2003-51

GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 15, 1795, doi:10.1029/2003GL017502, 2003

Modulation of Jovian electrons at 1 AU during solar cycles 22–23

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Received 8 April 2003; accepted 3 July 2003; published 5 August 2003.

[1] We report here, on the observation of Jovian electrons during the time period 1992 to 2002, using instruments on board SAMPEX and IMP8 at 1 AU. The Jovian electron flux diminished greatly from early 1996 to the end of 1997 and recovered subsequently and was observed till the end of 2001. The decrease in the Jovian flux was seen in three distinct instruments lasting for about two Jovian synodic periods. Such a dramatic and persistent decrease has not been observed before. The observed decrease could be due to changes at the source or variations in interplanetary conditions affecting transport of these particles. The latter may be solar cycle dependent as in the heliospheric modulation of cosmic rays. Long-term measurements from IMP8 suggest that solar cycle related propagation effects may not be responsible for the observed decrease. We suggest that either a change in the Jovian source strength or a softening of the Jovian electron energy spectrum produced the observed attenuation. *INDEX TERMS:* 2116 Interplanetary Physics: Energetic particles, planetary; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2162 Interplanetary Physics: Solar cycle variations (7536). **Citation:** Kanekal, S. G., D. N. Baker, J. B. Blake, M. D. Looper, R. A. Mewaldt, and C. A. Lopate, Modulation of Jovian electrons at 1 AU during solar cycles 22–23, *Geophys. Res. Lett.*, *30*(15), 1795, doi:10.1029/2003GL017502, 2003.

1. Introduction

[2] Pioneer 10 observations made over 30 years ago revealed that Jupiter is a source of high energy electrons in the heliosphere [*Simpson*, 1974]. High energy electron data from Pioneer 10 showed a monotonic increase in the electron flux from 1 AU as the spacecraft approached Jupiter (at 5.2 AU) and a gradual decrease as the spacecraft receded from Jupiter [*Pyle and Simpson*, 1977]. Earlier energetic electron data collected by IMP8 had shown unexplained increases in the measured flux levels during quiet times (times of no obvious solar activity) [e.g., *McDonald et al.*, 1972 and references therein]. The discovery of Jovian electrons by Pioneer 10 led to the recognition of quiet time electron increases as being of Jovian origin [*Teegarden et al.*, 1974; *Mewaldt et al.*, 1976]. Subsequent observations, ranging from 0.5–11 AU, up to 16° heliospheric latitude and over full 360° longitude, established that Jupiter is a strong and persistent source of energetic electrons in the heliosphere [*Chenette*, 1980].

[3] Observations both at Jupiter and in interplanetary space near the Earth showed that the energy spectrum of Jovian electrons was quite hard with a power law dependence of the type $J \propto E^{-\gamma}$ with $\gamma \leq 2$ [*Baker and Van Allen*, 1976]. Jovian electron observations at 1 AU showed a strong modulation once every 13 months [*Mewaldt et al.*, 1976], which is the Jovian synodic period. The nominal Parker-spiral interplanetary field lines connect Earth and Jupiter directly once every 13 months so that electrons travel easily along field lines to reach the Earth. At other times they have to diffuse across field lines to reach the Earth. Jovian electrons at 1 AU also exhibit a 27-day modulation due to corotating interaction regions inhibiting interplanetary propagation [*Conlon*, 1978]. Although it has been suggested that Jovian electrons could be a significant component of the Earth's radiation belts [*Baker et al.*, 1979], it is by now well established that internal acceleration processes are responsible for the relativistic electrons in the terrestrial magnetosphere [*Baker et al.*, 1989, 1998].

[4] In this study we report on the observation of Jovian electrons over the Earth's polar regions and at 1 AU in interplanetary space. These observations cover almost a decade starting from mid 1992 to late 2001. This time period is approximately 8 Jovian synodic intervals extending from the declining part of solar cycle 22 to the near-maximum of solar cycle 23.

[5] Our observations show an unexpected decrease of the Jovian electron flux from about mid 1995 to late 1997, i.e., for about 2 synodic periods. The attenuation of Jovian electrons was observed by three different sensors onboard the SAMPEX and IMP8 spacecraft. We suggest that this attenuation is probably caused by changing source characteristics rather than variation of interplanetary propagation conditions.

