On the red line emission in nighttime observed from ISIS-II spacecraft and implied thermospheric winds

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Downward looking vertical observations at 6300Å and the F-layer critical frequency from the ISIS-II spacecraft at equatorial, middle and high latitudes in the American zone are used to derive F-layer peak height \( h_{m}F_2 \). The observations refer to nighttime periods (2315 to 0250 hrs LT) in September 1972 for geomagnetically quite and disturbed conditions during low solar activity. The \( h_{m}F_2 \) values are entered into vector spherical harmonic model of the thermospheric dynamics to find winds in F-region. The equatorial ionospheric anomaly (EIA) in the emission are observed to move closer to the magnetic equator with time, and sometimes are not colocated with EIA in peak electron density \( n_{m}F_2 \) during disturbed conditions. Also the observed intensities do not always indicate the presence of gravity waves or oscillations during disturbed periods as expected.

1 Introduction

Observations at 6300Å have been a convenient and thus widely used technique for remotely sensing the properties of the upper atmosphere/ionosphere. In the past, extensive investigations have been carried out from the ground and space using a wide variety of photometers and interferometers. Since the launch of ISIS-II spacecraft in 1971, it has been productive of indepth optical investigations of a variety of physical properties of the ionosphere/magnetosphere at all latitudinal and longitudinal zones.

At low latitudes, the equatorial ionization (Appleton) anomaly (EIA) is a persistent manifestation of the coupling of the ionosphere and the thermosphere and, in the past, numerous investigations have been carried out to study its nature and morphology. The formation of EIA is mainly due to vertical electrodynamic drifts at the magnetic equator during daytime brought about by eastward electric fields generated in the E-region dynamo. As the plasma reaches higher altitudes, it diffuses downwards along the magnetic field lines leading to the formation of the two crests on either side close to the magnetic equator at about \( \pm 15^\circ \) dip latitudes and sometimes stretching to about \( 38^\circ \) dip latitudes. For recent reviews the proceedings on equatorial aeronomy \( ( J \text{ Atmos} \ & \text{ Terr} \ \text{Phys, 53, August 1991) may be consulted. The intensity and the north-south asymmetry are significantly controlled by the meridional winds. The anomaly is also influenced by the direct penetration of the magnetospheric electric fields involving the substorm current system, and the equatorward propagating disturbances originating from energy deposition at high latitudes. In addition, there are thermospheric responses to localized heat and momentum sources in the form of stable auroral red (SAR) arcs, which occur near the plasmapause boundary during geomagnetically disturbed periods.

Recently, Bhatnagar and Shepherd studied the meridional structure of the red arcs observed by the ISIS-II spacecraft at equatorial latitudes. One of the objectives was to infer qualitatively the direction of the transequatorial winds in the African and Asian sectors in the nighttime. In the present work, we deal with those passes which provide both the anomaly crests in the emission in the American zone, with the exception of one pass (i.e. pass 6729) which unfortunately does not provide any crest due to the absence of emission and \( f_0F_2 \) data. However, this has been retained simply to show \( f_0F_2, h_{m}F_2 \) and winds at middle and high latitudes, and that no wave structure/oscillations exist inspite of its being a highly disturbed period.

The emission is used with the observed \( f_0F_2 \) to deduce \( h_{m}F_2 \). These \( h_{m}F_2 \) and other geophysical parameters are then entered into the vector spherical harmonic model (VSH90, Version 1.25, Sep. 1990) originally described by Killeen et al. to infer meridional and zonal winds, not only at equatorial latitudes but at middle and higher latitudes as well.

