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Seasonal dependence of the Earth's radiation belt: new insight

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Abstract. Long-term variations of the relativistic (∼MeV) electrons in the Earth's radiation belt are explored to study seasonal features of the electrons. An L-shell dependence of the seasonal variations of the electrons is revealed for the first time. A clear ∼6-month periodicity is identified for 1.5-6.0 MeV electron fluxes in the L-shells between ∼3.0 and ∼5.0, representing two peaks per year. The two-peak variation is strong during solar cycle descending to minimum phases, with weaker/no variations during solar maximum. The peaks are largely asymmetric in amplitude. These are not essentially equinoctial: sometimes the peaks are shifted to solstices and sometimes one annual peak is only observed. No such seasonal features are prominent for L < 3.0 and L > 5.0. The results imply varying solar/interplanetary drivers of the radiation belt electrons at different L-shells. This has a potential impact on the modeling of space environment. Plausible solar drivers are discussed.

1 Introduction

Earth-orbiting satellites around the radiation belt Van Allen et al. (1958) are known to be vulnerable to the relativistic (∼MeV) electrons that can cause internal charging leading to satellite component damage or even satellite loss in extreme cases (e.g., Wrenn, 1995; Iucci et al., 2005; Horne et al., 2013; Baker et al., 2018, and references therein). The MeV electrons are known to be accelerated from the ∼10-100 keV (energetic) electrons which are injected into the nightside magnetosphere by magnetic storms and substorms (e.g., DeForest and McIlwain, 1971; Horne and Thorne, 1998). The temperature anisotropy of the electrons leads to plasma instability generating whistler-mode chorus waves (Kennel and Petschek, 1966; Tsurutani and Smith, 1974). Resonant interaction of the ∼100 keV electrons with chorus waves is considered to be the main mechanism for MeV electron acceleration (Inan et al., 1978; Horne and Thorne, 2003; Summers et al., 2007; Tsurutani et al., 2013).

From the above scenario, it implies that the injections of seed (∼10-100 keV) electrons through magnetic storms/substorms along with electron loss processes control the variability of magnetospheric MeV electrons. In other words, the solar wind-magnetosphere coupling processes that cause magnetic storms and substorms, play important role in MeV electron variability. The electrons are reported to vary in the time scales of a few minutes to several years. While short-scale variations are attributed to geomagnetic activity and associated solar wind and interplanetary variations, long-term variations are associated with solar activity cycle (e.g., Baker et al., 1986; Tsurutani et al., 2006; Miyoshi and Kataoka, 2011; Hajra et al., 2014, 2015; Li et al.,

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2015; Hajra and Tsurutani, 2018). Several studies of MeV electrons (e.g., Baker et al., 1999; Li et al., 2001; Kanekal et al., 2010) reported strong semi-annual modulations of the electrons, and discussed in the context of the Earth's position in the heliosphere (Cortie, 1912), relative angle of solar wind incidence with respect to Earth's rotation axis (Boller and Stolov, 1970), and geometrical controls of interplanetary magnetic fields (Russell and McPherron, 1973). The aim of this present work is a critical exploration of the seasonal features of the MeV electrons, and to identify their solar activity and L-shell dependencies, if any.

2 Data analysis and Results

Figure 1 (top panel) shows the variation of the monthly mean differential fluxes of the electrons in the energy range between 1.5 and 6.0 MeV in different L-shells from 0.5 to 8.5 from 1992 July to 2004 June. The L is the radial distance in Earth radii at the equator for dipole approximation of the Earth's magnetic field. The electron observations are made by the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX; Baker et al. (1993)) that monitored the radiation belts from a low-altitude ($\sim$520-670 km), highly (82°) inclined orbit. Figure 1 shows a classical picture of the Van Allen radiation belts: an inner belt with lower fluxes of 1.5-6.0 MeV electrons at L $<$ 2.0, separated by a slot region devoid of any electrons up to L $\sim$2.5, followed by an outer belt extending up to L $\sim$7.0. Peak fluxes occur around L $\sim$3.0-4.5, shown by superposed black lines.

