Chapter 4

Radio Emissions of the Sun and Associated Geomagnetic Parameters during Maximum Solar Activity

4.1 Introduction

Solar radio bursts originate in the same layers of the solar atmosphere where energy is released in solar flares, energetic particles are accelerated, and coronal mass ejections (CME) are launched. Solar radio bursts were amongst the first phenomena identified as targets for radio astronomy [1-3]. Characteristic studies of solar radio bursts are of great importance for determining the solar flare and Coronal Mass Ejections (CME) phenomenon. Solar radio bursts at frequencies below a few hundred MHz were classified into 5 types. They are type I, II (slow drift), type III (fast drift), type IV (broadband continuum) and type V radio bursts. The first radio emissions to arrive on earth following a flare are the Type III storm occurring for the first 5-6 minutes following a flare [4]. These are relativistic electrons released by the flare traveling through the sun’s magnetic field. The radio emissions begin around 300 MHz and drift downward in frequency at about 20 MHz/sec. Some of these electrons travel along the open field lines in a spiral motion, in relativistic speed producing continuum noise (wideband) from 10–300 MHz. Type III bursts are the most common type of solar radio activity. They can occur either singly (duration -5 s) or in groups. Only about one-third of Type III bursts are associated with flares. Type III bursts are caused by streams of ~100 keV electrons propagating outward through the solar atmosphere and exciting plasma waves. Because of their relatively high drift rates (20 MHz/s) to lower frequencies, they are referred to as fast drift bursts [5-7].

4.2 Activity of Solar Flares

Flares are enormous events on the surface of the sun that occurs when a built up of magnetic energy on sun’s atmosphere is suddenly occur near sunspots, on the dividing line between areas of opposite magnetic polarities [8-10]. A solar flare is classified into following classes (Table 4.1) according to the peak flux of 100 to 800 pico-meter X-rays near Earth (units in watt per square meter).
Table 4.1  
Classification of solar flare

<table>
<thead>
<tr>
<th>Solar Flare Class</th>
<th>Intensity (Watts/Sq. meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$10^8 \leq I &lt; 10^7$</td>
</tr>
<tr>
<td>B</td>
<td>$10^7 \leq I &lt; 10^6$</td>
</tr>
<tr>
<td>C</td>
<td>$10^6 \leq I &lt; 10^5$</td>
</tr>
<tr>
<td>M</td>
<td>$10^5 \leq I &lt; 10^4$</td>
</tr>
<tr>
<td>X</td>
<td>$I \geq 10^4$</td>
</tr>
</tbody>
</table>

4.3 Solar Radio Emission

The Sun is the strongest source of radio waves in our solar system. Radio emission from the sun can arises from several different phenomena and can be divided into three main components. These components are the quiet sun component, which is always present, the slowly varying component and the active sun component which is caused by sunspots and flare activity. The quiet sun component of the radio emission is from thermal emission from the hot ionized gas. The other two components are related to the sunspot activity on the sun. The slowly varying component is also thermal in origin and arises from the region above the sunspots where the electron density is higher. The blackbody temperature of these regions can be as high as 2 million K. Thus the regions above the sunspots can contribute more radio emission than the total area without sunspots and increase the total radio flux relative to the quiet sun. So the change in the total radio flux is dependent on the total number of sunspots [11-14].

4.4 Recorded Bursts

For recording solar radio bursts the instruments we used are Log Periodic Dipole Array (LPDA) antenna, constructed at Kalyani (22.98°N, 88.46°E) in the Department of Physics, University of Kalyani, in West Bengal, and a Digital Storage Oscilloscope (DSO) GDS-1000 Series (Figure 4.1), connected to a computer containing a signal analysis software which digitalized the vertical input (constantly varying solar radio signal voltages), create a data set out of it and stored it in the computer [15-17].
Figure 4.1 Digital storage Oscilloscope GDS-1000 Series