2 Observational data

ISIS-II, the last of the International Satellites for
Ionospheric Studies, was launched on 1 Apr. 1971 into a polar circular orbit at a height of 1400 km with an orbital period of 113 min. The red line photometer (RLP) experiment performs measurement and mapping of OI (6300Å) red line emission\(^{13}\). In cartwheel mode with its spin axis perpendicular to the orbital plane, the RLP gathered the data along the orbital track. In the orbital aligned mode, the RLP gathered the data along latitudinal circles. The RLP was operated throughout the whole pass, but data acquisition was limited to the locations of ground telemetry stations. We present the downward looking optical data in the vertical direction for six nighttime stations. We present the downward looking optical data in the vertical direction for six nighttime stations.

Since equatorial spread-F is present in August/September in the American zone in the 60-130°W longitudinal region and are given in Table 1. The observing stations are Ottawa (44°N, 76°W), Canada; Santiago (33°S, 289°E), Chile and Quito (0°N, 281°E), Equador. The optical data were then processed to obtain the vertical integrated emission using the software described by Thirkettle\(^{14}\). The corresponding data on \(f_{\text{o}}F_2\) and \(h_mF_2\) were obtained from the topside sounder on the same satellite. Since equatorial spread-F is present in August/September in the American zone\(^{15}\), the topside ionograms could not by themselves be analysed for \(h_mF_2\). Therefore, \(h_mF_2\) values were calculated as explained in Sec. 3.

### Theoretical treatment

The 6300Å emission originates from the metastable \(O(1D)\) decaying to the ground state \(O(3P)\), where \(O(1D)\) is produced from the dissociative recombination of \(O_2^-\) with electrons.

The vertical integrated emission \(I\) at nighttime, assuming dissociative recombination of \(O_2^-\) and \(n(e) = n(O^+)\) in the F-region, is given by

\[
I = A_{300} \int_{0}^{h} \frac{k n(O_2)}{A_0 + \nu n(N_2)} \, dh
\]

where, \(n\) denotes the number density of the constituents, \(A_{300}\) and \(A_0\) are the Einstein coefficients, \(h\) the height parameter, \(k\) the probability of the \(O(1D)\) production, \(\alpha\) the rate coefficient between \(O^+\) and \(O_2\), and \(\nu\) the rate coefficient for the major loss reaction between \(O(1D)\) and \(N_2\). The values adopted for these are described by Bhatnagar and Shepherd\(^2\). According to the formulation by Chandra et al.\(^{16}\), Eq. (1) can be integrated for nighttime to yield

\[
I = 7.6 \times 10^{-7} \frac{k n_m(e) n_m(O_2)}{H(O) F} \quad \text{..(2)}
\]

where,

\[
F = \frac{2.33 \times 2^{22} \Gamma (2s + 0.5)}{1 + 2^{1.75} q_m \left( \frac{1.2 \Gamma (2s + 0.5)}{\Gamma (0.25s + 0.25)} + 1 + q_m \right)} \quad \text{..(3)}
\]

\[
q_m = 1.1 \times 10^2 \nu n_m(N_2) \quad \text{..(4)}
\]

Now, using Eq. (4) in (3), we have

\[
F = \frac{5.91}{1 + 1.1 \times 10^{-8} n_m(N_2)} \quad \text{..(5)}
\]

Using Eq. (5) in (2), we get

\[
\frac{I}{(f_{\text{o}}F_2)^2} = \frac{4.6 \times 10^{-6} n_m(O_2)}{1 + 1.1 \times 10^{-8} n_m(N_2)} \quad \text{..(6)}
\]

Here, \(H(O)\) is the scale height of the atomic oxygen; \(n_m(e)\), \(n_m(O_2)\) and \(n_m(N_2)\) are the densities of electron, oxygen and nitrogen at \(h_mF_2\), respectively and \(s\) is the shape factor and is about 0.8 for the nighttime. Since \(n_m(e)\) or \(f_{\text{o}}F_2\) are known from the topside sounder and \(I\) from RLP measurements, \(h_mF_2\) can be obtained from Eq. (6) by numerical iteration. The expression on the right hand side of Eq. (6) is calculated at different heights, and the height at which the equation is satisfied is the required \(h_mF_2\). For this purpose, we require a thermospheric model of the constituents \(O_2\) and \(N_2\) and the temperature, and we adopted COSPAR International Reference Atmosphere (CIRA, 1972) for the corresponding solar activity and the geomagnetic indices of the days of the satellite passes chosen. Since we are interested in F-region heights, the choice of the model is not critical here. The choice of some other model may give a different \(h_mF_2\), but will still be in the F-regions. In Fig. 1 for pass 6704 recorded

