CHAPTER 6
PREDICTION OF SUNSPOT CYCLE 24

Precursor techniques, in particular those using geomagnetic indices, often are used in the prediction of the maximum amplitude for a sunspot cycle. In this chapter, I predict the maximum amplitude and timing of the current sunspot cycle 24 using precursor techniques. I also predict the annual mean geomagnetic activity for the solar maximum year for the current cycle 24.

6.1 Sunspot cycle Prediction: A brief overview:
Solar outbursts cause inclement space weather that sometimes wrecks havoc on technological systems on which our society is progressively more dependent. These outbursts involve the sudden release of energy that is stored in stressed coronal magnetic fields. They occur on a wide variety of scales depending upon the available free magnetic energy, which, however, is drawn from sunspot magnetic fields. Predictions of solar and geomagnetic activities are important for various purposes, including the operation of low-earth orbiting satellites, operation of power grids on Earth, and satellite communication systems. Various techniques, namely, even/odd behavior, precursor, spectral, climatology and neural networks and flux transport dynamo model have been used in the past for the prediction of the solar activity. Many researchers (Ohl, 1966; Kane 1978, 2007; Thompson, 1993; Jain, 1997; Hathaway and Wilson, 2006) have used the ‘precursor’ technique to predict the solar activity. Also the report entitled “Solar Cycle 23 Project: Summary and Panel Findings” (Joselyn et al., 1997) has mentioned precursor techniques as being the most successful. Jain (1997) used a ‘precursor’ technique to predict the amplitude of the solar cycle 23 using the geomagnetic activity aa index and predicted the maximum annual mean sunspot number for cycle 23 to be 166.2, which, however, was found to be higher than the observed values of 120. Had he used an error estimate, perhaps his forecast would have been within the error limits. The high level of geomagnetic activity occurs not only at sunspot maximum but also in the following two to four years, thereby supporting the idea of the ‘extended solar cycle’ where a solar
cycle really begins some years before solar minimum and where two solar cycles co-exist on the Sun for a number of years. Wilson and Hathaway (2008a, 2008b) observed that the variation of the $aa$ index usually peaks after a sunspot maximum, which appears to be directly related to increased solar wind speed, which probably is the result of high-speed streams from coronal holes. The prediction of maximum amplitude of a sunspot cycle using various aspects of the $aa$ index has been pursued for many years (since the 1960s) by many authors. For example, Ohl (1966, 1971) and Wilson (1990) showed that the $aa$ index values in the few years prior to a sunspot cycle minimum can be used to gauge the size of the next unfolding sunspot cycle. The level of geomagnetic activity near the time of solar activity minimum has been found to be a reliable indication of the amplitude of the following solar activity maximum (Hathaway and Wilson, 2006). In this view, I was motivated to predict the amplitude of the maximum annual mean sunspot number of solar cycle 24 using the technique employed by Jain (1997). I also attempt to predict the annual mean geomagnetic activity for the solar maximum year for the current cycle 24.

6.2 Data:
To predict the amplitude of a solar cycle, a few precursor techniques employ geomagnetic activity indices $viz.$ $Ap$ and $aa$. I have employed the $aa$ geomagnetic index in the current investigation. The details of the observatories and instruments are given in section 2.6 and the data acquisition has been described in section 3.7. Further, the details of the data acquisition related to yearly sunspot number are described in section 3.8. For our current investigation, I have used the data for the period January 1868 – November 2008.

6.3. Analysis and Results:
6.3.1 Defining the Sunspot Minimum Year of Cycle 24:
The trend of observed annual mean sunspot number and annual mean $aa$ index for the period 1868-1992 is shown in Figure 6.1 while for the period 1992-2008 is shown in Figure 6.2.
I observed from Figure 6.1 and 6.2 that the annual mean $aa$ index ranges from 9 nT in 1901 to 37.1 in 2003 which is an indicator of minimum and maximum geomagnetic activity respectively, during the period of 1868–2008. Whereas, the annual mean sunspot number varies between 1.4 in 1913 and 190.2 in 1957. Sunspot numbers rise steadily to maximum and then fall steadily to a low level during each sunspot cycle, whereas geomagnetic indices ($Ap$ or $aa$) show two or more maxima per cycle, one near or before the sunspot maximum and others in the declining phase, and the gap between the two primary maxima (the Gnevyshev gap) results in the quasi-biennial and quasi-triennial periodicities observed in the geomagnetic indices (Kane 1997).

