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Relativistic Electrons in the Outer-Zone: An 11 Year Cycle; Their Relation to the Solar Wind

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We examine Los Alamos energetic electron data from 1979 through the present to show long term trends in the trapped relativistic electron populations at geosynchronous-earth-orbit (GEO). Data is examined from several CPA and SOPA instruments to cover the interval from 1979 through June, 1994. It is shown that the higher energy electrons fluxes (E > 300 keV) displayed a cycle of ≈11 years. In agreement with other investigators, we also show that the relativistic electron cycle is out of phase with the sunspot cycle. We compare the occurrences of relativistic electrons and solar wind high speed streams and determine that on the time scale of 15 years the two do not correlate well. The long-term data set we provide here shows a systematic change of the electron energy spectrum during the course of the solar cycle. This information should be useful to magnetospheric scientists, model designers and space flight planners.

INTRODUCTION

The solar cycle is manifested in many ways. Along with the familiar 11-year sunspot cycle, there are other observables that may have similar cycles, but that may be out of phase with the solar sunspot number or indeed may have different cycles. For example, the solar magnetic field is known to vary in concert with the sunspot cycle but actually has a 22-year cycle made up of two 11-year cycles of alternating polarities.

Another well known solar cycle has to do with the solar wind velocity. This particular aspect of the solar wind was established during Cycle 20 nearly 20 years ago,[*Bame et al.*, 1976], [*Gosling et al.*, 1976]. The increased solar wind speed was attributed to weakening of the solar magnetic field and low coronal densities, both attributes of solar cycle minimum. The solar wind cycle manifests itself in a number of observables on the surface of the Earth and on-orbit.

Geomagnetic activity, known to correlate with solar wind speed, appears to have a cycle with a minimum that occurs about 1 to 1.5 years after sunspot minimum, [*Feynman, J.*, 1985]. However, geomagnetic substorms, which are manifestations of geomagnetic activity, appear to have two different components that peak at different times during the sunspot cycle. Storms that are associated with sudden commencements (solar wind shocks) are found to peak near solar maximum. Recurrent storm roughly associated with the solar rotation period seem to occur during the declining phase of the sunspot cycle.

In a report published in 1979, Paulikas and Blake showed a long term plot of energetic electron fluxes along with the Zurich sunspot number for the period of time from 1967 through 1977. This plot, although difficult to access because of the differences in spacecraft and in the detector electron energy levels, tends to show the effect we address in this paper, namely lower fluxes at solar maximum than at solar minimum.

Baker et. al. [1979] have shown relativistic electron data from the period after solar cycle minimum in 1976, 1977, and 1978 using data from the Los Alamos geosynchronous satellites. These data show a 27 day periodicity and declining average flux levels. Flaring activity during cycle 21 did not begin until 1978 when the relativistic electrons fluxes had decreased and the periodicity had broken down. In addition, [*Baker et al.*, 1986], have shown relativistic electrons behavior over the span of about 1/2 solar cycle also using data from the Los Alamos satellites. These data included both a solar sunspot maximum and minimum and indicated that the electron fluxes peak near sunspot minimum and were low at sunspot maximum.

INSTRUMENTATION

The data we will show are from two sets of instruments on geosynchronous orbit satellites: the Charged Particle Analyzer (CPA) instruments on four satellites, 1977-007, 1981-025, 1984-037, 1984-129; and the Synchronous Orbit Particle Analyzer (SOPA) instruments on 1989-046 and 1991-080.

The set of detectors comprising the CPA instrument has previously been described in Higbie et al., [1978], and the details will not be repeated here. Instead, we provide the following brief description. Data are only presented from two of the four detectors comprising the CPA. The LoE subsystem is a set of five, similar, solid state sensors arranged at angles of $\pm 60°$, $\pm 45°$ and 0° to the normal to the satellite spin axis which is directed toward the Earth. Each sensor is mounted in a collimating telescope with a half angle of about 4°, which provides a geometrical factor of 3.1×10^{-3} cm^2-sr [*T. E. Cayton, private communication, 1995*]. As the satellite spins, with a period of ~10 seconds, each telescope sweeps out a band of the unit sphere. During the course of one rotation, 200 samples of the unit sphere are recorded by the five LoE detectors for each energy channel. There are six nested energy channels with approximate lower thresholds of 30, 45, 65, 95, 140, and 200 keV. Each channel has an upper threshold of 300 keV. Although the CPA instruments have not been completely calibrated, their response to electrons and protons have been extensively modeled .

The HiE detector is a belly-band mounted single telescope with energy thresholds of 0.2, 0.3, 0.4, 0.6, 0.9, and 1.4 MeV and an upper cutoff of 2.0 MeV. The HiE is collimated with a half angle of about 7.7° which provides a geometrical factor of about 1.4×10^{-2} cm^2-sr [*T. E. Cayton, private communication, 1995*]

The SOPA instruments are also described elsewhere [*Belian et al.*, 1992]. The instrument consists of three solid state detector telescopes (T1, T2 and T3) that accept particles from three different directions relative to the spacecraft spin axis 30°, 90°, and 120°. Each telescope has a collimating aperture with a half angle of about 5.5°, which provides a geometrical factor of 1.1×10^{-3} cm^2-sr. During the course of one rotation, 10 sec, 64 samples of electrons, protons and helium are recorded over the unit sphere. There are 9 differential energy channels with approximate lower thresholds of 50, 75, 110, 160, 240, 340, 500, 740, and 1100 keV. The upper threshold for the 9^{th} energy channel is about 1.5 MeV. This is also the threshold for the 10^{th} channel which is integral. The data for each telescope is accumulated sequentially for 160 ms in the following pattern, T1, T2, T3, T2, T1, and so on. The SOPA detectors have been extensively calibrated using protons and other ions at the Los Alamos National Laboratory's Ion Beam Facility and electron, protons and helium at the calibration center at Goddard Space Flight Center run by Steve Brown.