The MeV electron flux variations are compared with monthly mean solar wind speed Vsw (Figure 1 (second panel), red curve, legend on the right), percentage occurrences of days with daily peak Vsw $\geq$500 km s^{-1} (D500, Figure 1 (second panel), histograms, legend on the left), monthly mean solar wind electric field VBs (Figure 1 (third panel)) where V represents Vsw, and Bs is the southward component of interplanetary magnetic field (IMF) or is zero in absence of southward component. The VBs has been shown to be the main driver of geomagnetic activity (e.g., Burton et al., 1975; Tsurutani et al., 1992; Finch et al., 2008). The bottom panel (Figure 1) shows the monthly mean F10.7 solar flux that depicts the $\sim$11-year solar activity cycle. The solar wind and IMFs are obtained from the OMNI website (https://omniweb.gsfc.nasa.gov/). OMNI database is formed by time-shifting the data collected from the NASA's ACE, Wind and IMP 8 spacecraft to the Earth's bow shock nose. The IMFs in geocentric solar magnetospheric (GSM) coordinates are used in this work.

An overall association of solar wind high-speed streams (HSSs) and MeV electron fluxes can be observed from the figure. Both Vsw and D500 exhibit two prominent peaks, one around 1994-1995 and another around 2003-2004, both of which are in the descending phase of F10.7 solar activity cycles. These intervals are characterized by flux enhancements and broadening of 1.5-6.0 MeV electron belt in space (L-shells). On the other hand, a clear narrowing of the belt in higher L-shells and flux decreases can be noted in the ascending and maximum phases of the solar cycle. A close-look in the fluxes reveals two-peak flux variations in each year around the heart of the outer belt. A similar short-scale variation is recorded in VBs.

Figure 2 shows Lomb-Scargle periodograms (Lomb, 1976; Scargle, 1982) of F10.7 solar flux, Vsw, D500, VBs and MeV electron fluxes at different L-shells, shown in Figure 1. As expected, F10.7 exhibits a single periodicity of $\sim$11 years depicting solar activity cycle. Interestingly, Vsw has a broad peak around $\sim$9.5-year period with additional significant peaks at $\sim$4.6 and

