molecule Reactions of Atmospheric Importance, Including $O^+ + N_2 \rightarrow NO^+ + N$", Planet. Sci., 13, 219, 1965a.

Fehsenfeld, F. C., P. D. Goldan, A. L. Schmeltekopf, and E. E. Ferguson, "Laboratory Measurements of the Rate of the Reaction $O^+ + O_2 \rightarrow O_2^+ + O$ at Thermal Energy", Planet. Space Sci., 13, 579, 1965b.

Ferguson, E. E., "Ionospheric Ion-Molecule Reaction Rates", Rev. Geophys., 5, 305, 1967.

Ferguson, E. E., F. C., Fehsenfeld, P. D. Goldan, and A. L. Schmeltekopf, "Positive Ion-Neutral Reactions in the Ionosphere", J. Geophys. Res., 70, 4323, 1965.

Föppl, H. and G. Haerendel, "Final Report About Experiment R-33 in ESRO Payload IV", Max-Planck Institut Für Physik und Astrophysik, 1965.

Garriott, O. K. and J. O. Thomas, "Some Numerical Solutions of the Continuity Equation for Electrons in the Nighttime F Region of the Ionosphere", J. Geophys. Res., 67, 4211, 1962.

Geisler, J. E., "Atmospheric Winds in the Middle Latitude F Region", J. Atmos. Terr. Phys., 28, 703, 1966.

Geisler, J. E., "A Numerical Study of the Wind System in the Middle Thermosphere", J. Atmos. Terr. Phys., 29, 1469, 1967.

Gunton, R. C. and T. M. Shaw, "Electron-Ion Recombination in Nitric Oxide in the Temperature Range 196° to 358°K", Phys. Rev., 140A, 756, 1965.

Haerendel, G., R. Lüst, and H. Föppl, "Motions of Artificial Ion Clouds in the Upper Atmosphere", München Germany, Max-Planck Institut Für Physik und Astrophysik, 1966.

Hanson, W. B. and R. J. Moffett, "Ionization Transport Effects in the Equatorial F Region", J. Geophys. Res. 71, 5559, 1966.

Hines, C. O., "Internal Atmospheric Gravity Waves at Ionospheric Heights", Can. J. Phys., 38, 1441, 1960.

Huxley, L. G. H., "The Investigation of Winds in the Upper Atmosphere by Means of Drifting Meteor Trails", Ann. IGY, 3, 250, 1957.

Jacchia, L. G., "The Atmospheric Region Above 200 km", Space Res. V, North-Holland Amsterdam, 1135, 1965.

Kasner, W. H. and M. A. Biondi, "Electron-Ion Recombination Studies in Oxygen", Bull. Am. Phys. Soc., 11, 218, 1967.

King, J. W. and H. Kohl, "Upper Atmospheric Winds and Ionospheric Drifts Caused by Neutral Air Pressure Gradients", Nature, 206, 699, 1965.

King-Hele, D. G., "The Rotational Speed of the Upper Atmosphere Determined from Changes in Satellite Orbits", Planet. Space Sci., 835, 1964.

King-Hele, D. G. and D. W. Scott, "Further Determinations of Upper Atmosphere Rotational Speed From Analysis of Satellite Orbits", Planet, Space Sci., 15, 1913, 1967.

Kochanski, A., "Atmospheric Motions from Sodium Cloud Drifts", J. Geophys. Res., 69, 3651, 1964.

Kohl, H. and J. W. King, "Atmospheric Winds Between 100 and 700 km and Their Effects on the Ionosphere", J. Atmos. Terr. Phys., 29, 1045, 1967.

Kwei, M. W. and J. S. Nisbet, "Presunrise Heating of the Ionosphere at Arecibo due to Conjugate-Point Photoelectrons", accepted by Radio Sci. 1968.

Lindzen, S., "Crude Estimated for the Zonal Velocity Associated with the Dirunal Temperature Oscillation in the Thermosphere", J. Geophys. Res., 71, 865, 1966.

Lindzen, S., "Reconsideration of Diurnal Velocity Oscillation in the Thermosphere", J. Geophys. Res. 72, 1591, 1967.

Maeda, H., "Worldwide Pattern of Ionization Drifts in the Ionospheric F Region as Deduced from Geomagnetic Variations", Proc. Intern. Conf. Ionosphere, 187, 1962.

Martyn, D. F., "Atmospheric Tides in the Ionosphere: Part I.-Solar Tide in the F2 Region", Proc. Roy. Soc. A189, 241, 1947.

Martyn, D. F., "Processes Controlling Ionization Distribution in the F2 Region of the Ionosphere", Australian J. Phys., 9, 161, 1956.

Mutuura, N. and T. Nagata, "Kinematic Viscosity Profiles", Rep. Ionos. Space Res. Japan, 16, 185, 1962.

McCrory, D. G., "Recombination Coefficient of the Nighttime F Region from Incoherent Scatter Measurements", Penn State Univ., Ionos. Res. Lab. Sci. Rpt. 279, 1966.