OBSERVATIONS

Solar-Like Cycle for Relativistic Electrons

In this section we show relativistic electron data for a period of time greater than one solar-sunspot-cycle. Our data covers the time period from day 221 of 1979 through the middle of 1994, a period of about 15 years. In addition our data are from two sets of detectors, each set of which is comprised of nearly identical detectors, and each set has nearly identical energy channels. All have been flown at the same geomagnetic position.

Therefore, the data are for a longer span of time and there is much better correspondence among different satellites than was available for previous studies. This statement is true even for the studies by *Baker et al.*, 1979 and 1986 even though they used data from the CPA detectors on LANL GEO satellites, because those investigations used data from satellites at different locations with respect to the Earth's magnetic field.

Figure 1 shows the long term history of the fluxes of >65 keV electrons - upper trace, >300 keV - middle trace, and >1.4 MeV fluxes - lower trace, averaged over 27 days (Bartell's averages). It is a composite of CPA and SOPA observations from six LANL GEO satellites at very nearly the same geostationary-orbit, and therefore, the same geomagnetic latitude - about -9.4°. The instrumental energy ranges and the designations of the satellites that provided the data are given in Tables 1 and 2 respectively. The upper trace does not appear to show a solar-like cycle, that is, the fluxes remain flat within about a factor of two or three throughout the 15 year period and what variations there are do not appear to be solar-sunspot-like in character. The middle and lower traces indeed do show cyclical solar-sunspot-like patterns. The >300 keV or middle trace is the lowest energy range that undeniably shows such a pattern.

Included on the figure are vertical lines indicating the time of the last two sunspot maxima and the minimum in between. It is clear from Figure 1 that the relativistic electrons (E>300 keV, middle and lower traces) were at minimum flux during the two solar maxima shown and at maximum flux sometime before the solar minimum shown and that the flux is increasing again in the current solar cycle as solar minimum is approached. The time between the solar maxima in late 1979 and mid 1989 is 10.5 years, very close to the average sunspot-cycle period for the last few cycles. This data is incontrovertible evidence that trapped relativistic electrons at GEO exhibited a solar-like cycle during cycle 22.

Trace	CPA Energy Range	SOPA Energy Range
Upper	65 - 300 keV	> 66 keV
Middle	300 - 2.0 MeV	> 284 keV
Lower	1.4 - 2.0 MeV	> 1.4 MeV

Table 1. Energy ranges for the various traces on Figure 1. All of the data taken before about day 4600 were recorded by CPA detectors - all data taken after then were recorded by SOPA detectors. The integral SOPA energy ranges were determined by T. E. Cayton, private communication, 1994.

Years of Coverage	Satellite Designation	Detector
1979.6 - 1984.5	1977-007	CPA
1984.5 - 1985.5	1981-025	CPA
1985.5 - 1988.0	1984-037	CPA
1988.0 - 1991.0	1984-129	CPA
1991.0 - 1992.0	1989-046	SOPA
1992.0 - 1994.5	1991-080	SOPA

Table 2. A list of the six satellites that recorded the data used for Figure 1. Also listed are the detector names.

The data shown in Figure 2 indicated that relativistic electron behavior is similar at another geostationary location. It is a composite of electron data taken from several Los Alamos GEO satellites at a different geostationary location for the same energy ranges as Figure 1. In this case all of the satellites were located within about 1° of the magnetic equator. Since none of the Los Alamos satellites occupied this particular station before 1985, the complete solar-electron-cycle is not shown. However, for the period shown, the behavior is clearly similar to the behavior seen in Figure 1 for the same energies. The information presented here indicate that relativistic electrons at, at least two different geomagnetic locations behave in similar fashion.

Data from other satellites at other geomagnetic locations is fragmentary and will not be presented here, but to the extent that we have it these data are consistent with the pattern seen in Figure 1 at all locations. These other satellites vary from a maximum latitude of 11.5° to a minimum of 1.2°.

The data shown in Figure 3 indicate that instrumental effects are not responsible for the observed electron behavior. Figure 3 is three channels of electron count rates recorded by a different instrument on one of the satellites, 1989-046, from which Figure 1 was produced. Instead of the SOPA instrument on that satellite, electron data from the Energetic Spectrometer for Particles or ESP detector are displayed. These instruments, which have been flown since 1989, have yet to be described in the literature and will not be described in this paper. It is significant to note that for the period of time shown the behavior is similar to that of the middle and lower traces in Figure 1. The apparent floor in the bottom trace is likely due to cosmic rays.