In this investigation the year of the sunspot minimum of solar cycle 24 is of greatest importance and thus at least its precise determination is explicitly necessary. According to “The Weekly” report by NOAA/Space Weather Prediction Center (available at http://www.swpc.noaa.gov/weekly/pdf2008/prf1688.pdf the first sunspot of solar cycle 24 was observed on 4 January 2008 and it was numbered NOAA AR 10981. Later, NOAA AR 10990 and 10993 were observed in April and
May 2008 respectively, and these have also been classified as sunspots of cycle 24.

Figure 6.2: The observed annual mean $aa$ index and annual sunspot number for the period of 1992 – 2008. Note that the annual mean $aa$ index for the period of 2004 – 2008 is 18.4.

However, in parallel and simultaneously, sunspots of solar cycle 23 were also been appearing near the equator until and even after mid 2008. Thus, the year 2008 is considered as the transition period from one cycle to the next. Monthly $aa$ values for 2008 are identified at the website only for January–November. The $aa$ value for December 2008 is estimated to be about 14.4 +/- 4.3, which is found close to the observed value 10.1. In this investigation, however, I employ the 2008 $aa$ to be about 14.6, and the average $aa$ value for the sunspot minimum year together with the preceding four years (2004 – 2008) is estimated to be about 18.4. The annual mean sunspot number for the year 2008 is found to be 2.9 (lower than 7.5 in 2007), which is well within the range of a typical sunspot minimum value (Dabas et al., 2008). Therefore in the current study I considered 2008 as the year of the sunspot minimum and August 2008 as the month of the year of the sunspot minimum of solar cycle 24.
6.3.2 Prediction of the Maximum Annual Mean Sunspot Number:

Following to the method described by Jain (1997), I examined the level of geomagnetic activity to predict the amplitude of solar cycle 24. The annual mean sunspot number for the period 1868 – 2008 and the annual mean of geomagnetic activity $aa$ index for the period 1868 - 2008, are considered in the present investigation. I have determined $(aa_n^*)_{dsc}$, an average of the geomagnetic $aa$ index for the year of sunspot minimum and preceding four years of the descending phase of the $n^{th}$ cycle (i.e. in total 5 years) and compared with the observed maximum annual mean sunspot number $(R_{n+1})_{max}$ of the next, $(n+1)^{th}$, cycle. The variation of observed amplitude $(R_{n+1})_{max}$ for the $(n+1)^{th}$ cycle is plotted as a function of $(aa_n^*)_{dsc}$ as shown in Figure 6.3. I obtained the best linear fit to the data with the correlation coefficient ($r$) of 0.89. Figure 6.3 demonstrates the validation of Ohl’s precursor method for deducing the size of maximum amplitude for a sunspot cycle. Ohl (1966) observed that the geomagnetic activity level during the declining phase of a solar cycle was related to the maximum level of solar activity of the next cycle.

![Figure 6.3: Plot of $(R_{n+1})_{max}$ of the $(n+1)^{th}$ cycle as a function of $(aa_n^*)_{dsc}$. The solid line is the best fit with a correlation coefficient of $r=0.89.$](image)
The linear equation derived from the fit of the data ranging for cycle 11 to 23 is of the following form:

\[(R_{n+1})_{\text{max}} = 7.44 (a a_n)^{\text{dsc}} - 44.12 \quad (6.1)\]

Using equation (6.1), I predicted the maximum annual mean sunspot number \((R_{n+1})_{\text{max}}\) for cycles 12 to 24 using \((a a_n)^{\text{dsc}}\) of the previous cycle. The predicted (open circle) and observed (triangle) maximum annual mean sunspot number, \((R_n)_{\text{max}}\) for cycle 12 to 23 as well as predicted value for cycle 24 are shown in Figure 6.4. I found the amplitude of the predicted annual mean sunspot number of cycle 24 to be 92.8 ± 19.6 (1-sigma accuracy). The maximum amplitude of cycle 24 is estimated to be about 92.8 ± 35.5 (the 90% prediction interval). This suggests that there is only a 5% chance that \((R_{24})_{\text{max}}\) is expected to exceed 128.3 or be below 57.3, unless cycle 24 proves to be a statistical outlier. My predicted amplitude of 92.8 ± 19.6 for cycle 24 is in agreement with the predictions made by a few other investigators (Kane, 1999; Wang et al., 2002; de Meyer, 2003; Sello, 2003; Duhau, 2003, Schatten, 2005; Svalgaard, Cliver, & Kamide, 2005; Xu et al, 2008).

