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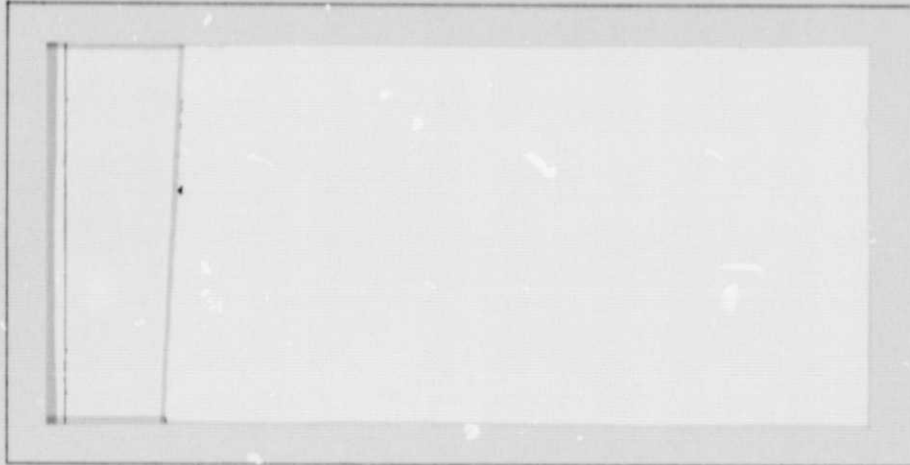
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IONOSPHERIC PLASMA CLOUD DYNAMICS

Final Report

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ABSTRACT

The first part of this report discusses measurements of the thermospheric neutral wind and ionospheric drift made at Eglin AFB, Florida (geomagnetic latitude $\theta \sim 41°$) and Kwajalein Atoll ($\theta \sim 4°$). The neutral wind measurements at Eglin had little variation over a period of four years for moderate magnetic activity (Kp < 4); the ionospheric drifts are small. Evidence is presented that indicates that increased magnetic activity has a significant effect on the neutral wind magnitude and direction at this midlatitude station. The neutral wind at dusk near the equator is generally small although in one case out of seven it was significantly larger.

The second part describes how observations of large barium releases can be used to infer the degree of electrodynamic coupling of ion clouds to the background ionosphere. Evidence is presented that indicates that large barium releases are coupled to the conjugate ionosphere at midlatitudes, while at $\theta \sim 4°$ they are not coupled along the whole magnetic field line.

1. MID- AND LOW-LATITUDE NEUTRAL WINDS AND IONOSPHERIC DRIFTS DETERMINED BY LARGE BARIUM RELEASES

Barium releases have been conducted in various parts of the world in order to map the electric field patterns in the ionosphere. In this section we indicate that large barium releases can be used to measure neutral winds and ionospheric drifts. We will report on the observations of barium releases conducted at Eglin Air Force Base, Florida, between 1967 and 1971, and barium releases conducted in 1973 and 1975 at Kwajalein Atoll in the Marshall Islands near the geomagnetic equator. In the next section of this report we will discuss the relevance of the observations of large barium releases in regard to their electrodynamic coupling to the ionospheric-magnetospheric system.

Barium releases deployed in the lower ionosphere at dusk produce spherical clouds of neutral BaO and Sr that remain visible sufficiently long so that their motion may be tracked. The ion cloud is easily seen due to the presence of strong resonance lines in singly-ionized barium. The neutrals maintain a Gaussian shape, diffuse, and drift with the ambient neutral wind. Small ion clouds act as tracers and essentially drift with the ambient ionospheric velocity, $\vec{E}_a \times \vec{B}/B^2$, perpendicular to the magnetic field. The rate of diffusion perpendicular to the magnetic field is slow but the diffusion rate parallel to the magnetic field is faster than the neutrals due to ambipolar diffusion. As a result ion clouds have a greater dimension parallel to the magnetic field than do neutral clouds except for a settling due to gravity at high

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altitudes. Their drift parallel to the magnetic field is essentially that of the neutrals. Releases of small ion clouds have been conducted worldwide in order to obtain information on ionospheric electric fields. The cloud of neutral particles also allows a determination of the neutral wind.

When a large chemical payload is used, a dense barium ion cloud is formed and the phenomena observed are more complex as illustrated in Figure 1.1. This figure shows two views of the same 48 kg release. The view on the left is at a large angle with respect to the magnetic field and can see the elongation parallel to the magnetic field. The view on the right is more nearly looking up the magnetic fieldl lines and thus the ion cloud has a considerably different shape. The circular cloud in both views, whose center is marked by a X, labeled N, is the neutral cloud. The large conductivity of the dense ion cloud perturbs the ionospheric electric field and generates polarization fields with the result that the bulk of the ionization is more closely coupled to the neutral wind. The center of the main ion cloud is marked with a dot labeled C. However, the low density part of the cloud farthest from the neutral cloud does act as a tracer and moves with the ambient ionospheric drift. This low-density leading edge is marked by a dot labeled E in both views.

The subject of the motion and distortion of the dense ion cloud is beyond the scope of this report. We are concerned here only with the results of measurements of the thermospheric wind above 150 km and the ambient ionospheric drift that have been obtained by observing large as well as small barium releases. The locations of these barium

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SPRUCE

190 km – 48 kg

R + 10 min
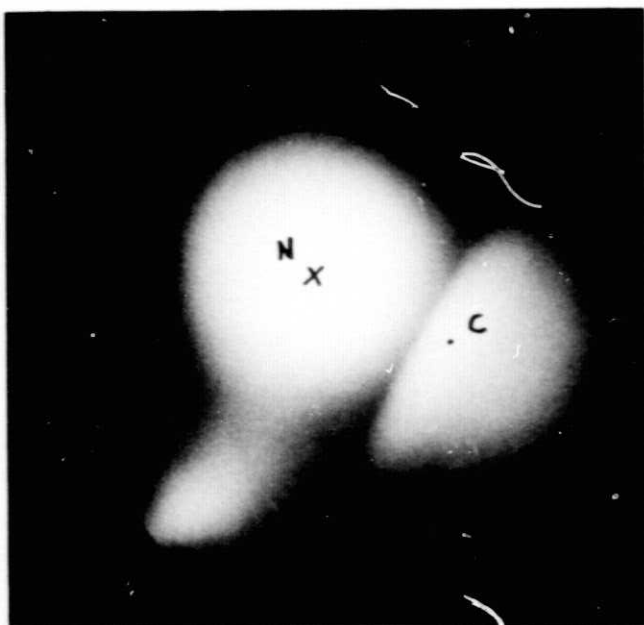
VIEW ≈ 45° WRO $\vec{B}$
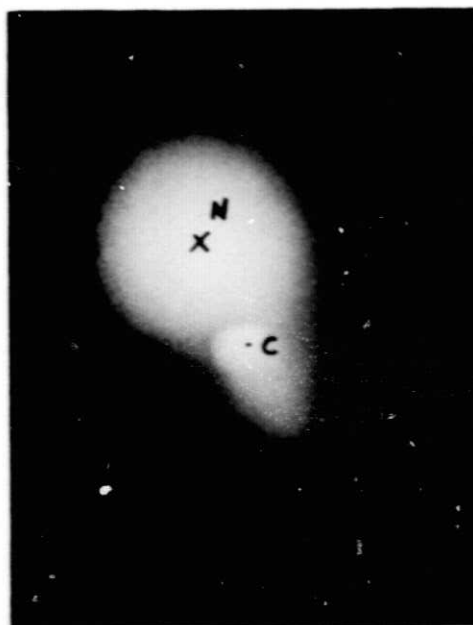
VIEW ≈ 6° WRO $\vec{B}$

Figure 1. 1 Two Views of the Spruce Ion and Neutral Clouds. The centers of the neutral cloud, main ion cloud, and low-density leading edge are labeled N, C, and E respectively. The bright image at the lower left of the photograph on the left is a reflection from the moon and should be ignored.

releases are Eglin AFB, Florida (~ 30°N, 86° W; geomagnetic
~ 41° N, L ~ 1.9) and Kwajalein Atoll, Marshall Islands (~ 9° N, 167½° E,
geomagnetic ~ 4° N. The observations were made typically around
45 min. after local sunset at solar zenith angles of 99° ± 2°. Preliminary
reports of these results have been given previously (Boquist, et al., 1974;
Linson, 1975).