Solar Wind - Relativistic Electron Correlation

In this section we address the extent to which the occurrences of relativistic electrons in the magnetosphere are governed by the speed of the solar wind. Several authors have shown high correlation between the fluxes of energetic electrons and the speed of the solar wind [*Paulikas and Blake*, 1979, *Baker et al.*, 1986]. *Paulikas and Blake* in their Figures 5 through 7 show striking examples of >3.9 MeV electron fluxes rising with similar rise times but delayed a few days from the solar wind speed during times of highly structured high speed solar-wind streams. They also show good correlation between 27-day averaged 140 - 600 keV and >3.9 MeV electron data and solar wind speed for several months in 1974 - reproduced here as the upper panel of Figure 4. And finally they find good correlation in several energy ranges for semiannual averages over the period of time June 1975 through August 1977, our lower panel, Figure 4. *Baker et al.*, 1986, show similar results for selected short periods of high solar wind speed. In discussing their Figure 4, herein shown as Figure 5, they pointed out the dearth of high energy electrons during solar maximum in late 1979 and indicated the rise in count rate as solar minimum approached, i.e., during 1982, 1983, and 1984.

The evidence of Paulikas and Blake, and Baker, et. al., is highly convincing, but does not tell the entire story. Indeed there can be no doubt that high speed stream occurrences very effectively determine the occurrences of relativistic electrons at GEO, but only for selected, generally short, periods of time. Over the long term, the correlation is weak - indicating that other factors probably enter in.

Figure 6 again shows the >1.4 MeV electron data for the 15 year period on the bottom trace. Plotted on the upper trace is Bartel's averaged solar wind speed values. It is evident that during the period 1979 through about the middle of 1987 the overall envelopes of the two traces rise and fall in concert. Indeed in many cases, individual fluctuations, for example those from mid 1986 through the end of 1987, follow each other closely. But, after 1987 the correlation clearly breaks down. Whereas the solar wind speed remains high, and appears almost to have a floor, the E> 1.4 MeV electron flux first declines by nearly a factor of 10 and then increases by more than 10. Indeed after 1987 there appears to be no convincing correlation between the two traces. This is the same period of time that *Richardson et al.*, [1994], using data from IMP-8 and Voyager 2, have found a 1.3 year modulation of the solar wind speed, suggesting a fundamental change in the sun. Our measurements suggest that there is no simple, linear relationship between the solar wind speed and the flux of high-energy electrons.

We have made a more direct determination of the correlation, or lack thereof, by plotting Bartel's average values of the fluxes of >1.4 MeV electrons against their counterpart Bartel's average values of the solar wind speed in Figure 7. It is clear from Figure 7 that even though there is a threshold effect in operation that produced the dearth of points in the upper left part of the plot, there is no clear correlation. That is, given any solar wind speed, any flux may be found up to a maximum, which increases with the speed. We also compared flux values with solar wind dynamic-pressure and solar wind density data (not shown). These showed similar lack of correlation. These facts tell us that high solar wind speed is a necessary but not sufficient condition for production of intense fluxes of relativistic electrons.

DISCUSSIONS AND CONCLUSIONS

We have shown incontrovertible evidence that trapped relativistic electrons during Cycle 22 exhibited a cycle that was solar-like in nature, and with a period of about 10.5 years - the current average for the sunspot cycle. In agreement with other investigators, we have shown that the electron cycle is out of phase with the sunspot cycle, that is, instead of peaking at solar maximum, the electrons show a minimum at that time. Furthermore, the peak in electron flux occurred near but before solar minimum.

It is also clear from the evidence we have presented that the picture of solar wind control of the occurrences of relativistic electrons is by no means fully understood. For some periods of time the solar wind does seem to control the flux of trapped relativistic electrons, but the control is not one to one. On the other hand, for the very long period from the end of 1987 to mid 1994 the correlation is very poor (see Figure 6). From Figure 7, we can say that high values of solar wind are necessary for the occurrence of intense fluxes of relativistic electrons, but not sufficient. Judging from Figure 7, it seems to be about as likely to have low fluxes as high fluxes for any given solar wind speed. Even for the highest solar wind values shown, it is possible to have very low electron fluxes.

Possibly the most important consequence of these results is that space flight planners need to take into account these data in the design of satellites, and the timing of launches. Armed with this information, planners should have a better handle on the amount and type of shielding required for spacecraft components and instruments than before. Also, when circumstances allow, they should be able to plan launch times to take advantage of the periods of time in the solar cycle when relativistic electron fluxes are likely to be lowest.

These data will also improve our knowledge of the total dose a satellite will experience over its expected life, thereby increasing the ability to predict gradual degradation of various components.

Magnetospheric model designers should take these data into consideration when designing their models.

Finally, it is important to develop understanding of the breakdown that occurred after 1987 in the coupling between solar wind speed and the occurrence of high fluxes of relativistic electrons in the magnetosphere. Whether this was an event unique to this solar cycle or not, it must impact our understanding of the interaction between the solar wind and the earth's magnetosphere.

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A. J. Lazarus, Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139.

Fig. 1. Electron data for the 15 year period beginning in mid 1979. The upper trace is E>65 keV electrons, the middle trace is E>300 keV electrons and the lower trace is 1.4 to 2 MeV electrons. Vertical lines are provided to delineate the years and heavy vertical markers for the various solar sunspot epochs.

Fig. 2. Similar to Figure 1, except that the data are from a different set of Los Alamos geostationary satellites at a different geomagnetic location. This particular station was not in use until the 1985 time frame.

Fig. 3. Similar to Figure 1, except that the data are count rates from a different instrument on satellite 1989-046. This plot uses data from the Energetic Spectrometer for Protons (ESP) detector. From top to bottom the traces are counts /second for 1.1 - 1.8 MeV, 3 - 4.8 MeV, and 4.8 - 7 MeV electrons.