<table>
<thead>
<tr>
<th>Pass number</th>
<th>Date</th>
<th>Time hrs UT</th>
<th>(A_p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6691</td>
<td>10</td>
<td>0735</td>
<td>15</td>
</tr>
<tr>
<td>6704</td>
<td>11</td>
<td>0749</td>
<td>11</td>
</tr>
<tr>
<td>6716</td>
<td>12</td>
<td>0633</td>
<td>5</td>
</tr>
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<td>6729</td>
<td>13</td>
<td>0725</td>
<td>53</td>
</tr>
<tr>
<td>6741</td>
<td>14</td>
<td>0554</td>
<td>54</td>
</tr>
<tr>
<td>6742</td>
<td>14</td>
<td>0749</td>
<td>54</td>
</tr>
</tbody>
</table>
over Ottawa for a quiet period, the variations of $I$, $f_0$F2 and the calculated $h_m$F2 are shown against latitude. This is a cartwheel pass for a longitude (~100°W) close to that for Ottawa. In Fig. 1 is shown the lowest scaled real height of about 305 km from the topside ionogram by a circle. This value is lower by 13% than the calculated one of 345 km. However, a much more detailed comparison should be undertaken to ascertain the applicability and the limitations of the present method to estimate the $h_m$F2. It should be noted that the calculated $h_m$F2 values may be in error at high latitudes if some other processes, in addition to the dissociative recombination, contribute to the emission such as particle precipitation.

The $h_m$F2 values thus obtained are entered into the VSH90 model of thermospheric circulation to infer the winds at these peak heights for the corresponding day, time, latitude, longitude, solar flux and the geomagnetic index. Positive values are assigned to nothward meridional winds and eastward zonal winds in geographic coordinates.

4 Results and discussion

4.1 Geomagnetic quiet periods

Pass 6691:

This pass was recorded over Santiago and Quito on 10 Sep. 1972, a mildly active day ($A_p = 15$), at 0735 hrs UT and is shown in Fig. 2. The previous day was quieter ($A_p = 8$). The squares show the observed vertically integrated red line intensity ($I$) at intervals of a spin period (18 s) of the satellite. The observed points were filtered using a simple three-point filter method and the continuous line is the average through these filtered points in 2° latitude intervals. The dashed line shows the $f_0$F2 and the line through crosses shows the $h_m$F2 deduced from $I$ and $f_0$F2 as discussed in Sec. 3.

The intensity curve shows two equatorial anomaly peaks on either side of the magnetic equator.

![Graph showing variations of vertical integrated intensity, $f_0$F2 and $h_m$F2 with geographic and magnetic latitude for pass 6704 recorded on 11 Sep 1972 ($A_p = 11$) at 0744 hrs UT. The circle represents the lowest scaled real height from ionogram at Ottawa.]
Fig. 2—Variations of the vertical integrated intensity (•), \( f_0F_2 (\triangle) \) and \( h_mF_2 (*) \) with geographic and magnetic latitude for pass 6691 recorded on 10 Sep. 1972 (\( A_p = 15 \)) at 0735 hrs UT.