Figure 1.2 shows the results of five measurements made at
Eglin Air Force Base in January 1971. The neutral wind measurements
are shown by open circles while the ionospheric drifts are given by solid
dots on a polar plot. The letters labeling the dots designate the appro-
priate pairs. One observes that all five results are remarkably consistent
with each other. The geomagnetic field was quiet on four of the nights
and moderately active on only one night (the event labeled P). One can
fairly well conclude that the mid-latitude thermospheric wind in winter
shortly after sunset during magnetically quiet times is likely to have a
value indicated by the dashed box. When more than one release was
conducted from the same rocket, the open circle represents the average
value while the actual measured values are at the ends of the lines
projecting from the open circle giving the appearance of error bars. At
the same time, the ionospheric drifts were small and tended to be
southerly.

We now compare these results with a number of barium releases
conducted at the same location by AFCRL during 1967 and 1969 as
shown in Figure 1.3. The purpose of making this comparison is to show
the degree of agreement of the neutral wind velocity with the 1971
measurements and to show an apparent effect due to high magnetic activity.
Several clouds were often released from the same rocket at different

NEUTRAL WINDS AND IONIZATION DRIFTS

EVENING   JANUARY, 1971

$K_p \leqslant 2, 3$
$\Sigma K_p \leqslant 23, 32.$

EGLIN AFB, FLORIDA
($\sim 30°$N, $86°$W)
$\sim 41°$N GEOMAGNETIC

o NEUTRAL
• IONIZATION DRIFT

$V_N = 0 \pm 25$ m/s
$V_E = 80 \pm 40$ m/s
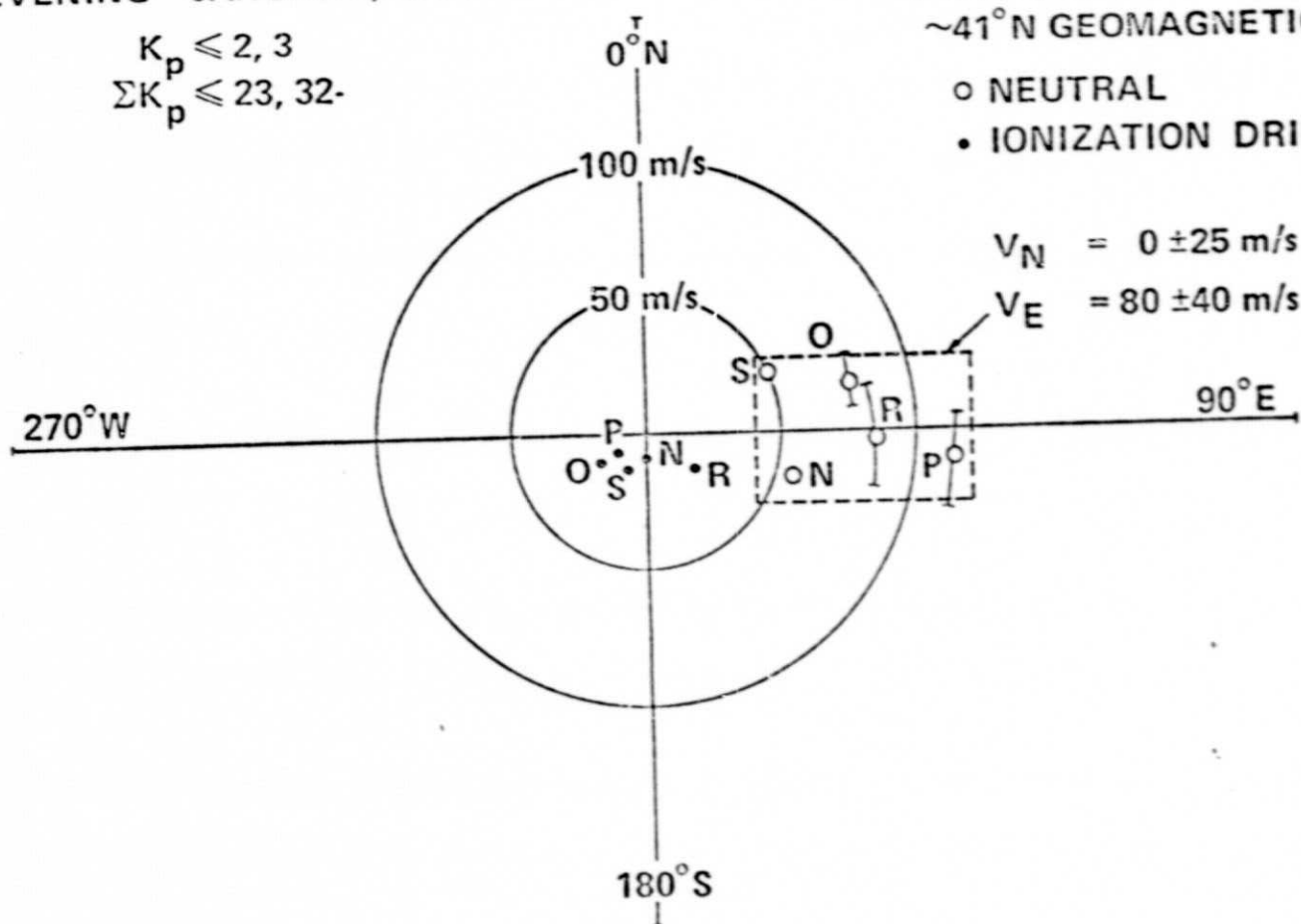
Figure 1. 2.   Northward and Eastward Neutral Winds and Ionospheric Drifts
Measured at Eglin, Florida in January, 1971.

NEUTRAL WINDS AND IONIZATION DRIFTS

EGLIN AFB 1967 AND 1969

SOURCE: AFCRL

$K_p \leqslant 2$-
$\Sigma K_p \leqslant 17$

EGLIN AFB, FLORIDA
($\sim 30^\circ$N, 86°W)
$\sim 41^\circ$N GEOMAGNETIC

o NEUTRAL
• IONIZATION DRIFT

V_N = 0 ±25 m/s
V_E = 80 ±40 m/s

0°N

100 m/s

50 m/s

270°W

90°E

APRIL

K_p = 5, ΣK_p = 37-
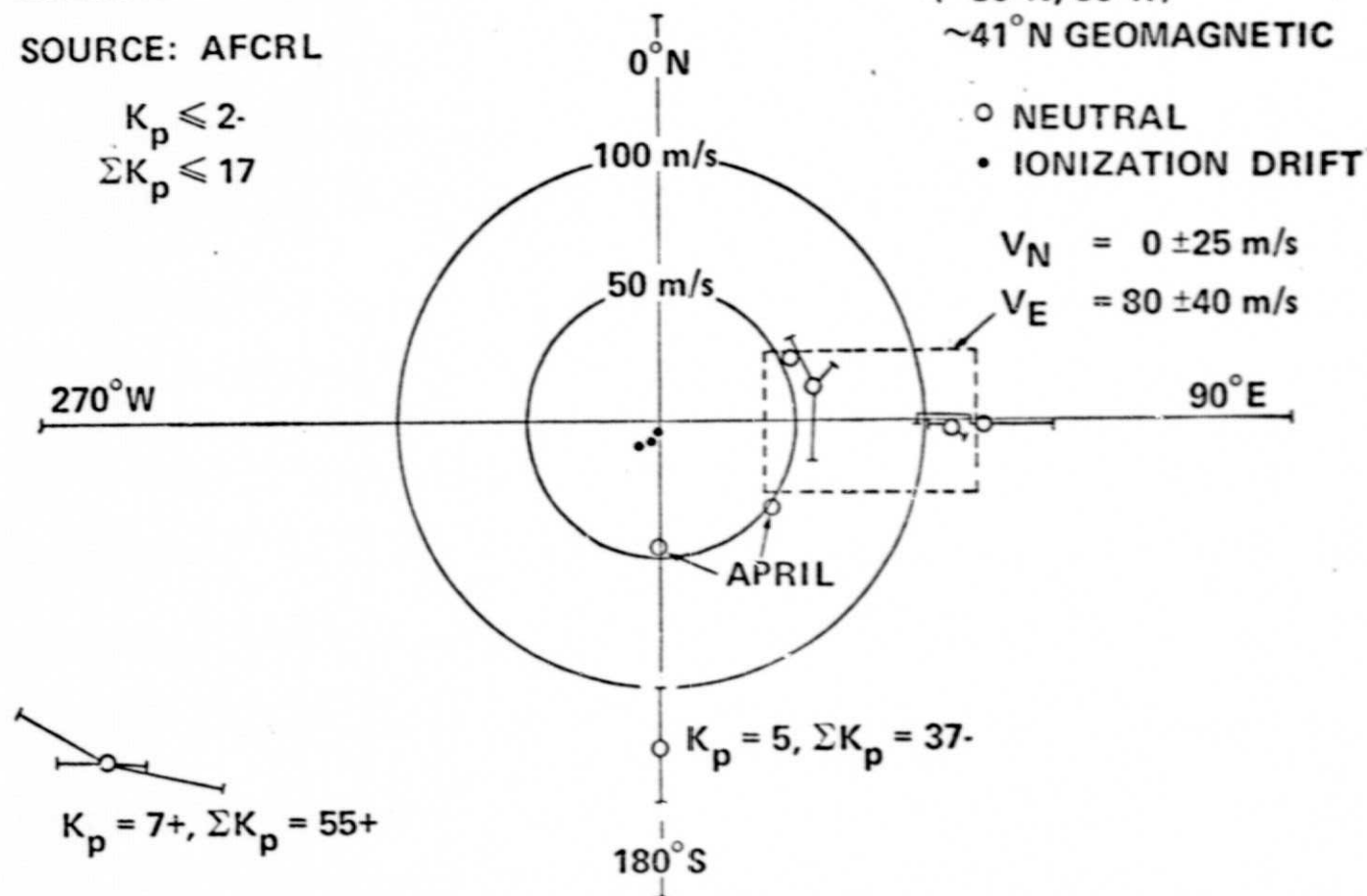
K_p = 7+, ΣK_p = 55+