Fig. 4. Plots taken from *Paulikas and Blake*, [1976]. The upper panel (their Figure 17) is 27 day average fluxes of E>1.55 MeV electrons from ATS-6 plotted against solar wind velocity for June 1974 - August 1977. The lower panel (their Figure 20) is semiannual average fluxes of the same.

Fig. 5. Plots taken from *Baker et al.* [1986], their Figure 4. The upper panel is the count rate profile of 5 - 7 MeV electrons from satellite 1979-053 for the 1979 - 1981 period. The lower panel is the count rate profile of 5 - 7 MeV electrons from satellite 1892-019 for 1982 - 1984. At the top right of the lower panel are tick marks spaced 27 days.

Fig. 6. A plot similar to Figure 1, except that the two upper traces of Figure 1 have been eliminated and 27 day Bartel's averages of the solar wind speed from IMP-8 have been added. The label for the flux level is on the left while the label for the solar wind speed is on the right.

Fig. 7. 27 day averages of fluxes of E>1.4 MeV electrons from the geostationary satellite at station 1 plotted against 27 day averages of solar wind speed from IMP-8.

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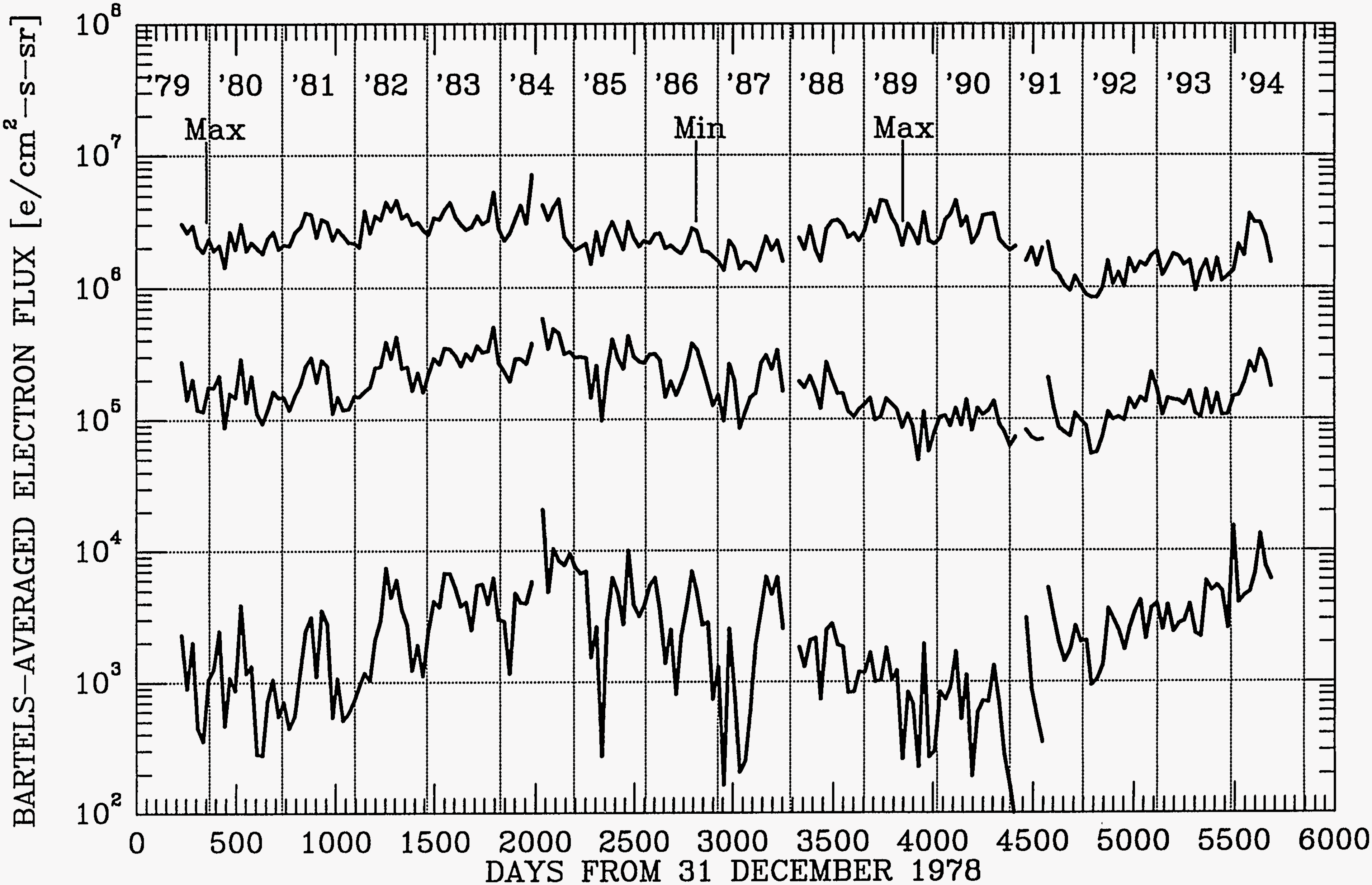
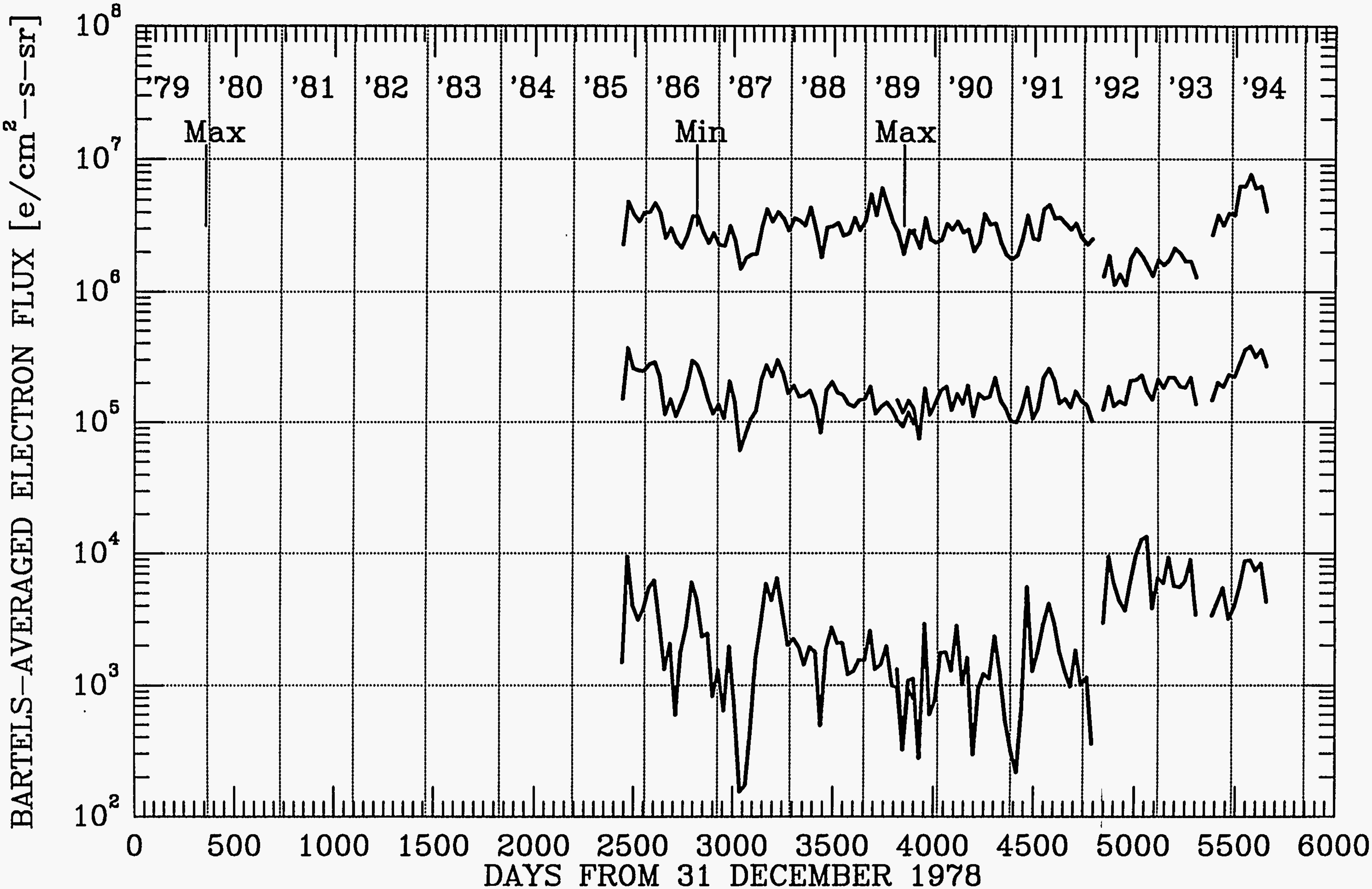
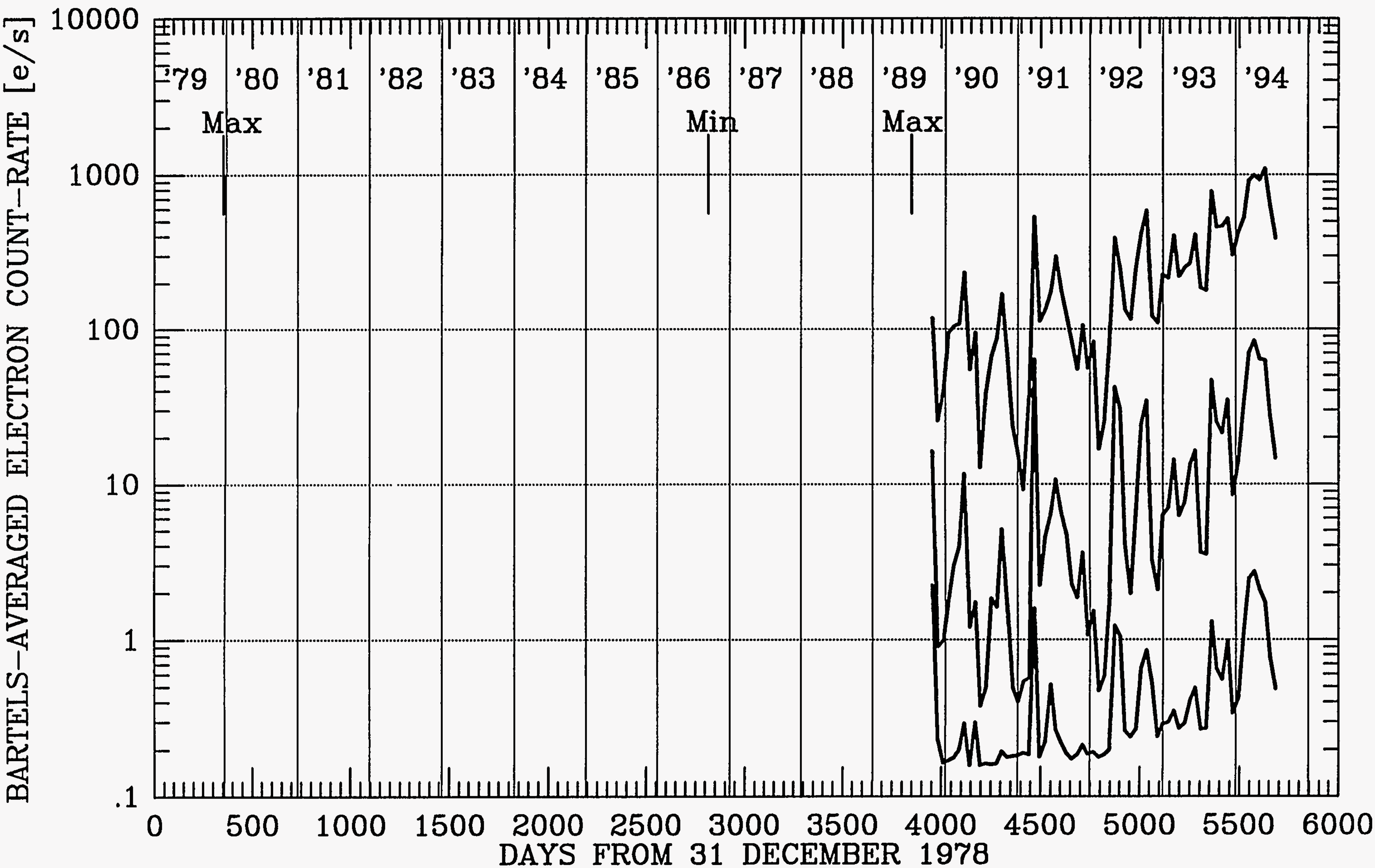