2. Spacecraft, Instrumentation and Data Analysis

[6] Energetic electron sensors from SAMPEX (Solar Anomalous and Magnetospheric Particle Explorer) and IMP8 (Interplanetary Monitoring Platform) provide data used in this study. SAMPEX is in a low earth polar orbit at an altitude of ≈600 km and an inclination of 82° [*Baker et al.*, 1993]. IMP8 was launched in 1973 into a nearly cirular orbit of ≈35 R_E and has been measuring energetic particles for nearly three decades providing a long term view of the near-Earth environment.

[7] The PET (Proton Electron Telescope) instrument onboard SAMPEX measures electrons in the energy range of 0.4 to 30 MeV [*Cook et al.*, 1993]. We use the ELO channel from PET which measures electrons in the range of 2- to

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0094-8276/03/2003GL017502$05.00

6- MeV to detect the Jovian signal. The Cosmic Ray Nuclear Composition (CRNC) instrument [*Chenette*, 1980] and the Goddard Cosmic Ray Experiment (GCRE) [*McDonald*, 1972] onboard IMP8 measure high energy electrons at 1 AU in the near-Earth region. The 2- to 12- MeV channel, ID3, from CRNC and the 3.5- to 18.5- MeV channel from the GCRE are used to observe Jovian electrons.

[8] SAMPEX data cover a time period of nearly a decade from mid 1992 to late 2001 which is about 8 Jovian synodic intervals. This time period starts during the declining phase of solar cycle 22 and extends up to the near-maximum of cycle 23. It thus covers both the times when high speed solar wind streams are well established and the times when CME (coronal mass ejection) activity is high. IMP8 data cover the period from late 1973 to 2001, i.e., nearly 3 solar cycles, and thus enable comparison of solar cycles 22–23 with previous solar cycles.

[9] Daily averaged electron fluxes are the starting point of the analysis. The Jovian electron signal is rather weak and is swamped by solar electrons occurring during periods of solar activity [*Mewaldt et al.*, 1976]. Solar electron spectra are generally softer than Jovian electron spectra. Active solar periods can therefore be identified as periods of high fluxes of low energy electrons and excluded from the data sample. The details of our data analysis for both SAMPEX and IMP8 measurements are described below.

[10] The SAMPEX daily averaged particle fluxes are collected over the Earth's polar region defined here as the region with invariant latitude greater than 77°. The precise location in invariant latitude does not affect the analysis as long as care is taken to exclude terrestrial radiation belt electrons. We use the singles rate from the front detector (P1A) of PET to identify solar activity. The P1A channel has a threshold of 0.4 MeV for electrons and a large geometry factor. The P1A count rate increases significantly during days of high solar activity. We require the P1A flux to be less than 1.4 $[\mathrm{cm}^2\text{-sec-sr}]^{-1}$ to exclude days with high fluxes of low energy electrons. During the earlier part of the SAMPEX mission, the PET instrument was partially turned off during certain orbits. These time periods are easily identified as the daily averaged rates during such times are artificially low. Therefore we also require that P1A flux be greater than 0.5 $[\mathrm{cm}^2\text{-sec-sr}]^{-1}$ to exclude these days. The exact values of P1A threshold flux were obtained by examining a histogram of this flux for the entire time period. Our conclusions are however rather insensitive to the exact cutoff values. For example, varying the lower cutoff value by about 10% has a very negligible affect on the background. Increasing the upper cutoff value from 1.4 to 2.0 $[\mathrm{cm}^2\text{-sec-sr}]^{-1}$ only increases the background slightly.

[11] High resolution data (15 minutes time resolution) from the CRNC instrument were also converted into daily averages taking into account the appropriate live time for the averaging period. A low energy electron channel, ID2, of the CRNC instrument which measures electrons in the range 0.7- to 2.0- MeV is used to identify solar electrons. As in prior analyses [*Chenette*, 1980], we use the ratio of ID2 electron rate to the ID3 rate to select quiet times. Days during which this ratio has a value of less than 2.5 and greater than 0.5 are termed as quiet times. The results of our analysis are again insensitive to variations (at 10% level) in these cutoff values. These selection criteria remove most days with high solar electron fluxes with the exception of about 8 days which were removed by inspection.