180°S

Figure 1.3. Neutral Winds and Ionospheric Drifts Measured by AFCRL
at Eglin, Florida in 1967 and 1969.

altitudes. We show here only measurements above 165 km because the neutral wind is highly variable at lower altitudes and we represent each rocket flight by a single data point; the measurements obtained from each separate cloud are indicated as described above. On all but two of the releases the magnetic activity was low (Kp $\leq$ 2-; Σ Kp < 17). Five of these six measurements were in excellent agreement with the 1971 measurements; the sixth might be indicative of a seasonal effect (April 28) although one of the other five was also in April. The other four releases within the dashed box were conducted in January as were the 1971 releases. The remaining two were conducted in May 1969 during geomagnetic storm conditions as indicated. They differ greatly from the other measurements both in magnitude and direction. There is an indication that the magnitude increases and the direction rotates more clockwise (in a direction opposite to local midnight) with increasing geomagnetic activity. The measured drifts of the small ion clouds that were produced during the geomagnetically quiet times during these series are also shown and are consistent with the drifts shown in Figure 1.3.

Figure 1.4 shows the results of measurements of four barium releases, two large and two small, that were conducted at Kwajalein Atoll in June, 1973. The horizontal component of the neutral wind is shown on the left in a polar plot as before while the ionospheric drifts are shown in a vertical plane looking north. The neutral wind data show that the East-West component was consistently small. In three out of four cases the most significant component was southward as might be expected for midsummer. There seems to be no apparent explanation for the northward component measured once; it does not correlate with geomagnetic activity.

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KWAJALEIN ATOLL (10°N, 167-1/2°E)
~4-1/2°N GEOMAGNETIC

I, III 48 kg
II, IV 1 kg

	I, II, IV	III
K_p	$4 \leqslant K_p \leqslant 5$	2+
ΣK_p	$26\text{-} \leqslant \Sigma K_p \leqslant 34\text{-}$	22

HORIZONTAL NEUTRAL WIND

VERTICAL AND EASTWARD
IONIZATION DRIFT

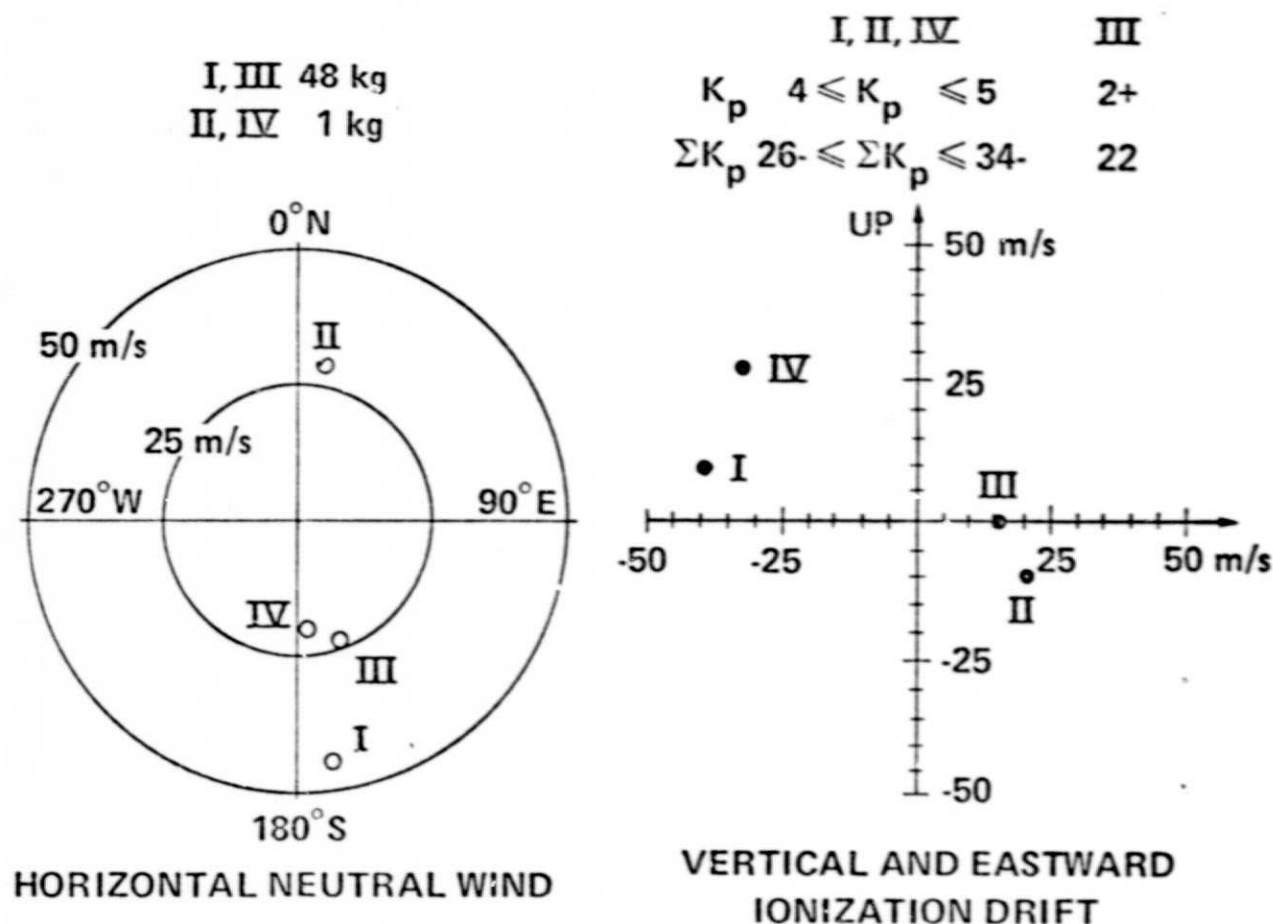Figure 1.4. Neutral Winds and Ionospheric Drifts as Determined by Four Barium Releases Conducted at Kwajalein in June, 1973. On the left is shown the eastward and northward components of the neutral wind velocity. On the right is shown the vertical and eastward components of the ionization drift. The northward component of the ionization drift is essentially equal to the northward component of the neutral wind velocity.

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Now we examine the ionospheric drifts measured at Kwajalein.
It is known from a variety of measurements at Jicamarca and Thumba
that the F-region equatorial ionosphere typically reverses its drift
from upward and westward in the afternoon to downward and eastward in
the evening (Balsley, 1973). The reversal in the vertical drift typically
occurs around one hour after sunset at Jicamarca while the reversal
from westward to eastward drift typically occurs around 1600 local
time at Jicamarca but at 2100 local time at Thumba. The Kwajalein data
shown suggest that two releases were pre-reversal while two were post-
reversal. The reversal time at Kwajalein thus appears to lie between
the reversal time at Jicamarca and Thumba, and this location is roughly
midway between these geophysical stations.

The results of three barium releases conducted at Kwajalein
in January, 1975 are shown in Table 1.1. Summarizing the equatorial
data given in Fig. 1.4 and Table 1.1, we find that the neutral wind was

TABLE 1.1

NEUTRAL AND ION CLOUD VELOCITIES*

EVENT	NEUTRAL CLOUD			ION CLOUD		
	North	East	Vertical	North	East	Vertical
A-I	-30 ± 10	30 ± 10	0 ± 10	-33 ± 10	50 ± 15	-10 ± 15
A-II	112 ± 7	4 ± 3	-24 ± 6	107 ± 7	23 ± 3	-19 ± 6
A-III	-34 ± 5	28 ± 2	-4 ± 5	-31 ± 5	13 ± 2	-6 ± 5

* In m/s.