BARTELS–AVERAGED ELECTRON FLUX [e/cm²–s–sr]
10^8
10^7
10^6
10^5
10^4
10^3
10^2
'79
'80
'81
'82
'83
'84
'85
'86
'87
'88
'89
'90
'91
'92
'93
'94
Max
Min
Max
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
DAYS FROM 31 DECEMBER 1978



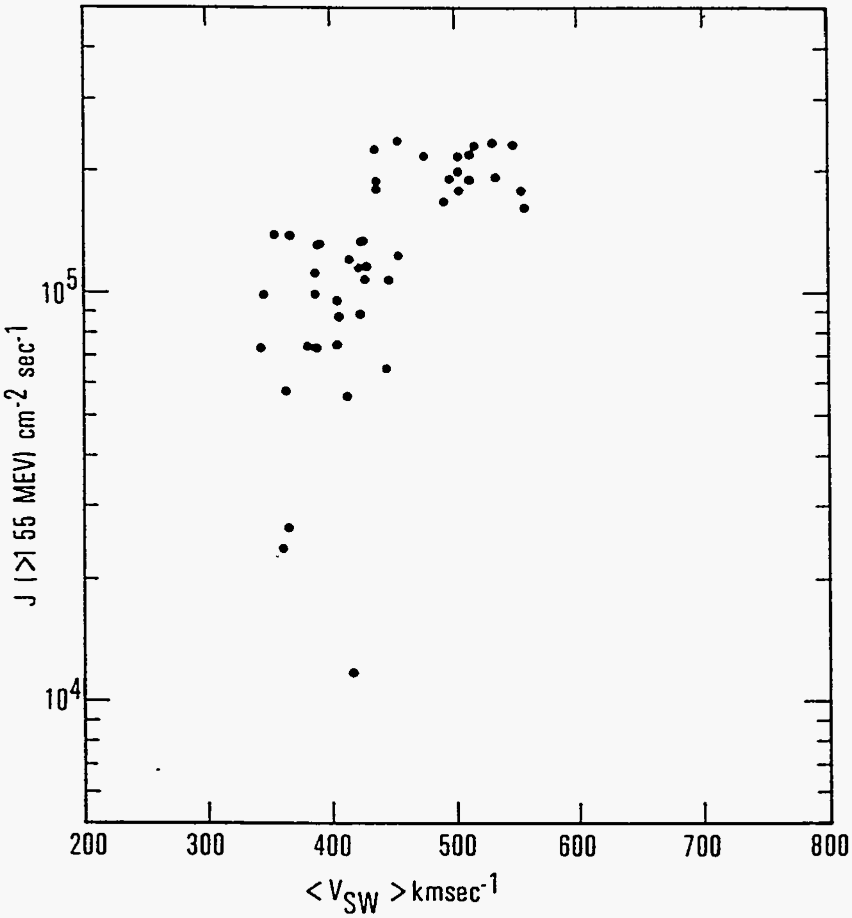
BARTELS–AVERAGED ELECTRON FLUX [e/cm^2–s–sr]
10^2
10^3
10^4
10^5
10^6
10^7
10^8
'79 '80 '81 '82 '83 '84 '85 '86 '87 '88 '89 '90 '91 '92 '93 '94
Max
Min
Max
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000
DAYS FROM 31 DECEMBER 1978

