Chapter 3. Observation and Image Analysis

The ESF irregularities are generated over magnetic equator and grow vertically upward by non-linearly to reach very high altitudes. In this process, the low density flux tubes are distributed along magnetic field lines to low latitudes. Thus, imaging observations in the post-sunset period conducted over a station near the equator gives the details of the depletions at or immediately after their generation. On the other hand, observations from off-equatorial stations are useful to study the features of well-developed depletions. In the present analysis, images taken at two different locations, one over a low-latitude station Mt. Abu, and other one over the equatorial station Kavalur are used. This chapter gives the details of the observations at both the stations and the steps used to analyze the images.

3.1 Observations at Mt. Abu

![Figure 3.1](image)

Figure 3.1 The coverage of the all sky imager and observation geometry at Mt. Abu for the observations in 1999. The circle gives the approximate FOV assuming an emission altitude of 250 km, for a zenith angle of 75°. The dark line denotes the geomagnetic equator.
The PRL’s all sky optical imaging system was operated from Mt. Abu (24.5°N, 72.7°E, 18.5°N Magnetic) during 12-18 April 1999. The images were taken using 630 nm emission line. Observations start after the local sunset and continue till local moonrise, depending on the sky conditions. Normally observations are taken with 15 minutes interval between consecutive exposures. An exposure time of 30 seconds was used in the present experiment. From a low latitude station like Mt. Abu, it is possible to study the movement of the northern end of the plasma depletions. In principle the all sky imaging system is capable of covering 180° field of view (FOV). But in calculations, the actual FOV was restricted to ±75° from zenith to minimize the possible errors at the edges of the FOV. Figure 3.1 gives the observation geometry and the coverage of the all sky imager centered at Mt. Abu.

In general, the observations start around 1930-2200 LT, immediately after the local sunset. During the observations at Mt. Abu, the CCD camera was not available, and hence an SLR camera with photographic film was used to take the images. Thus, each frame was taken manually, and after each exposure, the film is advanced to take the next frame. The observations were continued until about 0000-0100 LT, depending on the moonrise time. Though imaging was carried out during 12-18 of April 1999, out of the 5 nights, plasma depletions were observed on two nights, 14th and 15th April 1999. The days were geo-magnetically quiet.

Since the images at Mt. Abu are taken using an SLR camera, the image analysis is very sophisticated. First, the photographic films are carefully washed. The developed negatives are then digitized to convert the data to electronic format. This process was done using the digitizer at the Udaipur Solar Observatory. Note that, as described in section 2.6, while taking the observations, cover images are taken at specific intervals to remove the system noise. The digitized images are then processed to remove such system noise as well as background contamination. Here, one major disadvantage is that the locations of the center of the image in individual images do not coincide. This is because, while digitizing, the photographic film is manually advanced frame by frame. In this process the individual frames do not necessarily align with the light source in the same as the previous or next frame, and there will be a slight offset in the location of the center pixels.
Thus, to carry out further image analysis of the Mt. Abu images, each image has to be checked manually, and the center pixels of the circular image caused by the airglow is determined. This is done in IRAF. First, a circle is drawn so that it coincides with the image, and its center locations and radius are noted. This is repeated for each frame taken in a given night. Once the process is completed, a reference center location is determined and each frame is processed so that it center is now the reference center. This makes sure that the center of all the images taken in one night is now aligned, and that further image analysis such as averaging, subtraction, etc. could be carried out. The entire process is repeated for all the 5 nights. Later, these images are analyzed to derive information of the images such as the scale-size, velocity, etc. A detail description of the observation, digitization, and image analysis for an imaging system using photographic film is given in the Ph.D. thesis of Shikha, 1999.

3.2 Observations from Kavalur

Though in the initial stages the all sky observations were taken using photographic films, the PRL’s imaging system was subsequently modified and updated using CCD camera. With the inclusion of the CCD camera, the observation as well as image analysis became much simple. The software that controls the CCD camera is used to run the all sky camera in a semi-automated mode. And, since the images are directly stored in electronic format, the center locations are identical for all the images, as long as the position of the imaging system is not disturbed. This simplifies the operation as well as analysis in a great way. Though a CCD camera was incorporated with the PRL all sky imager in 1998, unfortunately it failed during one of the observation campaigns in 1999. A replacement camera could be purchased only by the end of the year 2001. With the arrival of the new camera, the all sky imager optics was modified to suit the new camera and the system was made ready to conduct observations in early 2002. Further improvements were made in the optical alignment and image quality. Meanwhile, a computer controlled filter wheel mechanism was also introduced, which made it easier to employ multiple filters with minimum manual operation. This time, it was decided to carry out observations from Kavalur (12.5° N, 78.8° E, 4.6° N Magnetic), which is an equatorial station from where the depletions at their formative stages could be imaged.
Figure 3.2 The coverage of the all sky imager and observation geometry at Kavalur for the observations in 2002. The circle gives the approximate FOV assuming an emission altitude of 250 km, for a zenith angle of 75°. The dark line denotes the geomagnetic equator.