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typically southward $(V_s \sim 30 \pm 10$ m/s) with an eastward component $(V_e \sim 15 \pm 20$ m/s) independent of solstice. On two occasions the wind was northward $(V_s \sim -30$ m/s on 6/19/75 and -110 m/s on 1/31/75). The ionospheric drift was westward and upward twice and downward and eastward twice in June 1973 but always downward and eastward in January 1975.

The unusual event was cloud A-II. The aspect of this event that was unusual was the large neutral wind towards the north, compared to the other 6 values of the northward component of the neutral wind. This test was conducted at approximately 0730 on February 1, 1975 (UT). Magnetic activity measured locally and indicated by Kp index has been examined and ionograms recorded at Kwajalein have been examined. There is no particular unusual characteristic associated with this event that didn't occur at other times. There is the possibility that such large variability in the northward neutral wind occurs more frequently than our seven data points allow us to conclude.

In conclusion, data on the values of the neutral wind and ionospheric drifts at mid- and low-latitudes are useful in order to compare with model calculations of thermospheric winds. The variability of the values observed is also important when attempting to use this data to evaluate numerical codes that predict winds and drifts. In summary:

⊙ The values observed at Eglin in 1971 were remarkably consistent with values obtained at Eglin earlier in 1967 and 1969 by AFCRL. Hence, a value of 80 m/s ± 40 m/s to the east for the neutral wind at this location a half hour after local sunset around winter solstice is well-documented. During the 20 to 30 minute observation period only occasionally were there any indications of a vertical wind shear or a change in the direction of the neutral wind.

• Two measurements by AFCRL were made during magnetic storm conditions (Kp = 5 and 7) and showed significantly different values for both the magnitude and direction of the wind.   These measurements, coupled with the consistency of the quiet time measurements cited above, are direct evidence that the lower thermospheric winds are significantly affected at mid-latitudes by geomagnetic activity.

• The ionospheric drifts were consistently southward at Eglin but had a fair degree of variability in the east-west component.

• At Kwajalein during summer solstice the neutral wind was southward five times out of seven.   The variability has not been correlated with any other geophysical parameters.

• The east-west component of the neutral wind was consistently low at Kwajalein.

• The ionospheric drift was upward and westward twice and downward and eastward twice in June, 1973.   The inference can be made that the reversal in the ionospheric drift at Kwajalein tends to occur roughly a half hour after sunset.   This time is roughly midway between the east-west reversal times that have been reported for Thumba, India and Jicamarca, Equador.

• In January, 1975, the ionospheric drift was consistently downward and eastward.   Measurements at Jicamarca during this time of low solar activity (Bowhill, personal communication), have indicated that the ionosphere did not have a large vertical velocity near sunset as had been typical during solar maximum (Woodman, 1970).

2. THE ELECTRODYNAMIC COUPLING OF BARIUM ION CLOUDS WITH THE IONOSPHERE

The magnetospheric-ionospheric-atmospheric system corresponds to a complex nonlinear electrodynamic circuit. The purpose of this section is to explore some of the theoretical concepts that have been used for understanding the electrodynamic coupling amongst these various elements to emphasize that observations of the motion and distortion of large barium ion clouds provide information on the electrodynamic nature of the ionosphere and to compare observations of the behavior of ion clouds with these theoretical concepts. We shall present evidence that indicates that the interaction must be more complicated than the simplest models predict. Basically this report will conclude with the observation of a paradox that indicates we have more yet to learn.

Two of the early concepts that have been employed for investigating the dynamic motions of the magnetosphere and the electrodynamic nature of the ionosphere are the frozen-in fields concept and layer conductivities. The basis for the first concept is the large conductivity parallel to the magnetic field that exists in the magnetosphere. Because of this large conductivity, the approximation is often used that the magnetic field lines are equipotentials. The electric field is thus everywhere perpendicular to the magnetic field and the magnetic flux tubes convect as rigid entities with the velocity $\vec{E} \times \vec{B}/B^2$. The electrodynamic nature of the ionosphere is often approximated by the use of layer conductivities. This approximation allows one to calculate electric field patterns and current flow patterns by treating the ionosphere as a conducting plate with a conductivity that depends on the local dip angle of the magnetic field.

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While both of these assumptions have been extremely useful in modeling many of the complex characteristics of the ionospheric-magnetospheric system, it is becoming more and more apparent that they are inadequate to explain many observed phenomena. The first additional feature that has been added to this system has been the presence of magnetic-field-aligned current flow. Actually, the presence of these parallel currents need not violate either of the above concepts. However, there is growing evidence that points to the existence of electric fields parallel to the magnetic field which violates the concept of rigid motion of magnetic flux tubes. In addition, illumination of magnetic flux tubes with the use of shaped-charge barium releases has indicated that a complex set of motions can take place during increased magnetic activity (Wescott, et al., 1975). Within the lower altitude portions of the ionosphere, the concept that magnetic field lines are equipotentials breaks down at lower altitudes for smaller scale sizes. Furthermore, nonuniformities in the ionosphere at one altitude will give rise to electric field patterns that will cause inhomogenieties to appear at other altitudes. These effects have been called the generation of image striations. Likewise there is some evidence that the magnetic flux tubes do not convect as rigid bodies (Wescott, et al., 1974b).

Barium releases can be employed to examine the electrodynamic nature of the coupled ionospheric-magnetospheric system. Small barium releases that do not perturb the ambient ionospheric electric field act as tracers and have successfully been employed worldwide in order to obtain information on the temporal and spatial variations of the ambient ionospheric electric field. Insofar as they act as a probe of the complex circuitry such releases are equivalent to potentiometers, a passive

measuring device. On the other hand, large barium releases can create a large change in the ionospheric conductivity locally. Such a change will affect the ionospheric current flow and, by generating polarization electric fields, modify the electric fields perpendicular to the magnetic field along the whole magnetic field line. Among the effects that are produced are a modification of the convection velocity in the magnetosphere, the generation of currents parallel to the magnetic field, and changes in the electron concentration in the E-region of the ionosphere. Thus, by varying one of the elements of the complex circuit, large barium releases can be employed as active probes of the electrodynamic coupling of the ionosphere and the magnetosphere. Observation of the motion of the released ionization provides a measure of the electrodynamic response of the system.

An example of the results of releasing large ion clouds at mid- and low-latitude will be discussed. In particular, the observed electrodynamic coupling of these barium ion clouds will be examined in terms of the degree to which their behavior agrees with simple concepts of the interaction process. The conclusion that we will reach is that the simple concepts lead us to a paradox that indicates additional factors must be taken into account.

We shall adopt a simple model in order to illustrate the complex factors that we have been discussing. Some of the factors that limit this simple approximation within the ionosphere are different winds at different heights, the fact that finite scale sizes do not impose their perpendicular electric field patterns over the full length of the magnetic field, and changes in density are induced in the E-region due to irregularities in the F-region. Within the magnetosphere there are a number of

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indications of the existence of parallel electric fields and the nonrigid motion of magnetic field lines. These indications result from measured distributions of backscattered auroral electron fluxes (Evans, 1974), the times of arrival of auroral primaries, the anomalous behavior of shaped barium charge releases (Wescott, et al., 1974a; Wescott, et al., 1975), the fact that photoelectrons from a conjugate ionosphere are not energized in spite of the fact that they originate in a region of higher electrical potential (Banks, personal communication), and observations of the lack of tracking of two ends of a magnetic field line (Wescott, et al., 1974b).

In this section we wish to make two principal points. The first point is that by observing the nature of the deformation and stretching of large barium releases, one can infer the degree of electrodynamic coupling of the ion cloud to the background ionosphere. The second point results from a comparison of similar large barium releases at Eglin and Kwajalein. The conclusion reached is that at Eglin large barium releases are electrodynamically coupled to the conjugate ionosphere (Linson, 1971) while at Kwajalein they are not coupled to the complete ionosphere along the whole length of the magnetic field line (Linson, 1974). We shall proceed to discuss the development of a simple model that can be compared with the data obtained from observations of large barium releases.

In order to illustrate the simple model we assume that the electric field parallel to the magnetic field is everywhere zero. The magnetic field lines thus truly are equipotentials. We also neglect the Hall effect which is appropriate in the evening and at night. This approximation is consistent with the assumption that the product $\Omega \tau \gg 1$ where Ω is the ion gyrofrequency and τ is the ion-neutral

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collision time. This approximation indicates that the principal currents
that flow are Pedersen currents and that the dominant effects that we
will be discussing are due to changes in the Pedersen conductivity.