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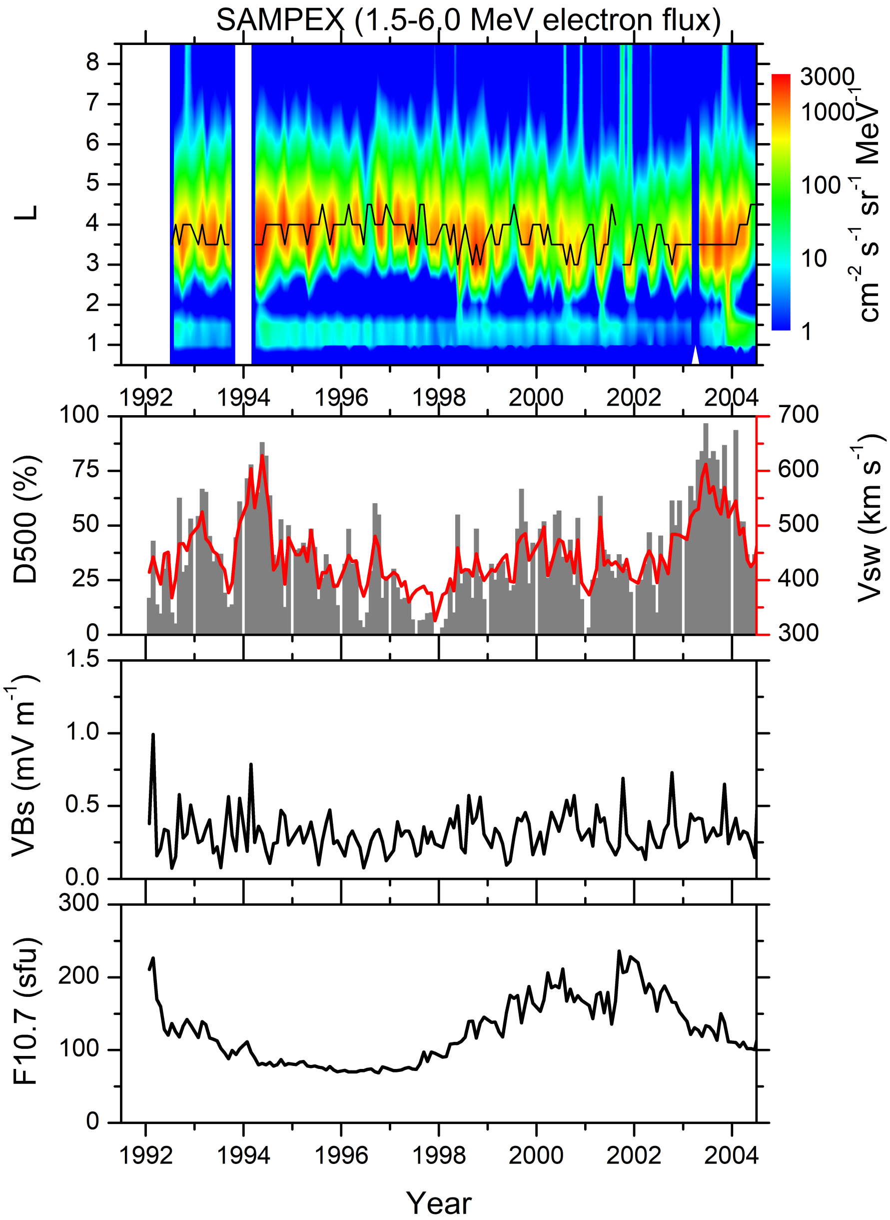

Figure 1. From top to bottom, the panels show the L-shell variation of monthly mean differential 1.5-6.0 MeV electron fluxes (legend on the right showing flux values corresponding to different colours) and L-shells corresponding to peak fluxes (black curve), monthly percentage of days with peak solar wind speed Vsw $\geq$500 km s^{-1} (legend on the left) and monthly mean Vsw (red curve, legend on the right), monthly mean VBs, and F10.7 solar flux for the years 1992 through 2004.