Figure 6.4: Variation of predicted (open circle) and observed (triangle) maximum annual mean sunspot number \((R_n)_{\text{max}}\) as a function of sunspot cycle number \((n)\). The predicted \((R_n)_{\text{max}}\) are connected with dashed line.
6.3.3 Prediction of the Ascending Period of Cycle 24:
The ascent duration of a solar cycle is observed to be inversely correlated with the maximum amplitude of a solar cycle. Waldmeier (1935) showed that there is an inverse correlation between the length of the ascending duration of a solar cycle, and the peak sunspot number of that cycle. This phenomenon is often called the "Waldmeier effect". To predict the ascending period for solar cycle 24, I studied the relationship between the ascending period in months, \((P_n)_{\text{asc}}\) (often simply defined as the elapsed time in months from sunspot minimum amplitude to sunspot maximum amplitude) and \((R_n)_{\text{max}}\).

![Graph](image)

Figure 6.5: The ascending period (in months), \((P_n)_{\text{asc}}\) is plotted as a function of \((R_n)_{\text{max}}\) for cycles 11 to 23 (Cycle 19 is omitted). The solid line is the best fit with \(r = -0.86\).

\[
(P_n)_{\text{asc}} = 66.14 - 0.18(R_n)_{\text{max}} \\
(P_{24})_{\text{asc}} = 50 +/- 4 \text{ months}
\]

In this investigation, I have considered the ascending period in months for cycles 11 to 23, however, excluding cycle 19 to improve the correlation. The statistical relation between maximum annual mean sunspot number, \((R_n)_{\text{max}}\) and the corresponding \((P_n)_{\text{asc}}\) for the cycle 11 to 23 is shown in Figure 6.5. This figure unambiguously shows that the \((P_n)_{\text{asc}}\) of a solar cycle decreases with the increase in maximum annual mean sunspot number, which is the manifestation of "Waldmeier effect". Figure 6.5 is the best linear fit with a
negative correlation coefficient of $\sim 0.86$ and a standard error of estimate of 4 months. Figure 6.5 gives a linear relationship which can be expressed in the form of following relation:

$$(P_{n})_{asc} = 66.14 - 0.18 (R_{n})^{max} \quad (6.2)$$

From equation (6.2) the $(P_{n})_{asc}$ for cycle 11 to 23 is calculated. Considering $(R_{24})^{max} = 92.8 \pm 19.6$ (Section 6.3.2) in relation (6.2) suggests $(P_{n})_{asc} = 50 \pm 4$ months with 1-sigma accuracy or $50 \pm 8$ months being the 90% prediction interval. Provided that minimum amplitude indeed occurred in August 2008, the maximum amplitude would be expected about October 2012 $\pm 8$ months, inferring only a 5% chance that maximum amplitude for cycle 24 will occur after June 2013 or before February 2012.

6.3.4 Prediction of the annual mean geomagnetic activity for the solar maximum year:

Next, in order to predict the level of geomagnetic activity for the sunspot maximum year in cycle 24, I obtained $aa^*$, which is the annual mean of $aa$ during the year when sunspot is maximum for each cycle 11-$23$. And then the relation between the observed $(R_{n})^{max}$, and $aa^*$ is studied. Figure 6.6 represents the relationship between $(R_{n})^{max}$ and $aa^*$ for a given cycle. A linear fit is obtained between the two with a correlation coefficient of $\sim 0.85$ which can be expressed as

$$aa^* = 0.09(R_{n})^{max} + 13.4 \quad (6.3)$$

Using the above relation, I predicted $aa^*$ for each cycle 11-$23$, which is in good agreement (standard deviation between the observed and calculated (predicted value is 2.03) with the observations. Considering the predicted amplitude of cycle 24 to be $92.8 \pm 19.6$ (cf. section 6.3.2) enabled me to estimate the $aa^*$ during the sunspot maximum year for cycle 24 to be $21.5 \pm 3.8$. This predicted value of $aa^*$ is lower relative to the observed 31 (in 1989) and 25.4 (in 2000) for cycle 22 and 23 respectively. This depicts the decreasing trend of geomagnetic activity during the sunspot maximum year of the upcoming cycle 24 as compared to previous two cycles.
6.4 Discussion and Conclusion:
In the current investigation, I have used the long term data of sunspot numbers and aa indices from year 1868 to 2008 to predict the amplitude of sunspot cycle 24 employing the ‘precursor technique’ of Jain (1997). However, the prediction by Jain (1997) for cycle 23 was not accompanied by error estimates. Further, the linear relation derived by him (Equation (1) in his paper) to predict the sunspot amplitude for cycle 23 requires modification. For example, if relation (6.1) is used to predict the amplitude of cycle 23, then \((R_{23})^{\text{max}} = 138.6\) with error estimates \(\pm 19.6\) (Figure 6.4), which is closer to the observed 120. This suggests that the precursor technique employed by Jain (1997) is successful if the current linear relation with error estimates is considered.