The electrostatic approximation $\nabla \times \vec{E} = 0$ implies that
$\nabla \cdot \vec{E} \times \vec{B}/B^2 = 0$. This result states that the ionospheric flow perpen-
dicular to the magnetic field is incompressible. It is equivalent to
saying that the number of electrons on a field line remains constant.
Indeed, the equation that describes the convection of different regions
of ionization is the continuity equation for the electrons in the frame of
the neutrals;

$$\frac{\partial \Sigma_p}{\partial t} + \frac{\vec{E} \times \vec{B}}{B^2} \cdot \nabla \Sigma_p = 0 \tag{2.1}$$

where Σ_p is the magnetic-field-line-integrated Pedersen conductivity.
In our simple one layer model, Σ_p is proportional to the field-line-
integrated electron content, N, by $\Sigma_p = eN/\Omega \tau B$.

The equation that governs the electrical field patterns and current
flows can be derived by integrating the current continuity equation along
a magnetic field line. This operation results in

$$\int \nabla \cdot \vec{J} \, ds = \nabla \cdot \int \vec{J}_\perp \, ds = 0$$

which implies that

$$\nabla \cdot \Sigma_p \vec{E} = 0 \tag{2.2}$$

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This simplified equation describes the distribution of the electric field perpendicular to the magnetic field due to inhomogenieties in the magnetic-field-line-integrated Pedersen conductivity. More generally, the same equations (2. 1) and (2. 2) apply if the field-line-integrated Hall conductivity is small compared with the Pedersen conductivity and we define

$$\Sigma_p = \frac{e}{B} \int \frac{n\Omega\tau}{1+(\Omega\tau)^2} \, ds$$

where n is the electron density.

If we are given a distribution $\Sigma_p(x,y)$ of the conductivity (henceforth the word conductivity will represent the magnetic-field-line-integrated Pedersen conductivity and we will avoid repeating those words) in the plane perpendicular to the magnetic field, Eq. (2. 2) can be solved for the resulting electric field distribution. We note that this equation is identical to the equation that describes the electric field variation in a dielectric medium with a dielectric constant equal to Σ_p. When the electric field pattern perpendicular to the magnetic field has been calculated, Eq. (2. 1) can then be used to calculate the movement of the ionization. In particular, this equation states that the motion of a region of enhanced conductivity is governed by the value of the electric field at that point. When one makes a barium release, the ion cloud that is produced is initially approximately cylindrically symmetric. The charge in the conductivity due to the presence of the cloud may be indicated by

$$\Sigma_p(x,y) = \Sigma_p^a + \Sigma_p^c(x,y) \tag{2.3}$$

where Σ_p^a is the conductivity due to ambient ionosphere and assumed constant and $\Sigma_p^c(x,y)$ is the conductivity change due to the presence of the cloud. The symbol Σ_p alone will represent the maximum of $\Sigma_p^c(x,y)$ initially at the center of the cloud.

The electric field given by Eq. (2.2) in the neutral wind frame initially has a minimum at the center of the ion cloud. Equation (2.1) indicates that the motion of any piece of the cloud depends on the local value of the electric field. In particular the motion of the center of the ion cloud depends on the value of the electric field at the center of the ion cloud.

At this point we introduce the coupling parameter ζ by writing the velocity of the ion cloud as

$$\vec{V}_c = \vec{V}_n + \zeta\left(\frac{\vec{E}_a \times \vec{B}}{B^2} - V_n\right) = \vec{V}_n + \zeta\frac{\vec{E}_o \times \vec{B}}{B^2} \quad , \quad (2.4)$$

where $\vec{E}_a$ is the ambient ionospheric electric field (assumed constant) measured in the earth-fixed frame and $\vec{E}_o = \vec{E}_a + \vec{V}_n \times \vec{B}$ is the electric field measured in the frame of the neutrals. The electric field may be written $\vec{E} = \vec{E}_o + \vec{E}_p$ where $\vec{E}_p$ is the electric field induced by the presence of the ion cloud. Thus ζ is the ratio of the electric field at the center of the ion cloud, to the electric field measured in the frame of the ambient neutrals, $\vec{E}_o$.

This model and solutions of Eq. (2.2) allow us to calculate $\zeta(\Sigma_p^c/\Sigma_p^a)$. ζ depends on the distribution of ionization within the ion cloud, the assumed shape of the ion cloud, and the amount of the
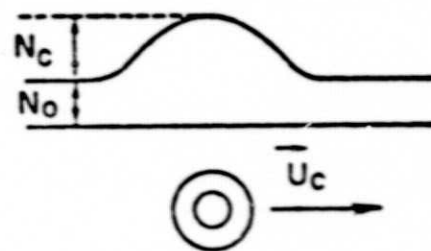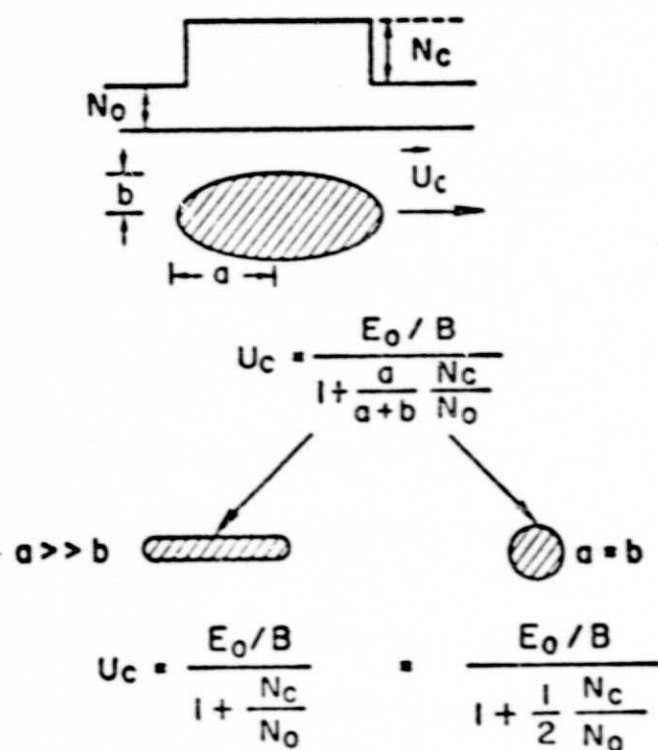
enhancement in the conductivity. Equation (2.2) may be rewritten

$$\nabla \cdot \vec{E}_p = -\vec{E} \cdot \nabla \ln \left[1 + \Sigma_p^c(x,y)/\Sigma_p^a \right] \qquad (2.5)$$

In this form we see that the polarization charges that give rise to the polarization electric field are given by the expression on the right-hand side of the equation.

Figure (2.1) indicates some of the types of solutions that can be obtained from Eq. (2.5). On the left-hand side of this figure the ion cloud is assumed to have uniform density but with an arbitrary elliptical shape with major and minor semiaxes a and b. $\vec{U}_c$ shown in this figure is the velocity of the ion cloud in the frame of the ambient neutrals equal to $\vec{V}_c - \vec{V}_n$. The solution for the electric fields within an ellipse with constant density is well-known and is uniform. This implies that the elliptically-shaped ion cloud moves with constant velocity without changing in shape. The expression for this velocity is given on the left-hand side. Also shown are the simplified expressions for the dependence of the cloud velocity for two special values of a and b. The first case represents a sheet of ionization with its long direction in the direction of motion, $a \gg b$. The second case with $a = b$ corresponds to a cylindrically symmetric distribution of ionization.