Figure 4.2 Solar signal variation data on the day in which no burst was observed

Figure 4.2 shows solar signal amplitude vs. time plot, obtained from the one hour data recorded on February 7, 2013, the day in which no significant bursts were recorded. From the graph plot, we can see that, the amplitude has an average value of 0.0015 volt, with few peaks at 0.002 volt. This can be considered as the quiet sun component of solar radio emission, which comes from thermal emission from hot ionized gases of the sun [18].
Figure 4.3 shows the one hour plot obtained on February 28, 2013 and on February 26, 2013, 6:00 AM (UT) and 5:30 AM (UT) onwards respectively. From the plot of February 28, we can see that the amplitude level remained at about 0.05 volt with a sudden increase to about 0.25 volt from 6:18 AM (UT) to 6:21 AM (UT). We considered this event as a burst of duration 3 minutes. Clearly the burst component has amplitude 100+ times greater than the quiet sun component. Similarly, we recorded many more radio burst, having different amplitudes and durations. Some bursts occurred for duration as long as 30 minutes as that on February 26, 2013, 5:30 AM (UT) onwards. We can consider these two as the active sun component of radio emission which are associated with sunspots and flare activity.

Some bursts occurred only for few seconds, as on March 12, 2013 at 7:43 AM (UT). Normally most of the burst component recorded by us, have amplitude about 0.1 volts, however we also obtained bursts having amplitude about 1 volt or above, as that obtained on March 4, 2013 around 9:45 AM (UT). These bursts components have amplitude 1000 times greater than the quiet sun components. These bursts are shown in Figure 4.4.
Figure 4.4 Bursts obtained on March 4 and March 12, 2013

The bursts obtained could be any of the five principal types, as mentioned earlier. These are, type I noise-storm bursts, type II slow-drift bursts, type II fast-drift bursts, type IV, a broadband continuum emission and type V which is a continuum emission at meter wavelengths. Types II and III drift down in frequency with drift speeds of about 20 MHz/min and 20 MHz/sec respectively. With our instruments we were unable to record any data corresponding to the frequency of the bursts. Therefore, we cannot classify the solar radio bursts that we observed. However, we correlate these bursts with different solar events, X-ray events, and other solar observations which were recorded by various observatories around the globe.

4.5 Effects of Coronal Mass Ejection on the Earth

We now consider the flare process in details. It is believed that the strong magnetic field lines emanating from the sunspots become so strong that hot burning gasses from the sun are suddenly sucked out of the interior of the Sun and carried along the magnetic field lines of the disturbance in a violent explosion. While the interior of the sun is exposed at the flare site, gamma and x-rays are allowed to escape, travelling outward at a speed equal to the speed of light. This explosion creates a shockwave which carries some of the burning solar mass out into space [19]. The mass ejected is plasma containing electrons and protons as main constituent and also may contain heavier elements like helium, oxygen, and even iron in small amount. They travel at speeds greater than 1000 km/sec. On reaching the Earth, it can disrupt the long-distance radio communication. It can disrupt the Earth’s environment as well [20]. There is a risk of exposure to intense radiation for the people working in space.
or the high altitudes in airplanes, spaceships etc. Skin irritation or skin cancer might be seen
due to this highly intense radiation. The energetic particles ejected during the shock wave of
the CME can be dangerous for the astronauts or destroy electronic equipments in satellites
[21, 22].

4.6 Solar Wind and Geomagnetic Storms

Solar winds are streams of highly energetic charged particles originating from the sun,
flowing radially outward from the sun through the solar system. Although these particles
are continuously released from the corona of the Sun, their numbers increase greatly
following solar flares. The Solar wind consists mainly of a mixture of protons, electrons,
and nuclei of some heavier elements in smaller numbers. The particles that make up the
solar wind are formed when the coronal gases expand and evaporate. By this process about
a million tons of gas flow away per second from the sun. The particles are accelerated by
the high temperatures of the corona to speeds great enough to allow them to escape from the
sun's gravitational field. Earlier it was believed that the solar wind was constant, at around
350 km/sec. which the escape velocity of the sun. Now it is known that, the speed of solar
wind is variable, and it ranges from 350 km/sec. (minimum value, also the escape velocity
of the Sun) to 2,000 km/sec. or more following a major solar flare. These high energy
particles could have endangered life on Earth. But the Earth’s magnetosphere protects us
from these space radiations. These particles are forced to move around the Earth by this
magnetic field of the Earth. These particles drift around the Earth within two large donut-
shaped regions called radiation belts [23].