In the present investigation, I have predicted the maximum amplitude of cycle 24 considering the error estimates. I predict the maximum amplitude for cycle 24 to be \(92.8 \pm 19.6\) (1-sigma accuracy), which is expected to peak in
October 2012 ± 4 months (1-sigma accuracy). My results suggest that cycle 24 will be about 40\%, 41\% and 22\% weaker than cycle 21, 22 and 23, respectively. Further, my prediction is found to be in agreement with the predictions made by some investigators (Kane, 1999; Wang et al., 2002; de Meyer, 2003; Sello, 2003; Duhau, 2003; Schatten, 2005; Svalgaard, Cliver, and Kamide, 2005; Xu et al., 2008) but in disagreement with many others who have predicted either an acute minimum or an extraordinarily high amplitude of cycle 24. Recently, Wilson and Hathaway (2009) have published a technical report (NASA/TP-2009-215687, February 2009), which appears on the website http://solarscience.msfc.nasa.gov/papers.shtml. They have identified 11 statistically important single-variate fits, and 22 statistically important bi-variate fits for estimating the size of the sunspot maximum amplitude, applying the fits to cycle 24. The weighted mean prediction of 11 statistically important single-variate fits is 116 ± 34 and that of 22 statistically important bi-variate fits is 112 ± 32. Both predictions appear to be on a higher side than our prediction. Many investigators have used different “precursor techniques”, and their predictions for the maximum amplitude for solar cycle 24 appear to be varying between 75 (Svalgaard, Cliver, and Kamide, 2005) and 190 (Li, Gao, and Su, 2005). Further, using the solar polar magnetic field strength, Svalgaard, Cliver, and Kamide (2005) have predicted that the approaching cycle (~ 2011 maximum) will have a peak smoothed monthly sunspot number of 75 ± 8, making it potentially the smallest cycle in the last 100 years. According to Dikpati et al. (2006), the upcoming cycle 24 will be about 30-50\% stronger ($R_z = 155-180$) using modified flux transport solar dynamo model and the data of sunspot area. Choudhuri et al. (2007) modelled the last few solar cycles by ‘feeding’ observational data of the Sun’s polar magnetic field into their solar dynamo model. They predict that cycle 24 will be about 35\% weaker than cycle 23. On the other hand, Nandy, Andrés & Petrus, 2011) reported results from kinematic dynamo simulations which demonstrate that a fast meridional flow in the first half of a cycle, followed by a slower flow in the second half, reproduces both characteristics of the minimum of sunspot cycle 23. Their model predicts that, in general, very deep minimum of a solar cycle is associated with weak polar magnetic field, which perhaps, explains the prolonged sunspot minimum in cycle 24.
However, I propose the following two hypotheses to explain the expected low amplitude of cycle 24. First, a given sunspot cycle is an extended sunspot cycle composed of two sunspot cycles, one main and the second sympathetic. The latter begins two-three years after the main cycle, and it produces a rather stronger geomagnetic activity. While comparing the geomagnetic activity during the descending phase of cycles 21, 22 and 23, I found that the aa index \((\text{aa}_n)_{\text{dsc}}\) was 27.06, 24.56 and 18.4 respectively indicating that the magnitude of the sympathetic cycle has been decreasing since cycle 21. The weak geomagnetic activity during the descending phase of solar cycle 23 is an indicator of low amplitude of solar cycle 24. My estimate of \(\text{aa}^*\) during the sunspot maximum year for cycle 24 is \(21.5 \pm 3.8\). This predicted value of \(\text{aa}^*\) is an indication of weak geomagnetic activity relative to the observed 31(in 1989) and 25.4(in 2000) for cycle 22 and 23 respectively. I propose that the sympathetic cycle plays an important role in governing the amplitude, length and activity of the next main cycle.