We see from the expressions given that the sheet is more closely tied to the neutrals than is the cylindrically-shaped cloud for the same enhancement in ionization. The coupling parameter ζ for this sheet is smaller than that for the cylindrically shaped cloud. On the right-hand side of Fig. (2.1) we indicate an example of a cylindrically-shaped cloud with a smooth distribution of ionization. The dependence of the

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$$U_c = \cfrac{E_0/B}{1 + \cfrac{a}{a+b}\cfrac{N_c}{N_0}}$$

$$U_c = \zeta\, E_0/B$$

a >> b

$$U_c = \cfrac{E_0/B}{1 + \cfrac{N_c}{N_0}}$$

a = b

$$= \cfrac{E_0/B}{1 + \cfrac{1}{2}\cfrac{N_c}{N_0}}$$

$$\zeta \sim \begin{cases} 1 - \dfrac{1}{2}\dfrac{N_c}{N_0}\; ; & N_c \ll N_0 \\[2em] \sqrt{3}\,(N_c/N_0)^{-3/4}; & N_c \gg N_0 \end{cases}$$

Figure 2. 1. Schematic of Solutions for Determining the Coupling Parameter ζ .
See text for discussion.

coupling parameter ζ on the ratio of cloud-to-ionospheric conductivity is indicated for this particular case and depends on the assumed distribution of ionization within the cloud.
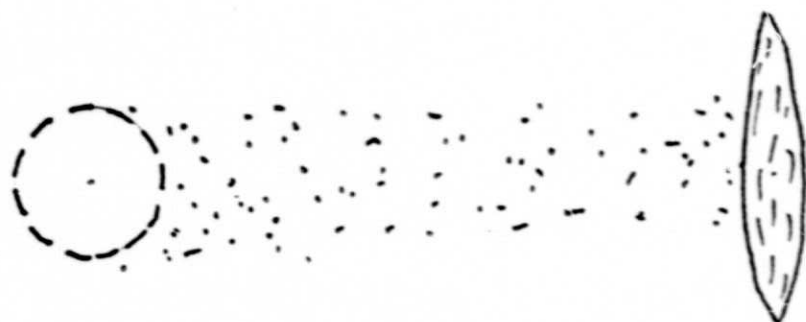
Two general properties of the function $\zeta(\Sigma_p^c/\Sigma_p^a)$ are exhibited by the special cases shown in Figure 2.1. (The ratio Σ_p^c/Σ_p^a is identical to the ratio N_c/N_o in our simple model.) The coupling constant ζ for cylindrically-symmetric clouds has the following limiting behavior for small and large clouds:

$$\zeta \sim \begin{cases} 1 - \tfrac{1}{2}\dfrac{\Sigma_p^c}{\Sigma_p^a} & ; & \Sigma_p^c \ll \Sigma_p^a \\[4mm] 0 & ; & \Sigma_p^c \gg \Sigma_p^a \end{cases} \qquad (2.6)$$

Figure 2.2 schematically illustrates these concepts in terms of the observations of small and large barium releases. The top part of the figure shows a typical view at a large angle to the magnetic field. The dashed circle represents the neutral cloud. The elliptically-shaped object represents the ion cloud elongated along the magnetic field. The dots indicate regions of low-density of barium ions. The object whose motion we have been discussing is the higher density elliptically-shaped ion cloud.

The situation for small clouds is indicated on the left-hand side of Figure 2.2. For $\Sigma_p^c/\Sigma_p^a \ll 1$ the ion cloud moves essentially with the ambient $\vec{E} \times \vec{B}/B^2$ velocity. In fact, small clouds have been

SMALL (~ 1 kg)   LARGE (~ 48 kg)

NEUTRAL
CLOUD

$$\vec{V}_c = \vec{V}_n + \zeta\left(\frac{\vec{E}\times\vec{B}}{B^2} - \vec{V}_n\right)$$

$$\zeta = \zeta\left(\frac{\Sigma_p^c}{\Sigma_p^b}\right); \quad \Sigma_p = \int \sigma_p \frac{\vec{B}\cdot d\Delta}{B}$$

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DENSITY CONTOURS
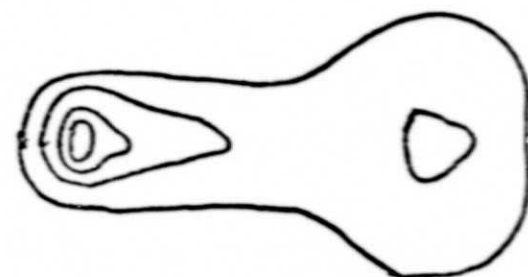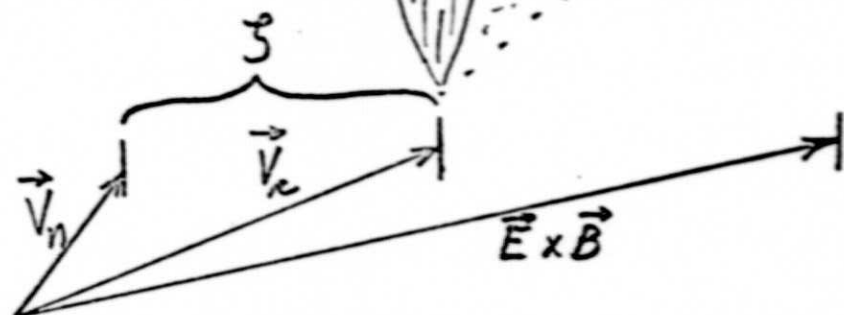
IN PLANE $\perp \vec{B}$

Figure 2. 2.   Schematic Showing Relative Appearance of Neutral and Ion Clouds
for Small and Large Barium Releases.   See text for description.

deployed world-wide in order to measure the ambient ionospheric electric fields by observing the motions of the ion clouds alone.

The situation for large barium clouds is indicated schematically on the right-hand side of Figure 2.2. This case is somewhat different and several points can be made. First, the neutral cloud containing much more material remains visible much longer and the motion of the ambient neutral particles, $\vec{V}_n$, in the atmosphere can be measured. Second, the center of the ion cloud is easily measured. Third, some of the low-density portions of the originally deployed ion cloud farthest from the neutral cloud are also present. The small amount of enhancement in the ionospheric conductivity resulting from this low density does not create significant polarization fields. Thus, by measuring the motion of this leading edge, a value for the ambient electric field can be obtained. These concepts are indicated by the vectors shown on the right-hand side of Fig. 2.2. The bottom portion of Figure 2.2 schematically shows equal density contours in the ion cloud for the two cases in a plane perpendicular to the magnetic field. We indicate here that indeed the bulk of the ionization for the large ion cloud is moving with the velocity $\vec{V}_c$ given by Eq. (2.4).

Figure 1.1 consists of a pair of photographs of event Spruce (discussed in the previous section) which illustrates the concepts that were sketched in Figure 2.2. The figure on the left shows a view at a large angle with respect to the magnetic field while the figure on the right shows a view of the same ion cloud at the same time looking nearly parallel to the magnetic field. The center of the neutral clouds and the main ion cloud are marked and labeled with an N and C respectively

in each view.   The low density leading edge of the ion cloud labeled E
is moving with the ambient $\vec{E} \times \vec{B}/B^2$ velocity.   The markings in the
figure were made on the original photographs and some loss of detail
has occurred in reproducing the photographs.

Measurements can be made directly on photographs such as
these in order to determine a value of the coupling parameter, ζ . In
this case $\zeta = 0.48$.   The value of the conductivity of the barium ion
cloud can be calculated from a knowledge of the density in the ion cloud,
its dimensions, and a model for the ambient neutral atmospheric
density.   The value of the Pedersen conductivity of the ambient ionosphere
can also be obtained by either using models or using electron density
profiles obtained from ionograms or, in some cases, from measurements
made by rocket probes.

From data such as this, enough information is in hand to
experimentally determine values of the function $\zeta\,(\Sigma_p^c/\Sigma_p^a)$.   These
data points can be compared with theoretical calculations of the same
function based on our simple model.   Data obtained from a number of
barium releases with chemical payload weights ranging from 1 to 288 kg
and released at altitudes between 150 and 255 km provide a fairly
extensive range in parameters for testing these simple theoretical concepts.
These barium releases were conducted at mid-latitude at Puerto Rico
and Eglin Air Force Base. Indeed, the latter releases were discussed
in the previous section and produced the neutral wind and ionization
drift data that was shown in Figure 1. 2.