Mitra, A. P., B. C. N. Rao, and K. K. Mahajan, "Determination of Loss Coefficient and Vertical Transport Velocity in the Ionospheric F Region", J. Atmos. Terr. Phys., 29, 43, 1967.

Murphy, C. N., "Ionospheric Winds Measured by Gun-Launched Projectiles", J. Geophys. Res., 71, 4535, 1966.

Nicolet, M., "Density of the Heterosphere Related to Temperature", Smithsonian Astrophysical Observatory Spec. Rpt., 75, 1961.

Nicolet, M., "Solar Radio Flux and Temperature of the Upper Atmosphere", J. Geophys. Res., 68, 6121, 1963.

Nisbet, J. S., "Photoelectron Escape from the Ionosphere", accepted by J. Atmos. Sci., 1968.

Nisbet, J. S. and D. R. McCrory, "Recombination in the Nighttime F Region from Incoherent Scatter Measurements", in Electron Density Profiles in Ionosphere and Exosphere, ed. by J. Frihagen, North Holland Pub. Co., Amsterdam, 1966.

Nisbet, J. S. and T. P. Quinn, "The Recombination Coefficient of the Nighttime F Layer", J. Geophys. Res. 68, 1031, 1963.

Paulson, J. F., "Low Energy Charge Exchange and Ion Molecule Reactions", Ann. Geophys., 20, 75, 1964.

Paulson, J. F., F. Dale, and E. Murad, "Laboratory Studies on Some Positive Ion-Neutral Reactions", DASA Symposium, Univ. of Pittsburgh, June 19-20, 1967.

Quinn, T. P. and J. S. Nisbet, "Recombination and Transport in the Nighttime F Layer of the Ionosphere", J. Geophys. Res. 70, 113, 1965.

Quinn, T. P. and J. S. Nisbet, "Author's Reply", J. Geophys. Res. 71, 350, 1966.

Rao, A. S. and B. R. Rao, "Horizontal Drifts in the F 2 Region at Waltair", J. Atmos. Terr. Phys. 25, 249, 1963.

Rao, B. R. and E. B. Rao, "Study of Horizontal Drifts in the F1 and F2 Regions of the Ionosphere at Waltair', J. Atmos. Terr. Phys., 14, 94, 1959.

Rao, G. L. N., "Horizontal Drifts and Anisotropy of Irregularities in the Upper Ionosphere-A Review", Aeronomy Rpt. No. 9, Univ. Illinois, 1966.

Rao, G. L. N., and B. R. Rao, "World-wide Study of Apparent Horizontal Movements in F2 Region of the Ionosphere, J. Atmos. Terr. Phys., 26, 213, 1964.

Ratcliffe, J. A., "The Formation of the Ionosphere Layers F1 and F2", J. Atmos. Terr. Phys., 8, 260, 1956.

Ratcliffe, J. A., E. R. Schmerling, C. S. G. K. Setty, and J. O. Thomas, "The Rates of Production and Loss of Electrons in the F Region of the Ionosphere, Phil. Trans., A. 248, 621, 1956.

Rishbeth, H., "F2 Layer Rates at Sunspot Minimum", J. Atmos. Terr. Phys., 28, 911, 1966.

Robertson, D. S., D. T. Liddy, and W. G. Elford, "Measurements of Winds in the Upper Atmosphere by Means of Drifting Meteor Trails-I", J. Atmos. Terr. Phys., 4, 255, 1953.

Rosenburg, N. W. and H. D. Edwards, "Observations of Ionospheric Wind Patterns Through the Night", J. Geophy. Res., 69, 13, 1964.

Schmeltekopf, A. L., F. C. Fehsenfeld, G. T. Gillman and E. E. Ferguson, "Reaction of Atomic Oxygen Ions with Vibrationally Excited Nitrogen Molecules", Planet. Space Sci., 15, 401, 1967.

Shimazaki, T., "Nighttime Variations of F Region Electron Density Profiles at Puerto Rico", J. Geophys. Res. 71, 3177, 1966.

Smith, D. M., J. Copsey, and R. A. Fouraere, "Reactions of O^+ Ions in Helium-Oxygen and Helium-Oxygen-Nitrogen Mixtures", Rpt. Dept. of Electron Physics, Univ. of Birmingham, England, 1966.

Swider, W., "A Study of the Nighttime Ionosphere and Its Reaction Rates", J. Geophys. Res., 70, 4859, 1965.

Van Zandt, T. E., R. B. Norton and G. H. Stonehocker, "Photochemical Rates in the Equatorial F2 Region from the 1958 Eclipse", J. Geophys. Res., 65, 2003, 1960.

Volland, H., "A Two Dimensional Dynamic Model of the Diurnal Variation in the Thermosphere", Part I, Theory, J. Atmos. Sci. 23, 799, 1966.

Warneck, P., "Laboratory Rate Coefficients for Positive Ion-Neutral Reactions in the Ionosphere", J. Geophys. Res., 72, 1651, 1967.

Yerg, D. G., "Analysis of Ionospheric Drifts Utilizing Data Obtained with Closely Spaced Receivers", Final Rpt. 1964, AFCRL Bedford, Massachusetts, 1964.