—a major one at 5°S (6°N, magn.) and a minor one at about 20°S (12°S, magn.) at 0239 and 0244 hrs LT, respectively. The trough is located at 0° magnetic. The persistence of the anomaly until about 0300 hrs LT was also noted by Walker and Strickland. The crest in \( f_0F_2 \) in the southern hemisphere is quite pronounced in comparison to that in \( I \). The \( h_mF_2 \) in the anomaly region is fairly constant at about 300 km. Hence the emission intensity is mainly controlled by \( f_0F_2 \) resulting in an excellent agreement between the locations of anomaly crests in \( I \) and \( f_0F_2 \). Also it can be noted from Fig. 2 that \( h_mF_2 \) tends to be low when \( f_0F_2 \) is high and vice versa around 10°N (geogr.), with a monotonic increase northward beyond that. The meridional and zonal winds as described in the Sec. 3 are shown against geographic latitudes in Figs 3 and 4, respectively.

Passes 6704 and 6716: The pass 6704 was recorded over Ottawa and Quito on 11 Sep. 1972 (\( A_p = 11 \)) at 0749 hrs UT.

and is shown in Fig. 1 together with \( f_0F_2 \) and \( h_mF_2 \). The \( A_p \) value on previous day was 15. The two anomaly peaks in emission lie at 3°N (13°N, magn.) and 26°S (17°S, magn.) at about 0214 and 0213 hrs LT, respectively. The anomaly in the northern hemisphere is visible in \( f_0F_2 \) at the same location. The southern one cannot be studied due to the absence of \( f_0F_2 \) data. The enhanced emission seen in the 50°-60°N range (geogr.) is most likely due to auroral processes.

The \( f_0F_2 \) peak in the northern hemisphere is larger than that in the southern hemisphere as suggested by the trend similar to that observed for the previous day in the southern hemisphere. However, the corresponding peaks in the emission intensity are reversed to those for the previous day. The reason for that is the higher sensitivity of the emission to \( h_mF_2 \) rather than to \( f_0F_2 \) (Refs 2 and 16). The \( h_mF_2 \) at the northern peak is about 30 km higher than that for the southern peak and may partly cause higher emission peak in the southern hemisphere. Pass 6716 was re-
corded over Ottawa on 12 Sep, 1972 at 0633 hrs UT on a quiet day \( (A_p = 5) \) and is shown in Fig. 5 with \( f_0F2 \) and \( h_mF2 \). The previous day was also quiet \( (A_p = 11) \). The anomaly crest in the emission occurs at \( 3^\circ S \left( 7^\circ N, \text{magn.} \right) \) at 0224 hrs LT. Unfortunately, we do not have \( f_0F2 \) data at equatorial latitudes due to the presence of equatorial spread-F and thus no \( h_mF2 \). The meridional and zonal wind velocities for these passes are shown against geographic latitudes in Figs 3 and 4, respectively.

### 4.2 Highly disturbed periods

**Pass 6741:**

This pass was recorded over Ottawa and Quito.

![Meridional Wind Velocity](image1.png)

*Fig. 3—Variation of meridional wind velocity with geographic latitude for passes 6691, 6704 and 6716 during quiet geomagnetic periods*

![Zonal Wind Velocity](image2.png)

*Fig. 4—Variation of zonal wind velocity with geographic latitude for passes 6691, 6704 and 6716 during quiet geomagnetic periods*

![Vertical Integrated Intensity](image3.png)

*Fig. 5—Variations of the vertical integrated intensity, \( f_0F2 \) and \( h_mF2 \) with geographic and magnetic latitude for pass 6716 recorded on 12 Sep, 1972 \( (A_p = 5) \) at 0633 hrs UT*
at 0554 hrs UT on 14 Sep. 1972 \( (A_p = 54) \). The previous day was equally disturbed with \( A_p = 53 \). The observed variation of emission intensity, \( f_0F2 \) and \( h_mF2 \) against latitude is shown in Fig. 6. This pass is characterized by two prominent peaks—one situated close to the magnetic equator \( 7^\circ S \) \((3^\circ N, \text{mag.})\) and the other at \( 9^\circ N \) \((19^\circ N, \text{mag.})\) latitudes, respectively. The equatorial anomaly in the emission can be inhibited or enhanced during highly disturbed periods depending upon time, longitude zone and the phase of the storm\(^{18,19}\). In the present case the intensity at the anomaly crests is about the same \((100-150R)\) as that during geomagnetic quiet periods. The large auroral emission is again visible at higher latitudes. It can also be seen that \( f_0F2 \) and \( h_mF2 \) are positively correlated at low latitudes in this high geomagnetic activity case rather than anticorrelated as in the quieter period of Fig. 2. The meridional and zonal winds are shown against geographic latitudes in Figs 7 and 8, respectively.