Figure 2. 3 shows a comparison of such data with model curves.
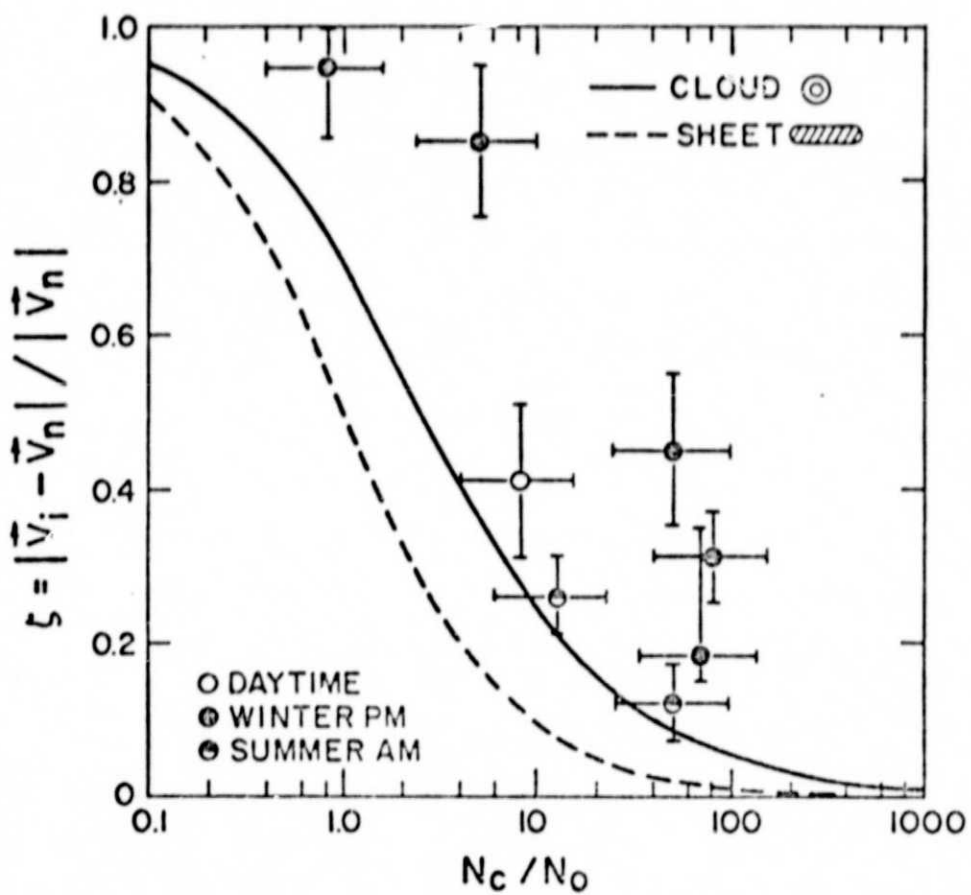The best guess for the uncertainty in the values for ζ is indicated by

Figure 2.3. Comparison of Data with Model Calculations of the Coupling Parameter ζ.

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the vertical error bars, and the horizontal error bars indicate the extent of a factor-of-two uncertainty in the estimate for the ratio of conductivities. The two curves shown represent the two extremes in coupling that depend on the configuration of the ionization. The most coupled to the neutral wind is the sheet-like shape, whereas the least coupled is the cylindrically symmetric cloud with a density profile.

A first glance at the data would suggest that the simple theory is inadequate to describe the degree of coupling of ion clouds to the neutral wind. Note that the disagreement for the winter evening releases is extreme, since the scale on the bottom is logarithmic and covers several decades. The ion clouds are observed to separate from their neutral clouds much faster than the simple theory would allow. They behave as though the background ionosphere were far more conducting than the measurements of the ambient ionosphere indicate.

The observation that the winter evening releases are those that are in most serious disagreement with the theory led to the suggestion that the conjugate ionosphere in the southern hemisphere was contributing to the background ionospheric conductivity. This suggestion seemed plausible because the ionosphere conjugate to Eglin (at 54° S, 103° W) is further west and was experiencing summer and hence was sunlit. On the other hand, the ionosphere conjugate to the summer morning releases at Puerto Rico was experiencing winter and thus was still in darkness. More quantitatively, when the sun was 9° below the horizon after sunset at Eglin in the last half of January, 1971, and 9° below the horizon before sunrise at Puerto Rico in the first half of May, 1969, the sun was 26° above the horizon and 23° below the horizon, respectively, at the corresponding conjugate ionospheres. Hence it is reasonable to assume that the field-line-integrated Pedersen conductivity of the conjugate

ionosphere for the winter evening releases had a typical daytime value of 6 mho, while for the summer morning releases it had a typical nighttime value of 1 mho. By adding these conductivities to the local values, we obtain new estimates for the ratio of cloud-to-ionospheric conductivity.

Figure 2.4 is a replotting of the data assuming that the conjugate ionosphere does contribute to the background ionospheric conductivity insofar as the motion of barium ion clouds is concerned. By making this assumption we see that there is no longer any disagreement between the simple theory and the data. It is apparent that these clouds do not move as though they were shaped like sheets. However, the data do not clearly distinguish between the two other cylindrical models whose theoretical curves are shown.

We note that this agreement with the theoretical curve includes data in which the ratio of conductivities ranges over two and one-half orders of magnitude. This agreement is highly suggestive that the conjugate ionosphere must participate in the dynamics of the motion of barium ion clouds. It is estimated that an Alfven wave can travel from the northern to the southern hemisphere and back in half a minute, so there is sufficient time to communicate the polarization electric fields between the two hemispheres. This assumption that the reconciliation between data and theory is achieved by including the effect of the conjugate ionosphere is a simple and plausible one.

There are several important implications that follow from this suggestion if it is correct. The first is that the cloud-produced polarization electric fields must project into the southern hemisphere, which suggests that the assumption that the earth's magnetic field lines are equipotentials for a large distance is a good one. A second conclusion
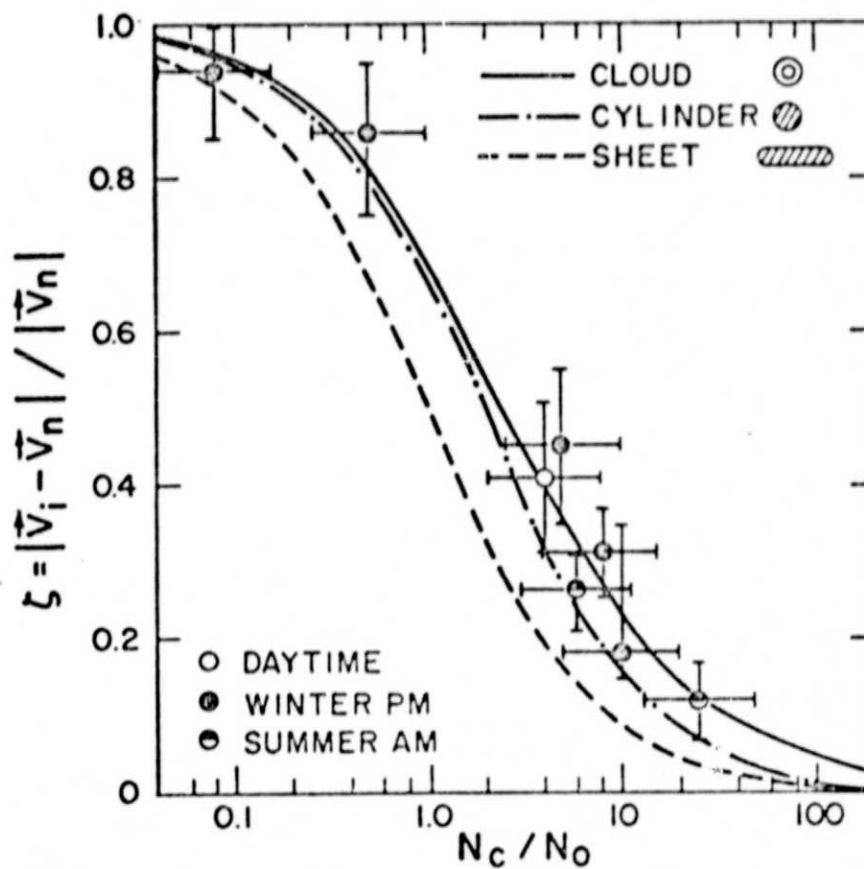
Figure 2. 4.   Comparison of Data with Model Calculations of the
Coupling Parameter ζ when the Influence of the
Conjugate Ionosphere is Included. The data points
shown in this figure represent the same points shown
in the previous figure.

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is that there must be magnetic-field-aligned currents in the magnetosphere. A third conclusion is that the presence of the ion cloud and its resulting motion in the northern hemisphere must cause a disturbance in the ion density in the conjugate ionosphere in the southern hemisphere. An independent verification of any of these effects would be very valuable.

Let us adopt a simplified model of an ion cloud in the ionospheric-magnetospheric system as shown in Figure 2.5 in order to make a quantitative estimate of some of these effects. We find that the magnetic field lines are sufficiently conducting so that the electric fields do not suffer any appreciable resistive losses in being projected into the con-jugate ionosphere (Linson, 1971). The most important effect is the disturbance in electron density that the current flow in the background ionosphere is likely to make. The parallel currents must be closed by Pedersen currents, which are due to the flow of the background ions. This ion flow will lead to significant changes in the local ionospheric density. These changes should be detectable by either optical or radar means.

Observations of large barium releases have also been made near the magnetic equator at a dip latitude of approximately 4.5°. We shall discuss parameters associated with one of these large releases conducted in June of 1973. A 48 kg chemical payload weight barium release named Weathervane I was released at an altitude of around 210 km. Table 2.1 shows a comparison of several other parameters associated with this barium release and the Spruce event shown in Figure 1.1.