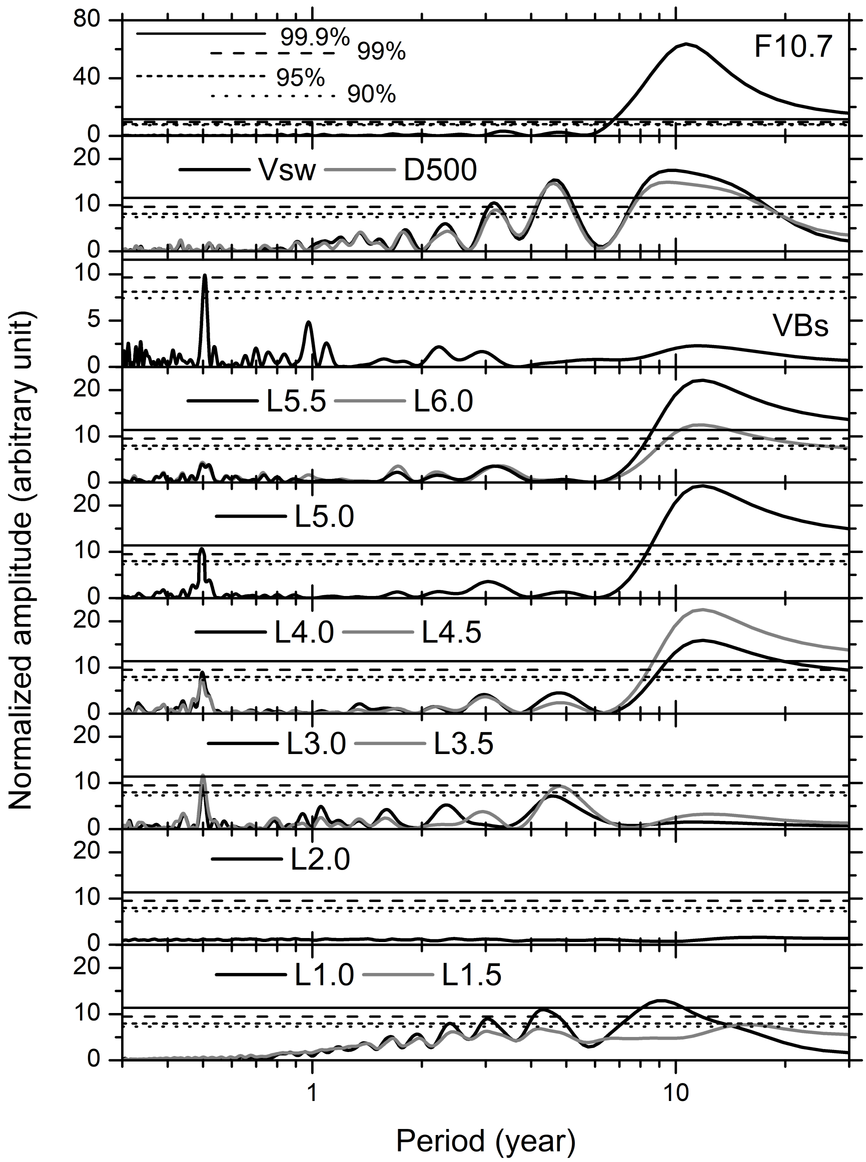

Figure 2. From top to bottom, the panels show Lomb-Scargle periodgrams of F10.7, Vsw and D500, VBs, and 1.5-6.0 MeV electron fluxes at different L-shells. The x-axis shows periods in year and the y-axis shows the normalized amplitudes in arbitrary unit. Confidence levels of the periodograms are shown in each panel by horizontal lines.

$\sim$3.2 year periods. The D500 exhibited a similar (to Vsw) periodogram. The coupling function VBs is independent of solar activity and has a significant period of $\sim$0.5 years or $\sim$6 months only.

The electron fluxes at different L-shells exhibit large variations in periodicity. At L = 1.0 (inner belt) electrons exhibit significant periods of $\sim$8.9 and $\sim$4.3 years. These seem to be associated with variations in Vsw (D500). For obvious reason, slot region electrons have no significant variation. At the inner edge of the outer belt (L = 3.0 and 3.5), electrons exhibit a significant periodicity of $\sim$6 months, but no periodicity related to $\sim$11-year solar activity cycle. In the shells between L = 4.0 to L = 5.0, an $\sim$11-year periodicity is accompanied by a prominent periodicity of $\sim$6 months. The $\sim$6-month periodicity in the electrons (for L = 3.0 to 5.0) can be attributed to the variations in the coupling function VBs. Electrons at L = 5.5 and 6.0 exhibit only significant periodicity of $\sim$11 years. At $L > 6.0$, there is no clear periodic variations in MeV electron fluxes.

Figure 2 clearly indicates varying solar activity and seasonal variations of the 1.5-6.0 MeV electrons in different L-shells, which can be attributed to different solar and magnetospheric drivers. This will be discussed later in the paper.

Figure 3 shows the year-month contour plots of monthly mean MeV electron fluxes at L = 3.5 and monthly mean VBs. Top panel shows the ratio of electron flux seasonal peaks in two halves of each year. This may give an estimate of seasonal asymmetry. It should be noted that months of the peaks varied from year to year, which will be discussed below. Monthly mean F10.7 solar flux is repeated from Figure 1 for a reference of solar activity cycle. Similar analysis is performed for electrons at other L-shells, however they are not shown here to avoid repetition and save space.