Disturbances to the solar wind due to a solar flare can trigger a geomagnetic storm. The
solar wind exerts a pressure on the earth’s magnetic field (earth’s magnetosphere) [24, 25].
If this pressure changes suddenly with the arrival of a shockwave from a solar flare, earth’s
magnetic field changes shape in response. This generates strong electric currents by the
dynamo effect, which travels along the lines of the magnetic field of earth, which in turn
generates noise on the HF (3-30 MHz) and VHF (30-300 MHz) bands of the radio
spectrum. Figure 4.5 shows the effects of Solar Wind on Earth’s magnetosphere [26].
To measure the condition of the earth’s magnetic field, magnetometers are used. The amount of movement of the earth’s magnetic field due is averaged and reported as the K Index every 3 hours. The K-index is a geomagnetic index which ranges from 0–9 representing quiet to severe conditions. There are other geomagnetic indices which are derived from these K indices. As for example the A index. The K indices are averaged over 24-hours to form the A Index, representing the overall planetary geomagnetic conditions. The A-index ranges from 0–20 for quiet conditions, up to 400 for extreme conditions as shown on Table 4.2 [27-29].
Table 4.2  
Geomagnetic conditions for different values of K and $A_p$-indices

<table>
<thead>
<tr>
<th>K index</th>
<th>$A_p$ index</th>
<th>Geomagnetic conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0-2</td>
<td>Very Quiet</td>
</tr>
<tr>
<td>1</td>
<td>3-5</td>
<td>Quiet</td>
</tr>
<tr>
<td>2</td>
<td>6-9</td>
<td>Quiet</td>
</tr>
<tr>
<td>3</td>
<td>12-19</td>
<td>Unsettled</td>
</tr>
<tr>
<td>4</td>
<td>22-32</td>
<td>Active</td>
</tr>
<tr>
<td>5</td>
<td>39-56</td>
<td>MINOR Storm</td>
</tr>
<tr>
<td>6</td>
<td>67-94</td>
<td>MAJOR Storm</td>
</tr>
<tr>
<td>7</td>
<td>111-154</td>
<td>SEVERE Storm</td>
</tr>
<tr>
<td>8</td>
<td>179-236</td>
<td>SEVERE Storm</td>
</tr>
<tr>
<td>9</td>
<td>300-400</td>
<td>EXTREME Storm</td>
</tr>
</tbody>
</table>

The K-index is a quasi-logarithmic local index of the 3-hourly range in magnetic activity relative to an assumed quiet-day curve for a single geomagnetic observatory site; over a 3-hour period, it classifies into disturbance levels the range of variation of the more unsettled horizontal field component. The K index was designed by Bartels et al. (1939) following the recommendations of the Washington Assembly of the International Association of Terrestrial Magnetism and Electricity (1939) [30]. The basic idea of using K-indices from a network of observatories to derive a planetary index of geomagnetic activity was proposed by Bartels et al. (1939) in the same paper in which the K indices were defined [31, 32]. The planetary 3-hour-range index $K_p$ is the mean standardized K-index from 13 geomagnetic observatories. The scale is 0 to 9 expressed in thirds of a unit, e.g. 5- is 4 2/3, 5o is 5 and 5+ is 5 1/3. This planetary index is designed to measure solar particle radiation by its magnetic effects. The 3-hourly $a_p$ (equivalent range) index is derived from the $K_p$ index shown in Table 4.3 [33-35]:

Table 4.3  
The 3-hourly $a_p$ (equivalent range) index is derived from the $K_p$ index