The Pedersen conductivity for the Weathervane ion cloud is less than that for Spruce because it was released at a higher altitude. A release at higher altitude lowers the Pedersen conductivity of an ion
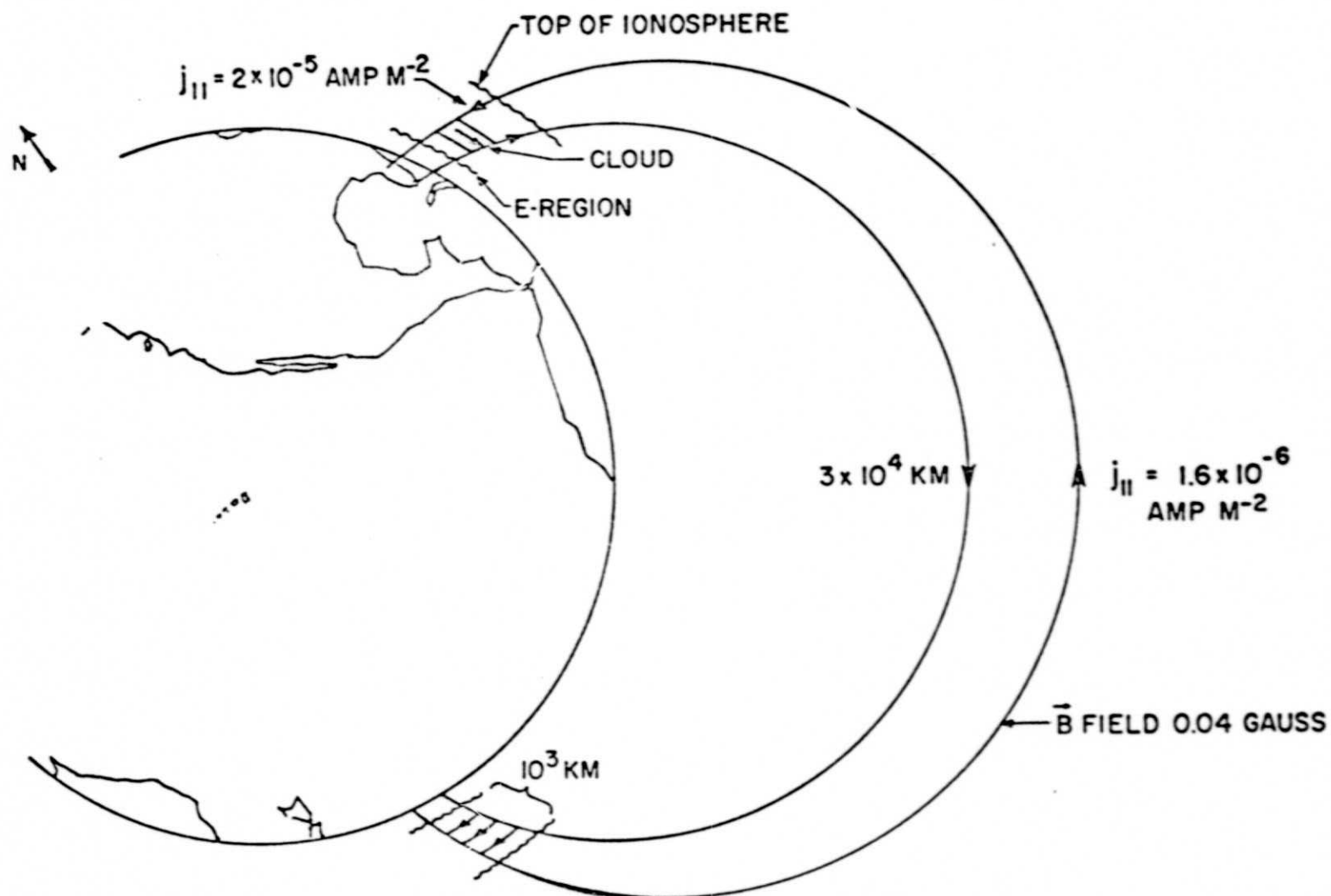
FIGURE 2.5 SKETCH OF MAGNETOSPHERIC CURRENT FLOWS THAT COUPLE THE CONJUGATE IONOSPHERE AND THE BARIUM CLOUD

TABLE 2.1

COMPARISON OF PARAMETERS FOR SPRUCE AND WEATHERVANE I		
EVENT	SPRUCE	WEATHERVANE I
GEOMAGNETIC LATITUDE	$\sim 41°$	$\sim 4.5°$
PAYLOAD	48 kg	48 kg
ALTITUDE	~ 190 km	~ 210 km
Σ_p^c	~ 35 mho	~ 15 mho
Σ_p^b , LOCAL (+ CONJUGATE)	~ 1.5 (7.5) mho	~ 12 (24) mho
APPARENT Σ_p^b	~ 10 mho	~ 2 mho

cloud because of two factors. First, the lower atmospheric density causes the neutral barium atoms to disperse more rapidly before they become ionized. As a result, the ion density created in the cloud is less. Second, the conductivity perpendicular to the magnetic field depends on collisions with neutrals which are less frequent at higher altitude. Without such collisions the ions cannot be transported across the magnetic field line in the direction of an applied electric field and the resultant conductivity is less. Whether the precise parameter values, believed to be accurate, are correct is irrelevant because the relative value of the Pedersen conductivity of the Weathervane cloud must have been less than half the value of that of the Spruce cloud due to the scaling resulting from the different altitudes.

One would normally expect that the magnetic-field-line-integrated Pedersen conductivity near the magnetic equator would be larger than that at mid-latitude as at Eglin. The reason is that the magnetic field line stays at low altitude in a denser portion in the atmosphere for a much greater distance than when the magnetic field has a significantly large dip angle. The magnetic field line that passes through the barium ion cloud at an altitude at 210 km at a magnetic latitude of 4. 5° never rises above 240 km even at the magnetic equator.

Estimates made of the electron density profile obtained by model calculations at NOAA based on ionograms made during the test series allow one to make an estimate of the local conductivity. The estimated conductivity between the E-region and the equator on the field line passing through the barium cloud is of order 12 mho, at least. Because of our experience from examining the data taken from barium releases at Eglin, one would conclude that the conjugate ionosphere must also be included, essentially doubling the estimated field-line-integrated Pedersen conductivity at Kwajalein as indicated in the table.

However, photographs of the Weathervane I ion cloud show that the main ion cloud was much more coupled to the neutrals than the Spruce cloud. Indeed, the estimated coupling parameter, ζ , for Weathervane I is 0. 2. The Weathervane I cloud behaved as though the ambient ionospheric conductivity were far less conducting in comparison with the photographs of the Spruce ion cloud. In fact, if one assumes that the calculated conductivity of the ion clouds are correct, one may deduce an inferred ambient conductivity from the observation of the apparent coupling constant. The apparent ionospheric background conductivity is given in the last row of Table 2. 1.

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We see that while there is satisfactory agreement with the Spruce cloud, there is lack of agreement with the observations of the Weather-vane I cloud. The suggestion was made (Linson, 1974) that perhaps the NOAA model of the equatorial ionosphere was inappropriate and rather than having an electron density of order 5×10^4 cm^{-3} at 200 km altitude, the actual electron density may have been as low as 10^4 cm^{-3}. If this were true, it would have two effects. The first effect would be to roughly reduce the estimated field-line-integrated Pedersen conductivity by a factor of 5, and reduce the estimated conductivity parallel to the magnetic field. Indeed, it was calculated that the magnetic field line would not be an equipotential over its whole length and roughly only half of the entire length should be included in the field-line integration.

In January, 1975 additional barium releases were conducted at Kwajalein. The rockets were instrumented with Langmuir probes and resonance probes in order to make in situ measurement of the electron density profile. In this way it was hoped that a conclusive measurement could be made that would resolve this apparent discrepancy between Weathervane I and Spruce. The Langmuir probes failed but the rf-resonance probes returned good data. These probes found that 1 1/2 years after Weathervane I, the electron density at an altitude of around 200 km was of order $4-5 \times 10^4$ cm^{-3}. Indeed, based on the measured electron density profiles, it would appear that the field-line-integrated conductivity from the E-region to the magnetic equator, is of order 12 mho's. Hence, the suggestion discussed in the previous paragraph did not apply.

Thus we are left with a paradox. The observations of those two large barium releases have indicated that something is incorrect with

the simple model. The simple model does not adequately describe the observed behavior. At the present time a number of possibilities have been suggested and examined but none has proven fruitful. A conclusion is that releases of large barium clouds can tell us something about the nature of the electrodynamic coupling of the ionosphere with the magneto-sphere.

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