While Figure 2 showed an $\sim$6-month (semi-annual) component both in electron flux variation at L = 3.5 and in VBs variation, a clear year-to-year variation can be seen in Figure 3. In the year 1993, electron fluxes peak around May and August, while two peaks are observed during the months of May and November in 1994. In both cases, first peaks are $\sim$1.5-1.7 times of the second peaks. Two electron flux peaks in April and October are much more distinct and comparable in amplitude in 1995. The semi-annual variation is much more weaker in 1996 with a peak in April $\sim$0.5 times of that in October. In 1997, a large peak in fluxes can be noted in May with no prominent equinoctial peaks. In 1998, which is in the ascending phase of the F10.7 solar cycle, two distinct and comparable peaks are recorded during May and September. In 1999, while electron fluxes are much lower, two peaks can be seen in February and October months. No clear seasonal feature can be conferred from 2000, while a solstice peak (May) is observed in 2001, and an October peak in 2002. A two-peak seasonal feature, with two distinct and comparable peaks in May in September, is again observed in 2003, in descending phase of the solar cycle. A consistent variation is observed in VBs with respect to month and year.

It can be concluded from the above analysis that while the 1.5-6.0 MeV electron fluxes at L = 3.5 exhibit mostly two peaks in a year, they are largely asymmetric in amplitudes and they are not essentially equinoctial. Same conclusions were drawn for electrons in other L-shells.

3 Discussion and Conclusions

Present work reveals that the MeV electrons in the Earth's radiation belt exhibit varying solar and seasonal features depending on the L-shells. No $\sim$11-year solar cycle trend was observed in the inner edge (L = 3.0-3.5) of the outer belt, where a dominating

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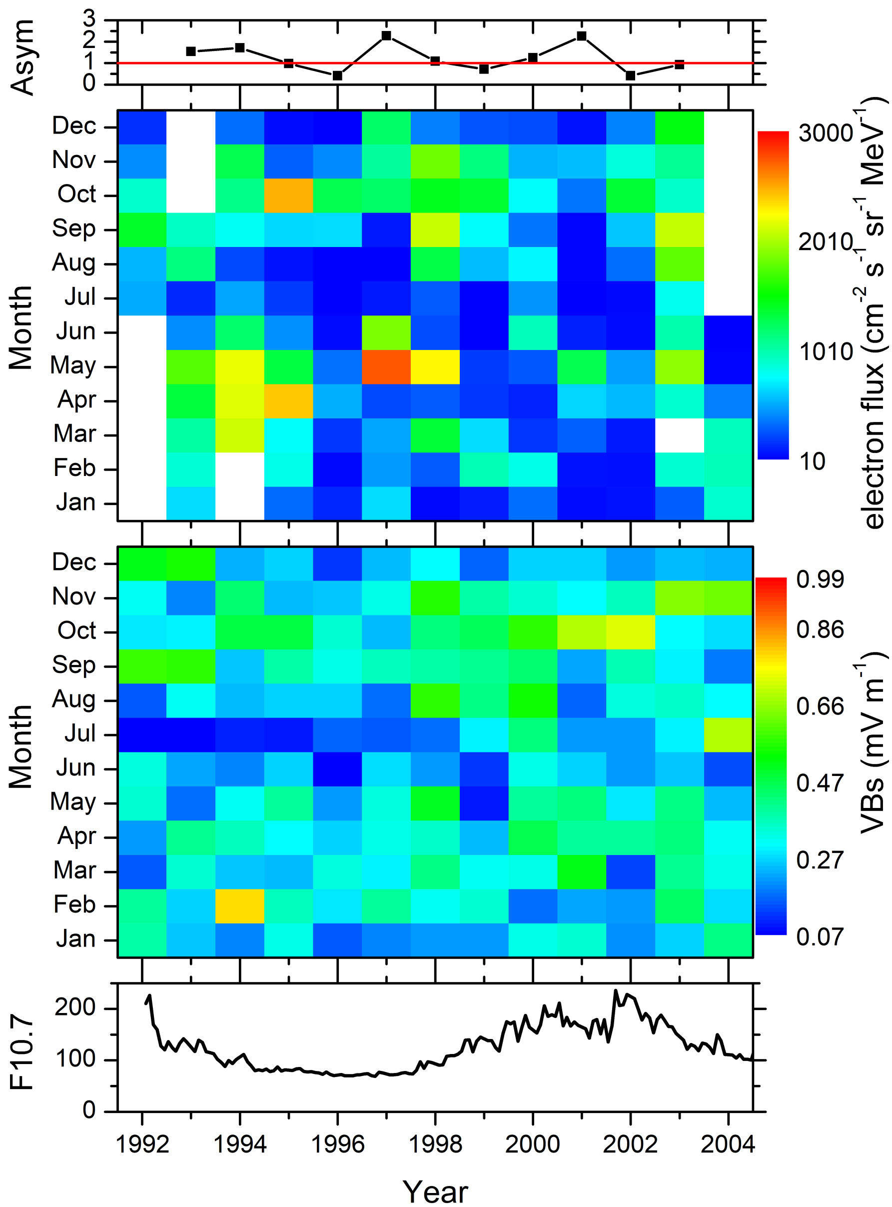