<table>
<thead>
<tr>
<th>$K_p$</th>
<th>0o</th>
<th>0+</th>
<th>1-</th>
<th>1o</th>
<th>1+</th>
<th>2-</th>
<th>2o</th>
<th>2+</th>
<th>3-</th>
<th>3o</th>
<th>3+</th>
<th>4-</th>
<th>4o</th>
<th>4+</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_p$</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>9</td>
<td>12</td>
<td>15</td>
<td>18</td>
<td>22</td>
<td>27</td>
<td>32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$K_p$</th>
<th>5-</th>
<th>5o</th>
<th>5+</th>
<th>6-</th>
<th>6o</th>
<th>6+</th>
<th>7-</th>
<th>7o</th>
<th>7+</th>
<th>8-</th>
<th>8o</th>
<th>8+</th>
<th>9-</th>
<th>9o</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_p$</td>
<td>39</td>
<td>48</td>
<td>56</td>
<td>67</td>
<td>80</td>
<td>94</td>
<td>111</td>
<td>132</td>
<td>154</td>
<td>179</td>
<td>207</td>
<td>236</td>
<td>300</td>
<td>400</td>
</tr>
</tbody>
</table>
In order to use $a_p$ as an equivalent amplitude, it is considered in relation to the conditions at a standard station, which is a station having the lower limit of 500 nT for $K = 9$. At such a station the average range in nT of the most disturbed of the two horizontal components in a three-hour interval can be taken as $2 \ a_p$ (for instance, for $K_p = 3+$, $a_p = 18$, i.e. 36 nT). In other words $a_p$ is an equivalent amplitude in the unit 2 nT. $A_p$ gives the daily average for the eight values $a_p$ per day. Therefore, it may be called the *equivalent daily amplitude* $A_p$, expressed in the unit 2 nT [36]. Since January 1997, $K_p$ and derived indices are calculated at the Geo-Forschungs-Zentrum, Potsdam. A qualitative estimate of overall level of magnetic activity for the day determined from the sum of the eight $a_p$ amplitudes.

With the occurrence of a solar flare, the solar flux increases, and solar bursts are observed as the amplitude of HF (3-30 MHz) and VHF (30-300 MHz) noise level increases. After a day or two, when the shockwave reaches the earth, K-index goes high which indicates the occurrence of a geomagnetic storm, and correspondingly increases the noise level [37, 38].

![Figure 4.6](image.png) Two strong solar radio signal recorded on February 26 and 28, 2013

**Table 4.4**

<table>
<thead>
<tr>
<th>Date</th>
<th>Kp</th>
<th>Ap</th>
<th>Date</th>
<th>Kp</th>
<th>Ap</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/1/2013</td>
<td>17</td>
<td>1</td>
<td>21/02/13</td>
<td>140</td>
<td>7</td>
</tr>
<tr>
<td>2/1/2013</td>
<td>67</td>
<td>4</td>
<td>22/02/13</td>
<td>193</td>
<td>10</td>
</tr>
<tr>
<td>3/1/2013</td>
<td>40</td>
<td>2</td>
<td>23/02/13</td>
<td>147</td>
<td>8</td>
</tr>
<tr>
<td>4/1/2013</td>
<td>47</td>
<td>2</td>
<td>24/02/13</td>
<td>63</td>
<td>3</td>
</tr>
<tr>
<td>5/1/2013</td>
<td>37</td>
<td>2</td>
<td>25/02/13</td>
<td>60</td>
<td>3</td>
</tr>
<tr>
<td>6/1/2013</td>
<td>77</td>
<td>4</td>
<td>26/02/13</td>
<td>107</td>
<td>5</td>
</tr>
<tr>
<td>7/1/2013</td>
<td>50</td>
<td>3</td>
<td>27/02/13</td>
<td>73</td>
<td>4</td>
</tr>
<tr>
<td>8/1/2013</td>
<td>90</td>
<td>4</td>
<td>28/02/13</td>
<td>133</td>
<td>8</td>
</tr>
<tr>
<td>9/1/2013</td>
<td>87</td>
<td>4</td>
<td>1/3/2013</td>
<td>350</td>
<td>34</td>
</tr>
<tr>
<td>10/1/2013</td>
<td>47</td>
<td>3</td>
<td>2/3/2013</td>
<td>223</td>
<td>14</td>
</tr>
<tr>
<td>11/1/2013</td>
<td>60</td>
<td>3</td>
<td>3/3/2013</td>
<td>173</td>
<td>9</td>
</tr>
<tr>
<td>12/1/2013</td>
<td>73</td>
<td>4</td>
<td>4/3/2013</td>
<td>87</td>
<td>4</td>
</tr>
<tr>
<td>13/01/13</td>
<td>187</td>
<td>10</td>
<td>5/3/2013</td>
<td>67</td>
<td>4</td>
</tr>
<tr>
<td>14/01/13</td>
<td>180</td>
<td>9</td>
<td>6/3/2013</td>
<td>53</td>
<td>3</td>
</tr>
<tr>
<td>15/01/13</td>
<td>113</td>
<td>5</td>
<td>7/3/2013</td>
<td>43</td>
<td>2</td>
</tr>
</tbody>
</table>
We received very strong and longer solar radio bursts on 26\textsuperscript{th} and 28\textsuperscript{th} February, 2013 (Figure: 4.6). The durations the bursts are thirty nine minutes and thirty four minutes respectively. So we consider these types of burst as long bursts. We observe the time sequences of these bursts. When we compare with the time sequences of the geomagnetic activity defined by Ap index, Table 4.4 clearly indicates that Ap value reaches high value (compared to other adjacent days) 34 and 14 on March 1\textsuperscript{st} and 3\textsuperscript{rd}, 2013 respectively (shade marks are given in the table). So the time difference between these solar burst and geomagnetic storm in the earth is two or three days.