My second hypothesis is based on long term periodicities of sunspots over and above 11-year primary sunspot cycle. The \(~200\)-year periodicity (Nordemann, Rigozo, and de Faria, 2005; Ma and Vaquero, 2009 and many previous studies) is well known and we propose that the low amplitude in cycle 24 may be an epoch of this periodicity, which previously occurred in 1816, approximately 196 years ago. However, there might be other possible mechanisms to switch over the Sun to lower amplitude of the solar activity such as the Wolf – Gleissberg cycle, which has a periodicity of about \(80 – 100\) years.

Nevertheless, currently, the sunspots are not appearing with faster speed, and, therefore, many US based scientists are predicting the sunspots hibernation. However, on the contrary to this statement, I would like to further emphasize in view of my validation of “Waldmeier effect” (cf. Figure 6.5) that slow growth is another indication of cycle 24 to be a low-magnitude cycle.
CHAPTER 7
DISCUSSION AND FUTURE PROSPECTS

In this chapter I discuss the results obtained and present the international scenario with future prospects.

Discussion:

In order to improve our current understanding on the solar activity and the Sun-Earth connection in context to the solar eruptions and their impact on Earth’s environment, I carried out the following investigations in this thesis:

- X-ray emission characteristics of solar flares (chapter 4).
- Solar flare plasma characteristics in association to CMEs and SEPs (chapter 5).
- Prediction of solar activity using precursor technique (chapter 6).

X-ray emission characteristics of Solar Flares:

In chapter 4 of this thesis I have investigated X-ray emission characteristics of solar flares in detail employing observations from “Solar X-ray Spectrometer (SOXS)” and “Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI)” missions. In the analysis of solar flares observed by SOXS and RHESSI simultaneously, the spectra in the dynamic range of about 4.1-24 keV (SOXS) and 13-100 keV RHESSI) were analyzed using multi-thermal plus single power-law (SOXS) and isothermal plus single power-law (RHESSI). I found that $\varepsilon_c$ ranges between 20-29 keV as determined by fitting thick2 function to the HXR spectra for 6-January-2004 event. The shift of $\varepsilon_c$ to higher energies is due to increasing contribution of thermal Bremsstrahlung at higher temperature of the flare plasma. Employing RHESSI observations, I estimated the thermal and non-thermal energies for different flare intervals for two M class flares (6-January-2004 and 5-April-2004). The investigation showed that the thermal and non-thermal energies are of the same order of magnitude ($\sim 10^{28} - 10^{29}$ erg). The integrated thermal
and non-thermal energies for these two flares range between ($\sim 10^{29}$ - $10^{30}$ erg). The $E_{nth} / E_{th}$ (%) ratio is observed to be 0.52 and 0.9. This result may be inferred as conversion of non-thermal energy to hot flare plasma. However, the thermal energy obtained from SOXS is about 1-2 orders of magnitude higher than the non-thermal energies obtained from RHESSI. This may be due to the different energy ranges chosen for the two different instruments and high value of the computed emission measure from SOXS observations. My result is in agreement to the following results. Aschwanden (2007), ignoring possible low-energy cutoff, has found the thermal-non-thermal crossover energy $18 \pm 3.4$ keV using the power law approximation of X-ray emission. However, Sui $et$ $al.$ (2005) found $24 \pm 2$ keV as the low-energy cutoff ($E_c$) to ensure that always thermal emission dominates over non-thermal emission in low energy. They estimated the non-thermal energy content in the electrons of the order of $1.6 \times 10^{30}$ ergs. Saint and Benz (2005) considering $20$ keV as the turnover energy, which is perhaps the same as the break energy ($E_b$), estimated the non-thermal energy to be $\approx 2 \times 10^{30}$ ergs, almost the same value as Sui $et$ $al.$ (2005) found for an M1.2 class flare. However, the low-energy cutoff seems physically not realistic as such a configuration leads to plasma instability. Such instabilities have a growth rate typically of the order of local plasma frequency, $i.e.$, orders of magnitude shorter than the propagation time of the beam within the acceleration region. Therefore, the turnover of break energy appears to be more physically realistic and needs to be measured as precisely as possible.

The correlation among the spectral parameters of the flare confirms the general flare scenario of contribution of non-thermal flux in heating up the plasma. This study strongly supports the thermal and non-thermal relationship which confirms the standard flare model. For both the flares, the temperature reached 40-45 MK (super-hot component) during the rise phase.