Figure 3. Second and third panels show monthly mean 1.5-6.0 MeV electron fluxes at L = 3.5 and VBs during each month of the years 1992 through 2004. Top panel shows seasonal asymmetry (defined in text) and bottom panel shows the F10.7 solar flux during the same interval.

∼6-month period was prominent. From L = 4.0 to 5.0, ∼11-year solar cycle variation is accompanied by a secondary ∼6-month period. These L-shell dependent seasonal and solar cycle features are reported for the first time. It may be mentioned

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that previous studies (e.g., Baker et al., 1999; Li et al., 2001; Kanekal et al., 2010) reported strong and "coherent" seasonal modulations of MeV electrons "throughout the entire outer zone" radiation belt.

Interestingly, no ∼6-month component was observed in solar wind speed Vsw, while it was most prominent in solar wind-magnetospheric coupling function VBs which represents interplanetary electric field under the condition of southward IMF. This is well consistent with previous results (e.g., Li et al., 2011) suggesting that HSS alone can not predict relativistic electron flux enhancements, but fast solar wind and southward IMFs are the main requirements for electron enhancements. This makes VBs, involving both solar wind speed and southward IMF, an important factor controlling MeV electron variation.

However, present study involving year-wise analysis of seasonal features in MeV electrons and solar/magnetospheric driver reveals that care should be taken in interpreting ∼6-month periodicity obtained through periodogram analysis (present work) or superposed analysis of electrons in the radiation belt (previous reports). Yearly two peaks in the electron fluxes (between $L = 3.0$ and 5.0) are only sometimes observed around descending phase of the solar cycle. The peaks are largely asymmetric in nature. In addition, the peaks are not essentially equinoctial: sometimes the peaks are shifted to solstices and sometimes one annual peak is only observed. Clearly the ∼6-month periodicity in periodogram (and semi-annual variation) of the magnetospheric MeV electrons is an artifact arising from long-term data superposition in years. Thus applying axial, equinoctial or some geometrical hypothesis to discuss Earth's radiation belt might be premature at this stage.

In summary, L-shell dependent solar and seasonal features and so-called semi-annual variations of magnetospheric relativistic electrons require further attention. Dual satellite Van Allen Probe observations involving multi-energy observations of the radiation belts can be useful for further confirmation of the results obtained in the present work.

Data availability. Relativistic (MeV) electrons analyzed in this work is observed by the SAMPEX. These can be obtained from the Coordinated Data Analysis Web (CDAWeb) (https://cdaweb.gsfc.nasa.gov/cgi-bin/eval1.cgi). The solar wind and IMFs are obtained from the OMNI website (https://omniweb.gsfc.nasa.gov/)

Author contributions. RH developed the paper with original idea, data analysis and conclusion of the paper.

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