Figure 3.2 gives the geometry and the FOV for the observations from Kavalur. It can be seen that the southern end of the imager covers the locations just to the south of the magnetic equator. Thus, it is possible to observe depletions, whenever they develop to the sensitive range of the spatial and intensity scales of the imaging camera. The images were taken using 630.0, 557.7, and 777.4 nm emissions, with exposure times of 60, 30, and 120 seconds, respectively. Interference filters of 1 nm bandwidth were used to isolate the emissions from the background. Each filter is repeated approximately in every 10-15 minutes, and observations are taken in each night depending on the sunset and moonrise times. Since the probability of ESF irregularities as well clear weather conditions are suitable in the February-April period, observations are conducted during this interval.
Table 3.1 Details of observations from Kavalur during February-April 2002

<table>
<thead>
<tr>
<th>Month</th>
<th>Nights of observations</th>
<th>Depletions in</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>630.0 nm</td>
</tr>
<tr>
<td>February</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>March</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>April</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Total</td>
<td>33 (100%)</td>
<td>27 (81%)</td>
</tr>
</tbody>
</table>

The all sky imager of PRL was operated from Kavalur during the months of February-April, in the year 2002. In this period, the imager was operated for 33 nights, with 10 days of observations in February (6-16), and 12 days in March (4-17), and 11 days in April (5-15). Out of this, depletions were observed in the 630.0 nm images in 27 (~80%) nights and in the 777.4 nm about 25 (~75%) nights. Also, about 19 (~57%) nights there were depletions in the 557.7 images also. The details of the imaging observations from Kavalur in 2002 are summarized in Table 3.1. It is rather unusual that depletions were observed in 630.0 nm in 11 consecutive nights of March (4-14), and April (5-15). About 70% (19/27) of the nights with depletions in 630.0 nm also had depletions in 557.7 nm images. The bright mesospheric 557.7 nm emission generally makes it difficult to observe the F-region signatures in ground based observations.

The observations in 2002 from Kavalur were remarkable in that there were several nights with intense depletions. Moreover, depletions appeared in all the three wavelengths in some of the nights. The generation of irregularities could be more during geomagnetic disturbances. Also, in the solar maximum year of 2002, magnetic disturbances could be frequent. In order to check the magnetic conditions during the period of observations in 2002, the Kp and Dst indices during February-April in 2002 are plotted in Figure 3.3. It can be seen from the figure that there is no significant geomagnetic activity during the observation period. The only magnetic disturbance in this period occurs after the observation in March is over, and the activity becomes normal well before the observation in April begins.
Figure 3.3 The Dst (top panel) and Kp (bottom panel) indices during February-April, 2002. The Dst plotted here are the daily average values, and the Kp values are the maximum value recorded in a 24 hour period. The values are taken from the national geomagnetic data center (NGDC). The shaded horizontal bar in the bottom panel represent the duration of imaging observations in each month in this interval. Note that there are disturbed conditions immediately before or during the experiment.

The images were taken at every 10-15 minutes interval using the 630.0, 557.7 and 777.4 nm airglow lines, with exposure times of 60, 30, and 120 seconds, respectively, when clear sky conditions were available between sunset and moonrise. Though several hours of the night are imaged in different days, depletions do not appear over entire period. Their occurrence varies from night to night. Also, it is different for each wavelength used. To give an idea of the period of observations in each night, as well as the duration for which depletions appear, the summary plots of observations and depletions are generated for each wavelength, whenever depletions appear. Figure 3.4 gives the details of the depletions observed in 630.0 nm. Three different shades of gray are used to denote depletions (light gray), no observation (medium gray), and no depletions (dark gray). The Y-axis is the days when depletions are observed. The X-axis is the time of observations with an offset of 18 hours. Thus, 0 on X-axis corresponds to 1800 LT, and 12 correspond to 0600 LT on the next morning.
Figure 3.4 The details of the hours of night for which depletions are observed in 630.0 nm during February-April, 2002. Three different shades of gray are used. The light gray shade denotes the period for which depletions appear in the images. The medium shade of gray corresponds to the period of no observation. The dark gray shade represents the period when imaging was conducted, but no depletion appeared in the images. The Y-axis is the days when depletions are observed in 630.0 nm. The X-axis is the time of observations with an offset of 18 hours. Thus, 0 on the X-axis corresponds to 1800 LT on the corresponding day and 12 correspond to 0600 LT on the next morning.
Figure 3.5 The details of the hours of night for which depletions are observed in 777.4 nm during February-April, 2002. Three different shades of gray are used. The light gray shade denotes the period for which depletions appear in the images. The medium shade of gray corresponds to the period of no observation. The dark gray shade represents the period when imaging was conducted, but no depletion appeared in the images. The Y-axis is the days when depletions are observed in 630.0 nm. The X-axis is the time of observations with an offset of 18 hours. Thus, 0 on the X-axis corresponds to 1800 LT on the corresponding day and 12 correspond to 0600 LT on the next morning.
Figure 3.6 The details of the hours of night for which depletions are observed in 555.7 nm during February-April, 2002. Three different shades of gray are used. The light gray shade denotes the period for which depletions appear in the images. The medium shade of gray corresponds to the period of no observation. The dark gray shade represents the period when imaging was conducted, but no depletion appeared in the images. The Y-axis is the days when depletions are observed in 630.0 nm. The X-axis is the time of observations with an offset of 18 hours. Thus, 0 on the X-axis corresponds to 1800 LT on the corresponding day and 12 correspond to 0600 LT on the next morning.
Similarly, Figure 3.4 gives the hourly details of the depletions in 777.4 nm images and Figure 3.5 gives that of the depletions in 557.7 nm. It can be seen that the depletions in 630.0 nm appear around 2000 LT in most of the nights. Further, in several nights the depletions are seen well beyond the post-midnight period. Note that in the night of 16 February 2002, depletions are imaged till sunrise hours. In the case of 777.4 nm also, the depletions appear around 2000 LT or earlier. However, there are only very less number of nights when they persist till post-midnight period. In most of the cases, depletions are not imaged beyond midnight. The appearance of depletions in 557.7 nm is slightly different from the other two emissions. In this case, the depletions start appearing only around 2300 LT or later. However, similar to the 630.0 nm, they persist well into the post-midnight hours.