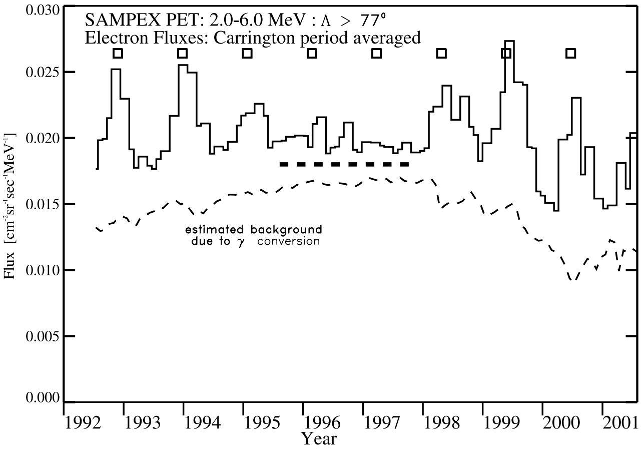

Figure 1. Carrington rotation-averaged 2- to 6- MeV electrons measured by SAMPEX PET at invariant latitudes >77°. Estimated background due to γ-rays is also shown.

[12] The Goddard Cosmic Ray Experiment onboard IMP8 measures electrons only in the energy range of 3.5- to 18.5- MeV and thus cannot unambiguously detect solar electrons which are usually less energetic. Therefore days with high solar electron fluxes were excluded on the basis of the SAMPEX PET detector. That is, days during which solar electron fluxes were high as determined by the PET-P1A channel were excluded from the GCRE data as well.

[13] The SAMPEX and IMP8 electron fluxes are then averaged over 27 day periods corresponding to Carrington rotation times after applying the selection criteria.

3. Observations

[14] Figure 1 shows the 27-day Carrington rotation period averages of SAMPEX 2- to 6- MeV electrons measured over the Earth's polar regions. Data have been median smoothed over 3 bins, i.e, each ordinate value is replaced by the median value of the 3 neighboring ordinate values [*Press et al.*, 1986]. Open squares indicate 13 month intervals starting from the first peak in the electron fluxes seen at about late 1992. The figure clearly shows peaks in electron flux with a periodicity of 13 months. This is characteristic of Jovian electrons. The figure also shows that during 1996 and 1997 the Jovian signal more or less "disappears" and reappears again from 1998 onwards. The time of decreased electron fluxes is indicated by the dashed line in the figure. This time period of greatly attenuated Jovian electrons corresponds to two Jovian synodic peaks. It can also be seen that the Jovian electron flux decreased slightly during 1995 compared to prior years. The Jovian electron signal stands above a background which is mainly due to γ-rays which produce Compton electrons within the PET instrument. Figure 1 also shows this background which is usual in instruments which use a stack of solid state detectors and has been well studied before [*Mewaldt et al.*, 1977]. We determine the shape of the background shape using cosmic ray neutron rates [*Mewaldt et al.*, 1977] and assume a reasonable value for the amplitude.

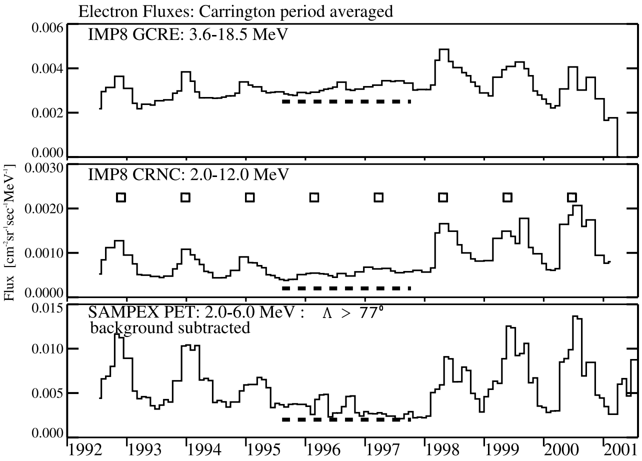

Figure 2. Carrington rotation-averaged electron fluxes at 1 AU measured by GCRE (top), CRNC (middle) and, PET(bottom) instruments. Neutral background has been subtracted from the 2- to 6- MeV fluxes measured by PET. GCRE measures electrons of 3.5- to 18.5- MeV and CRNC 2- to 12- MeV range.