I also investigated the temporal evolution of conductive and radiative power for 27-July-2005 and 5-April-2004 events. The study suggests that thermal conduction is a dominant during the rise phase which is more evident from 5-April-2004 event. This clearly indicates that in flare loops at higher temperatures, thermal conduction is a dominant mechanism during the rise
phase. Both events also indicate that in post-flare loops (or decay phase), radiative cooling is the dominant mechanism in thermal energy range.

**Flare-CME-SEP association:**

The flare-CME phenomena often occur in conjunction but the exact nature of the flare-CME triggers and the relationship between the cause and consequence is still open and quite puzzling (Jain et al. 2010).

In chapter 5, I analyzed the HXR emission of the flare and CME dynamics for 30 flare-CME pairs. I conclude that the initial linear speed of the coronal mass ejection right at the solar surface is strongly related (power-law relationship with r=0.77 for all 30 flares and r=0.84 for 19 flares for which the peak photon flux in 12-25 keV is <11000 c (4s)^{-1}) to the non-thermal spectral characteristics, however, before-the-peak interval of the associated flare event. My results indicate that the flare and the associated CME are the two components of one energy release system and perhaps occur together at the time of impulsive acceleration. Recent investigations regarding flare-CME relationship have been carried out by Aarnio et al. (2011) and Temmer et al. (2010). Comparing the X-ray flare fluxes with CME masses of 826 CME/flare paired events, Aarnio et al. (2011) found that CME mass increases with flare flux, following an approximately log-linear, broken relationship. Recent investigations by Temmer et al. (2010) indicated a correlation between the CME acceleration peak and the flare hard X-ray peak flux and suggested that a large sample of events may be studied to arrive to a better conclusion. They further suggested a possible relationship between the spectral slope of the HXR spectra and the CME acceleration. However, I studied in greater detail the 30 solar flare events associated with CMEs in contrast to 3 events investigated by Temmer et al., (2010) and achieved a new significant result that showing a good correlation between non-thermal hard X-ray spectral index and CME linear velocity. This new result rather strongly suggests that flare and CME are the two phenomena that occur together as a consequence of reconnection in the corona.

As mentioned in section 5.1.2, the flare-SEP relationship has been studied by many researchers. Saldanha et al. (2008) studied the progressive
spectral hardening in January 2005 solar flare events and confirmed that the progressive spectral hardening in these flares are related to solar energetic particle (SEP) events. Grigis and Benz (2008) studied the spectral hardening in large solar flares and proposed that the hardening during the decay phase is caused by continuing particle acceleration with longer trapping in the accelerator before escape. Grayson et al. (2009) studied 37 magnetically well-connected flares (W30°-W90°) observed by RHESSI and found that 12 out of 18 flares with SHH behavior produced SEP events and none of 19 flares without SHH behavior produced SEPs. However, all these studies are based on temporal evolution of spectra, while no study has been carried out in detail to estimating the evolution of the spectral index (hardness parameter) over time and its relation with spectral index of the associated SEP event. Therefore I studied hard X-ray spectra of the flares in greater detail in context to their relationship with the SEPs. I employed the RHESSI observations for this investigation and the results are presented in Chapter 5.

In chapter 5, I also investigated the flare-SEP relationship for 12 major solar flares. I obtained a correlation of $r=0.67$ between hardest flare spectral index and hardest proton spectral index for these events (neglecting 20-January-2005 event). The study shows a good relationship between the hardness of the flare spectra seen on the Sun and the hardest proton spectra observed at the earth. My current result is new in contrast to previously known for electrons, as well as soft-hard-hard nature of X-ray spectra because it suggests that proton (ions) acceleration is in simultaneous to electrons at the same site, and the source for SEP is in the solar corona.

Krucker et al. (2007) compared the hard X-ray (HXR) photon spectra observed by the RHESSI with the spectra of the electrons in the associated solar impulsive particle events and found that the HXR photon power-law spectral index and the in situ observed electron spectral index measured above 50 keV show a good linear fit ($r=0.83$) for prompt events and a weak correlation ($r=0.43$) for delayed events.

My results are consistent with earlier studies (section 5.1.2) suggesting that there exists a good relationship between solar flares and SEP events. It can be concluded from the investigations carried out in this chapter.
that the flare, CME and SEP events may be considered as a combined event as regards to Sun-Earth connection.