**Pass 6742:**
This pass was recorded over Ottawa and Quito on 14 Sep. 1972 \( (A_p = 54) \) at 0749 hrs UT. The variation of the emission intensity, \( f_0F2 \) and \( h_mF2 \) against latitude are shown in Fig. 9. The anomaly crests in the emission occur at \( 2^\circ N \) \((12^\circ N, \text{mag.})\) and \( 40^\circ S \) \((30^\circ S, \text{mag.})\) at 0206 and 0220 hrs LT, respectively. The \( f_0F2 \) is not available at southern latitudes due to the presence of ESF. The peak in \( f_0F2 \) at \( 22^\circ N \) \((\text{geogr.})\) is observed to be far removed from the corresponding peak in emission at \( 2^\circ N \) \((\text{geogr.})\) by about \( 20^\circ \), that is, they are not colocated. The \( f_0F2 \) is constant at the location of the emission crest in the northern hemisphere, while \( h_mF2 \) takes a minimum resulting in the crest. Again in other words, the peak emission can be obtained at a location where \( h_mF2 \) is minimum and not necessarily where \( f_0F2 \) is maximum. Also the intensities at the crests are slightly inhibited \(( \sim 75R)\) as compared to the previous pass. A discussion on enhancement or inhibition of the crest intensity during disturbed periods can be found elsewhere\(^2\).

In the present pass we can see oscillations in the intensity of wavelength around 500 km. However, in the previous pass and in pass 6729 (fol-
such oscillations are absent. Such oscillations can arise due to the imposition of magnetospheric electric fields or gravity waves in the presence of high latitudinal thermospheric energy sources. The winds are shown in Figs 7 and 8, respectively.

5 Conclusions

The down looking observations in 6300Å by the red line photometer and \( f_0F2 \) by the topside sounder in the ISIS-II spacecraft have been used to deduce \( h_mF2 \). This method is particularly useful when topside ionograms cannot be analysed.
Fig. 9—Variations of the vertical integrated intensity, $f_{p}F2$ and $h_mF2$ with geographic and magnetic latitude for pass 6742 recorded on 14 Sep. 1972 ($A_p = 54$) at 0749 hrs UT.

Fig. 10—Variations of the vertical integrated intensity, $f_{p}F2$ and $h_mF2$ with geographic and magnetic latitude for pass 6729 recorded on 13 Sep. 1972 ($A_p = 53$) at 0725 hrs UT.
for peak heights due to the presence of spread-F or other irregularities. However, a detailed analysis using various thermospheric models to ascertain the accuracy and limitation of the present method is required. At higher latitudes other mechanisms like particle precipitation play an additional role in the red line excitation and may introduce errors in the deduced $h_mF_2$. Also the possible production of the red line from the precipitation of neutral atoms from charge exchange of ring current ions with neutral hydrogen in the geocorona during very highly disturbed periods may introduce errors in $h_mF_2$ at all latitudes right up to SAR arc region. The peak heights obtained in our case agree within 13% with those obtained from ionograms at middle latitudes without irregularities. The observations refer to American zone for quiet and highly disturbed geomagnetic conditions during low solar activity in the nighttime (2315-0250 hrs LT) in Sep. 1972.