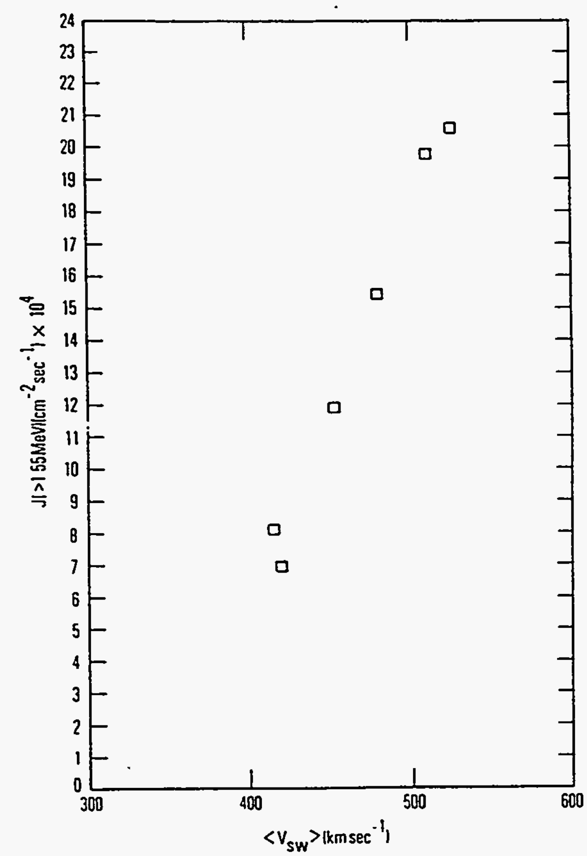
Fig 2

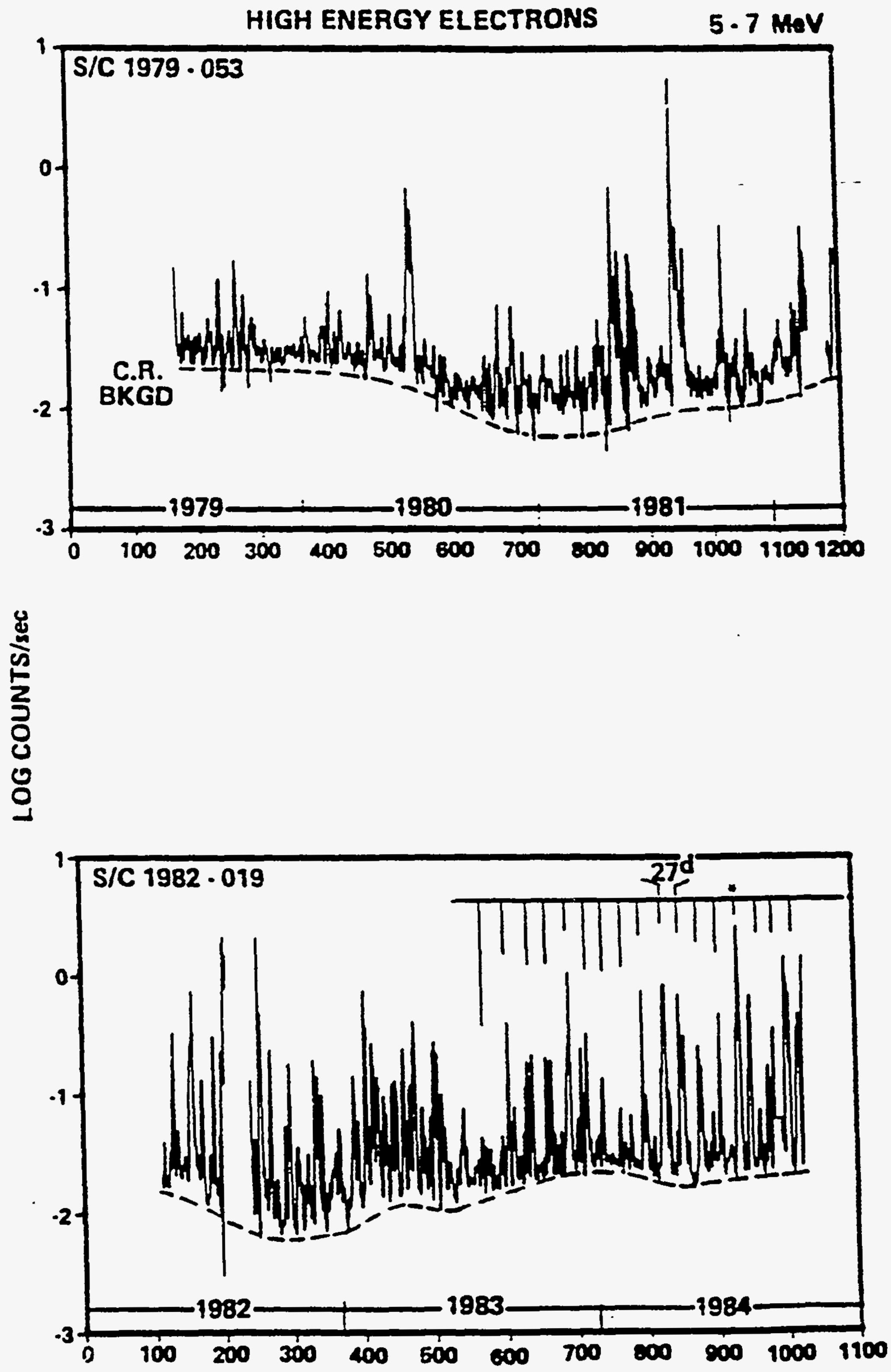


BARTELS–AVERAGED ELECTRON COUNT–RATE [e/s]
10000
1000
100
10
1
.1
'79
'80
'81
'82
'83
'84
'85
'86
'87
'88
'89
'90
'91
'92
'93
'94
Max
Min
Max
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
DAYS FROM 31 DECEMBER 1978