**Prediction of Solar Activity:**

Owing to the space weather impact of solar eruptive phenomena, I have predicted the maximum amplitude of cycle 24 using the long term data of sunspot numbers and aa indices from year 1868 to 2008 and employing the ‘precursor technique’ of Jain (1997). I predict the maximum amplitude for cycle 24 to be 92.8±19.6 (1-sigma accuracy), which is expected to peak in October 2012 ± 4 months (1-sigma accuracy). My results suggest that cycle 24 will be about 40%, 41% and 22% weaker than cycle 21, 22 and 23, respectively. In their overall performance during the course of last few solar cycles, precursor methods have clearly been superior to extrapolation methods (Petrovay, 2010). He stated that the current cycle 24 will probably mark the end of the Modern Maximum, with the Sun switching to a state of less strong activity and therefore it will be an important testbed for solar cycle prediction methods for our understanding of the solar dynamo. Many investigators have used different “precursor techniques”, and their predictions for the maximum amplitude for solar cycle 24 appear to be varying between 75 (Svalgaard, Cliver, and Kamide, 2005) and 190 (Li, Gao, and Su, 2005).

I propose the following two hypotheses to explain the expected low amplitude of cycle 24. First, a given sunspot cycle is an extended sunspot cycle composed of two sunspot cycles, one main and the second sympathetic. The latter begins two-three years after the main cycle, and it produces a rather stronger geomagnetic activity. While comparing the geomagnetic activity during the descending phase of cycles 21, 22 and 23, I observed that the aa index \((aa_n^*)_{dsc}\) was 27.06, 24.56, and 18.4 respectively indicating that the magnitude of the sympathetic cycle has been decreasing since cycle 21. The weak geomagnetic activity during the descending phase of solar cycle 23 is an indicator of low amplitude of solar cycle 24. My estimate of \(aa^*\) during the sunspot maximum year for cycle 24 is 21.5 ± 3.8. This predicted value of \(aa^*\) is an indication of weak geomagnetic activity relative to the observed 31 (in 1989) and 25.4 (in 2000) for cycle 22 and 23.
respectively. I propose that the sympathetic cycle plays an important role in governing the amplitude, length and activity of the next main cycle.

My second hypothesis is based on long term periodicities of sunspots over and above a 11-year primary sunspot cycle. The ~200-year periodicity (Nordemann, Rigozo, and de Faria, 2005; Ma and Vaquero, 2009 and many previous studies) is well known and I propose that the low amplitude in cycle 24 may be an epoch of this periodicity, which previously occurred in 1816, approximately 196 years ago. I would like to mention that the prediction along with the hypothesis has already been published (Bhatt et al. 2009b). The recently updated (4-April-2011) “Solar Cycle 24 Prediction” project Homepage (NASA MSFC team) states that the current cycle 24 maybe the smallest sunspot cycle in nearly 200 years which supports my hypothesis.

Future Prospects:
The solar eruptions such as flares/CMEs/SEPs are the most powerful explosions in the solar system, and they endanger astronauts and spacecraft. These eruptions have a significant impact on the Earth’s environment. Owing to this Sun-Earth connection, they are of the utmost importance and of scientific interest in order to understand this difficult process of connection.

X-ray emission from solar flares can be studied with the instruments such as SOXS and RHESSI. However, the nature of the flare emission below 10 keV is still not clear. Thus it is extremely important to characterize the soft X-ray emission below 10 keV. This is possible with the development of high spectral resolution instruments. The development of high resolution instruments can give precise information on the line emission and hence the elemental abundance can be studied in greater detail.

In recent years, the flare-CME relationship is fairly better understood in view that the both phenomena have comparable energy budgets and impulsive acceleration phases. However, there are many unaddressed questions viz. origin and initiation of the CMEs in general and is it precursor or a follow-up event with the associated flare event? After about 100 years of study of solar flares/SEPs we are not able to understand the physical process that links these two phenomena and the location and time of the acceleration
of the particles. Great efforts have been made to probe into these events in recent years and as of now, many questions remain unanswered such as: how is the energy built-up in the corona and by which mechanism does it store the energy for a long time? Further, how all these eruptive phenomena are suddenly released?

I believe that in near future, the advanced observations of these most explosive solar events will be possible with the development of new and highly sophisticated instrumentation. Also, they will allow accurate measurements of weaker events in the light of increased sensitivity of the instruments.