The analysis of the CCD based Kavalur images are less sophisticated than the images at Mt. Abu. However, the nights with depletions are much more in this case. The raw images were first corrected for the system noise. For this, cover images were taken by keeping the fisheye lens covered with the same exposure times used for different filters. The cover image was subtracted from each image to remove system noise. The background noise was removed by subtracting the average of the images taken in about 1 hour period from each of the corresponding images. In the average images, stationary features such as background noise, station light, etc. are retained, while non-stationary features such as the intensity variation due to depletions are smoothened out. Thus, subtracting the average image removes the background noise from the images, and enhancing the depletions. After the noise subtraction, the images are displayed so as to have the best possible contrast.

### 3.3 Apex mapping

Equatorial Spread-F (ESF) irregularities in the nighttime ionosphere manifest as dark bands of reduced intensity in all sky airglow images, known as plasma depletions [Weber et al., 1978]. It is generally understood that the depletions elongate to low- and mid-latitudes depending on the upward (vertical) movement of the irregularities at the equator [Weber et al., 1978; Mendillo et al., 2005]. The less density plasma associated with the irregularities when transported along the geomagnetic field lines to off-
equatorial latitudes modifies the airglow intensities, and result in North-South (N-S) aligned depletions. Thus, as the irregularities rise above the equator to higher altitudes, the flux tubes extending to lower altitudes and low latitudes will have less plasma density. At the locations of these low density flux tubes, the photochemistry also will be affected, resulting in less airglow emission, and produce plasma depletions in all sky images.

Thus, when the irregularities are driven to more and more altitudes at the equator, the latitude extension of the depletion also increases. The latitude extent of the depletion depends on the maximum altitude of the bubble above the equator [Mendillo et al., 2005]. In other words, a time sequence of images depicting the poleward extension of the edge of plasma depletion actually represents the vertical upward movement of the irregularities above the equator. This poleward extension of depletions in all sky images can hence be used to understand the vertical movement of the irregularities above the equator. This is done by mapping the latitude of the poleward end of depletion along the field line back to the corresponding altitude at the magnetic equator. This process of finding the altitude of the bubble above the equator is known as apex mapping. For apex mapping, observations conducted from a low latitude station such as Mt. Abu are more suitable. The northern limit of the plasma depletions can be mapped back to the corresponding altitude attained by the depletions at the equator with the help of the International Geomagnetic Reference Field (I.G.R.F.) Model. Detailed illustration of apex mapping is given below.
Figure 3.7 Illustration of apex mapping. Sketch of magnetic field geometry is used. The depletion is at different stages of vertical motion in the selected images. The thick dark lines over the field line geometry denotes the vertical motion of the bubble, and the associated latitudinal extension. When the bubble reaches higher altitude, depletion grows to more northern latitudes.
In Figure 3.7, the top panel represents the case after sunset when the bubble develops. The low density plasma regions grow to the topside non-linearly by the action of polarization electric field. The plasma bubble is denoted by the thick dark vertical line over the equator. As the bubble move upward, the low density plasma regions are distributed to lower latitudes along the field line as indicated by the thick black curves plotted over the field lines. In the top panel, an example for the image taken at 2050 on 14 Aril 1999 from Mt. Abu is shown. The depletion is seen almost above the center of the image here. In the second panel, the image taken at 2130 LT is shown. Here the bubble already moved to much higher altitude above the equator. Consequently, the dark regions of low plasma density also extends polewards, causing the depletion in the image to be seen extending Northward. Similarly, in the third panel at 2240 LT, the bubble rises to much higher altitudes over the equator. In this case it reaches about 950 km, and the corresponding latitudinal limit is about 23.1 N.

Thus, by noting the poleward latitudinal limit of depletion in a sequence of images, it is possible to map back the corresponding field line and estimate the maximum altitude the bubble might have reached at the equator for each of the image taken. Using this time series data of the altitude above the equator, the vertical velocity of the bubble above the equator is calculated.