4.7 Geomagnetic Indices from January 2009 to January 2014

As mentioned earlier, to observe the effect of these solar flares and activities on geomagnetic conditions, we have taken into account the values of different geomagnetic indices starting from January 1, 2009 to January 2014. We have plotted one day average value of $a_p$ index in Figure 4.7. It appears from this figure that geomagnetic condition is more disturbed for the years 2012 and 2013 and it also increase its strength as we go through from 2009 to 2013. The minor storms observed for sunspot cycle 24 are two, three, six and again six in the year 2010, 2011, 2012 and 2013 respectively. In addition to this, in 2012 two major storms were occurred while that number is only one for 2013 [39-41].

![Figure 4.7 Plot of geomagnetic $a_p$ index (1 day average) from 2009 to January 2014](image)
To relate the geomagnetic conditions with solar activity, we have plotted Kp and $a_p$ index with the sunspot number in the same panel (Figure 4.8). Here we have taken 27 days average as this average is more effective due to solar rotational period. For long time observation $a_p$ and Kp index increases due to enhanced sunspot activity when we compare the years 2009 and 2010 with 2012 and 2013. But when we compare for short duration e.g. shaded portions of the panel, the sunspot activity negatively correlated with geomagnetic indices and has a phase difference between them.

In Figure 4.9, thirty seven month running average of calculated Ap index is plotted from the year 1991 to January 2014. It is clear from this figure that geomagnetic condition is quiet in cycle 24 (up to 2013) compared to two previous two sunspot cycle, though variation of sunspot activity of those three cycles quite small.
Figure 4.9 Geomagnetic $A_p$-index variation during 1991 to January 2014 and 37 month running average [42]

4.8 Discussion

From years of satellite data, we now know that the sun’s electric field is not flat, but instead looks more like the “balerina skirt” model. When the earth’s orbit enters or exits the skirt, it is called a boundary crossing, often reported by NOAA. The sudden change in the solar wind speed, and direction of flow, can trigger a geomagnetic storm. The boundary crossing causes a stronger geomagnetic storm than a positive crossing. However, they are seldom severe and last only a few hours. The solar wind is constantly changing, causing minor geomagnetic storms, even during very quiet solar conditions.

Solar flares, the most powerful explosions in solar system, can equal the system of 1 billion hydrogen bombs. There are three stages of a solar flare. First is the precursor stage, where the release of magnetic energy is triggered. Soft x-ray emission is detected in this stage. In the second or impulsive stage, protons and electrons are accelerated to energies exceeding 1MeV. During the impulsive stage, radio waves, hard x-rays, and gamma rays are emitted. The gradual build up and decay of soft x-rays can be detected in the third stage called the decay stage. The solar cycle begins with magnetic field lines running from the poles of the Sun—the area in tachocline, where radiation and convection zones slide past each other. Because the higher layers of the Sun rotate faster near the equator, which is roughly around 26 days, as to near the poles, where it takes about 36 days, the magnetic field lines start to extend. As plasma flows, it alters these magnetic field lines, which energizes them. When the field lines become distorted, they increase in buoyancy and ascend, and then penetrate the surface of the sun in a variety of spectacular forms, of which one is solar flares. Flares are often accompanied by coronal mass ejections, a huge bubble of magnetized gas blown out from the sun. The bubble travels through the space at about million mollies per hour.
(1.6 million km), taking from 17 hours to 3 days to cross the distance from sun to earth’s orbit [43].

References


[42] National Geophysical Data Center
http://www.ngdc.noaa.gov/stp/solar/solardataservices.html