It can be seen from Figs 1, 2 and 5 that the anomaly peak in the emission in the northern hemisphere for quiet periods moves closer to the magnetic equator with time from 13°N at 0214 hrs LT (pass 6704) to 6°N (magn.) at 0230 hrs LT (pass 6691). The corresponding values for the southern hemisphere are from 16°S at 0213 hrs LT (pass 6704) to 13°S (magn.) at 0224 hrs LT (pass 6691). The longitudinal range for these passes is 270-290°E. This result also holds for the corresponding anomaly peaks in $f_0F_2$ and agrees with the result first pointed out by King. VanZandt and Peterson explained this equatorward movement in terms of downward drift of the F-layer and inverse fountain effect.

The anomaly peak in the emission have been found to be colocated with those in $f_0F_2$ except for the pass 6742 for a highly disturbed condition ($A_p = 54$). For this pass the $f_0F_2$ peak was displaced by about 20° northwards from the emission peak. Further, during disturbed periods the anomaly peaks moved further away from the equator up to 19°N (magn.) in the northern hemisphere and 30°S in the southern hemisphere in comparison to those for the quiet period. According to a recent modelling study by Klobuchar et al., the effects of the equatorial anomaly could extend to about $\pm 38°$ magnetic latitude depending on the $E \times B$ drifts at the equator. Higher the drifts farther they are from the equator.

The deduced $h_mF_2$ from the emission and $f_0F_2$ is input in the VSH90 model of the thermospheric general circulation to get the meridional and zonal winds at F-region heights. It can be seen from Figs 3 and 7 that the winds converge at low latitudes in the night rather than being trans-equatorial diverging. In the presence of high latitudinal heat sources and midnight temperature bulge located in the summer before midnight in the southern hemisphere, a converging wind pattern is naturally expected. For the inclusion of winds in the modelling efforts of the low latitude F-region, a recent review by Stening may be consulted. We also find that the crests in emission or in $f_0F_2$ either stay the same or are reduced in highly disturbed periods, and this is reflected in our resulting converging-type winds. This agrees with the results of Ruster and King that the meridional winds tend to reduce overall electron density and hence probably emission too at low latitudes. This converging wind system will result in a downward air motion $\frac{\partial U}{\partial y}H$.

\[
U_y = \frac{\partial U}{\partial y}H \quad \text{... (7)}
\]

which is about 0.6 m/s for our case implying adiabatic heating at equatorial latitudes. Here, $\partial U/\partial y$ is the meridional wind gradient and $H$ is the scale height.

6 Summary

The findings of the present study can be summarized as follows:

(i) The anomaly crests in the emission and $f_0F_2$ are observed up to about 0300 hrs LT, and tend to move closer to the magnetic equator with time.

(ii) The anomaly crests in the emission and $f_0F_2$ are, sometimes, not colocated during disturbed periods.

(iii) The implied meridional wind system is found converging at equatorial latitudes, with equatorward winds in both the hemispheres.

(iv) The implied zonal winds are eastward at low latitudes and westward at middle and high latitudes for both quiet and disturbed conditions. The transition from westward to eastward wind occurs at a fairly constant 20°N geographic latitude for both quiet and disturbed conditions.

(v) Occasionally waves/oscillations are observed in emission or $f_0F_2$ at low and middle latitudes during disturbed conditions. These are expected in the presence of the imposed substorm related electric field or the medium scale gravity waves generated by auroral energy sources and thus transporting energy equatorward.

(vi) The implied meridional winds are southward in the northern hemisphere reaching a speed up to 400 m/s at high latitudes and about 50 m/s
at low latitudes during disturbed periods as observed before by Hagan\textsuperscript{32}.

(vii) The 6300Å intensity at the crests is found either reduced (50-75R) or stays at the same level as for quiet periods (75-100R) during disturbed periods, and

(viii) The resulting downward air motion with velocity of about 0.6 m/s due to converging meridional winds at low latitudes could give rise to adiabatic heating/cooling.

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