[15] Figure 2 shows high energy electron fluxes measured by instruments onboard IMP8 in the upper two panels. The top panel shows the 3.6- to 18.5- MeV electrons measured by the GCRE instrument and the middle panel shows the 2- to 12- MeV electrons measured by the CRNC instrument. The bottom panel shows the background subtracted PET 2- to 6- MeV electron fluxes. Open squares in the middle panel indicate, as before, the times of expected peaks in the Jovian electron signal. The IMP8 measurements clearly show the Jovian electron peaks and the paucity of Jovian electrons during the expected peak times in 1996 and 1997. IMP8 measurements also show that the Jovian peak during 1995 was less than the preceding years. These observations are completely consistent with SAMPEX measurements over the Earth's polar regions. SAMPEX and IMP8 measurements are well correlated, and show similar temporal variability. All three instruments observe the Jovian electron flux peaks and their absence synchronously. This means that the observed decrease of the Jovian electrons is a real effect and not an instrumental artifact. Note that the electron energy ranges of the two IMP8 detectors differ and the Jovian electron signal is superposed on a background due to galactic cosmic rays. The amplitude and shape of this background of course depends on detector characteristics and is not identical for the two detectors. The absolute values of fluxes measured by PET and CRNC differ by about a factor of 10. The difference in energy intervals between the two instruments accounts for a factor of 2 and the rest is probably due to uncertainty in background levels.

[16] To complete the presentation of our observations, we show the daily averaged fluxes of the 2- to 12- MeV electrons observed by the CRNC detector in Figure 3. Daily average fluxes are shown for three periods of about 7 years each in three separate panels. The periods 1974 to 1981, 1984 to 1991, and 1994 to 2001, cover similar times of three solar cycles 20–21, 21–22 and 22–23. The 13-month Jovian electron signal is clearly seen during all cycles with the exception of the attenuated period of 1996 to 1998 during solar cycle 22–23. This period is marked by two vertical dashed lines dividing the panels into 3 time periods. Although the Jovian signal appears slightly decreased during 1976–77 and 1986–87 it is suppressed to a much greater degree during 1996–97. This suggests that the attenuation of the Jovian signal during 1996–97 is not entirely a solar cycle effect. That is, cycles 20–21 and 21–22 do not show such a decrease to the same extent as cycle 22–23. The figure also shows that the fluxes exhibit a 27-day periodicity in addition to the 13-month periodicity. This is due to modulation of electron intensity by corotating interaction regions (CIR) [*Conlon*, 1978; *Chenette*, 1980]. CIRs, which are due to quasi-stationary high speed solar wind streams interacting with low speed plasma, are well established during the declining part of the solar cycle (the first part of each panel) and less so during the ascending part of the cycle (the last part of each panel) when sporadic CMEs are more common.

4. Discussion and Conclusion

[17] In this report we have presented observations of Jovian electron modulation during solar cycles 22–23. Jovian electrons have been identified by their characteristic signature of 13-month periodicity [*Chenette*, 1980]. Our observations show a puzzling decrease in Jovian fluxes near the solar cycle minimum. This decrease has been observed by three different instruments onboard two separate spacecraft.

[18] The causes of the observed attenuation of the Jovian fluxes may be due to interplanetary transport which may be solar-cycle dependent or due to changes in the source characteristics itself. Using long term measurements from IMP8 we have established that the observed decrease is confined to solar cycle 22–23 alone. Earlier measurements of Jovian electrons have also not observed such a dramatic decrease during other solar-cycles [*Moses*, 1987]. *Chenette* [1980] has reported a decrease in the Jovian electron intensity during 1976–77 period and noted that it was

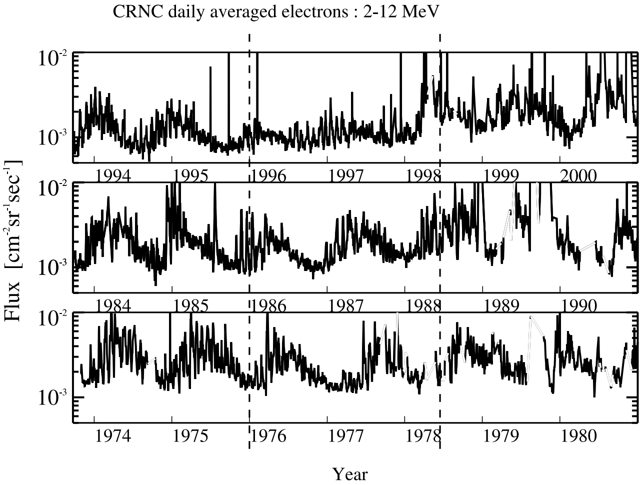

Figure 3. Daily averaged electron fluxes in the 2- to 12- MeV energy range at 1 AU measured by the CRNC instrument. The top, middle and bottom panels show electron fluxes for the years 1993 to 2001, 1984 to 1991 and 1974 to 1981 respectively. Dashed vertical lines delineate a two year period around solar cycle minima.

coincident with the disappearance of two prior established CIRs. Therefore he suggested that this decrease was due to transport effect rather than a change in the Jovian source.

[19] More recently however, *Morioka and Tsuchiya* [1996] found evidence for Jovian "source modulation" by examining Pioneer 11 data collected during the year 1974. They found that the Jovian electron intensity was inversely correlated with solar wind dynamic pressure. That is, the Jovian source intensity increased during times of decreased solar wind dynamic pressure. They concluded that both transport and source effects were needed to explain the observed variation of Jovian electron intensity [*Morioka and Tsuchiya*, 1996].

[20] The fact that the observed decrease during solar cycle 22–23 is much more dramatic than during previous two cycles suggests that it is unlikely to be a "transport" effect. Moreover, it has recently been shown that the interplanetary modulation conditions during the solar cycle 22–23 minimum in 1996–1997 were almost identical to those during 1976–1977 throughout the heliosphere [*McDonald et al.*, 2001]. Yet the decrease in Jovian electrons was very much stronger in solar cycles 22–23 than during solar cycles 20–21. Thus a decrease in the Jovian source intensity itself, is a more likely cause of the observed decrease of Jovian electrons at 1 AU.

[21] It is well known that Jupiter is a source of synchrotron radiation whose strength seems to be related to solar activity [*Bolton et al.*, 1989; *Galopeau and Gerard*, 2001]. Bolton et al. suggested that solar activity may possibly modulate Jovian radiation belt electrons and found that the best correlation between solar wind parameters and the Jovian synchrotron radiation required a two year lag time most of which is presumably the response time of the Jovian magnetosphere. The observations reported by Galopeau and Gerard cover the time period from 1994 to mid 1999 but have an unfortunate a data gap during the years 1996 and 1997. Moreover they conclude that there is no unique time lag for best correlations and show that both a lag of 245 days and 615 days appear plausible. This fact together withthe paucity of observations makes it difficult to use variations in Jovian synchrotron emissions as a proxy for variations in the intensity of Jovian relativistic electrons.

[22] Another possible explanation for the observed decrease would be a change in the Jovian electron spectrum. For example, a significant spectral softening could lead to decreased fluxes in the energy range of our observations. This is also a change in the source characteristics. It is unclear what would cause such a change. However, a thorough investigation of Jovian electron spectra at 1 AU is complicated by the presence of soft solar electrons. We suggest that changes in the Jovian source characteristics are more likely to have caused the observed decrease in Jovian electrons rather than modulation effects.

[23] **Acknowledgments.** This work was supported by NASA data analysis funding for the SAMPEX program. The authors thank F. B. McDonald and R. McGuire for providing the GCRE data. The CLIMAX Neutron monitor data server is supported by National Science Foundation, Grant ATM-9912341.

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