Fig 3


J (>1 55 MEV) cm-2 sec-1
10^5
10^4
200
300
400
500
600
700
800
< VSW > kmsec-1


J(>1 55MeV)(cm-2 sec-1) × 10^4
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
300
400
500
600
<Vsw>(kmsec-1)



HIGH ENERGY ELECTRONS
5 - 7 MeV
S/C 1979 - 053
C.R.
BKGD
1979
1980
1981
LOG COUNTS/sec
S/C 1982 - 019
27d
1982
1983
1984

FIG 5

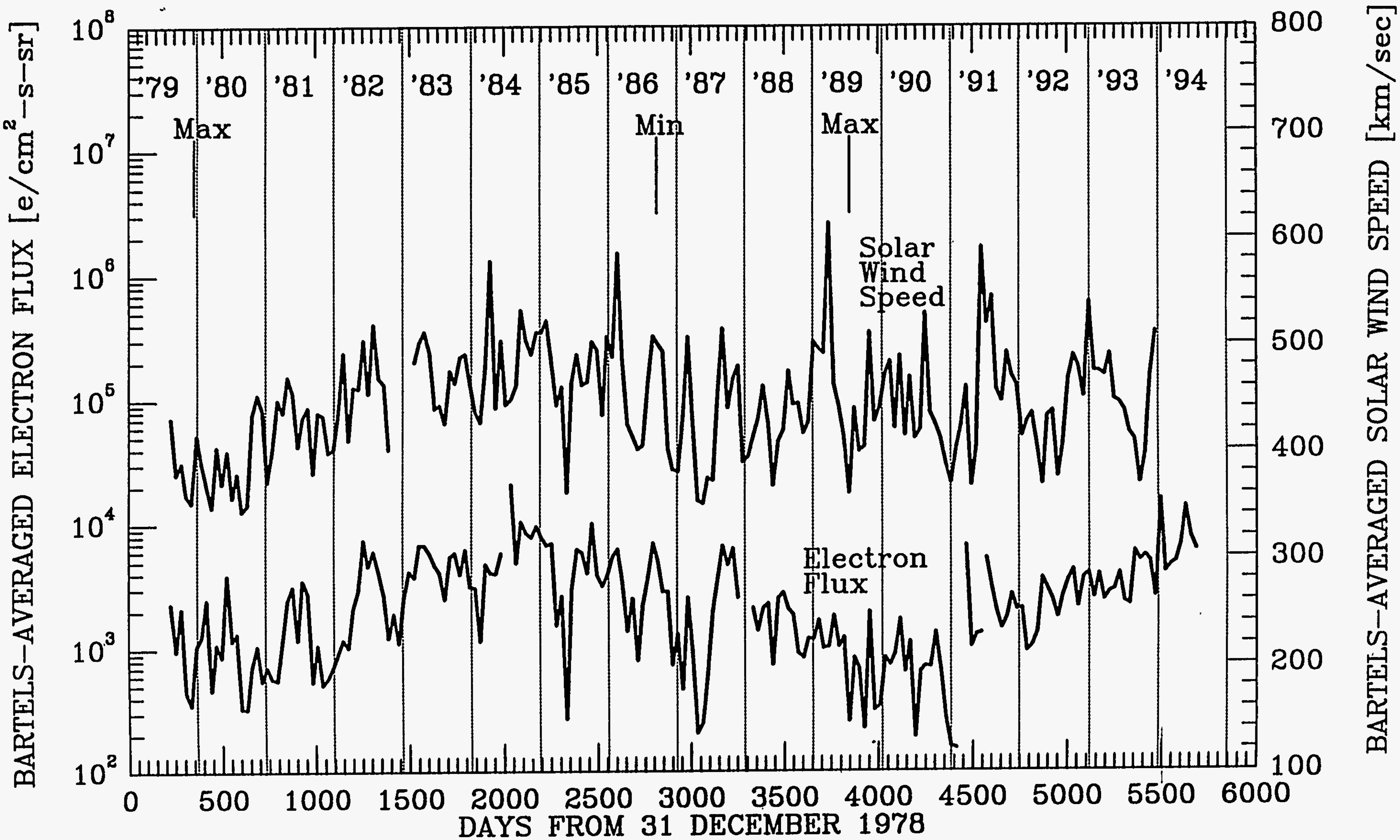

'79
'80
'81
'82
'83
'84
'85
'86
'87
'88
'89
'90
'91
'92
'93
'94
Max
Min
Max
Solar Wind Speed
Electron Flux
BARTELS-AVERAGED ELECTRON FLUX [e/cm²-s-sr]
BARTELS-AVERAGED SOLAR WIND SPEED [km/sec]
DAYS FROM 31 DECEMBER 1978

FIG 6

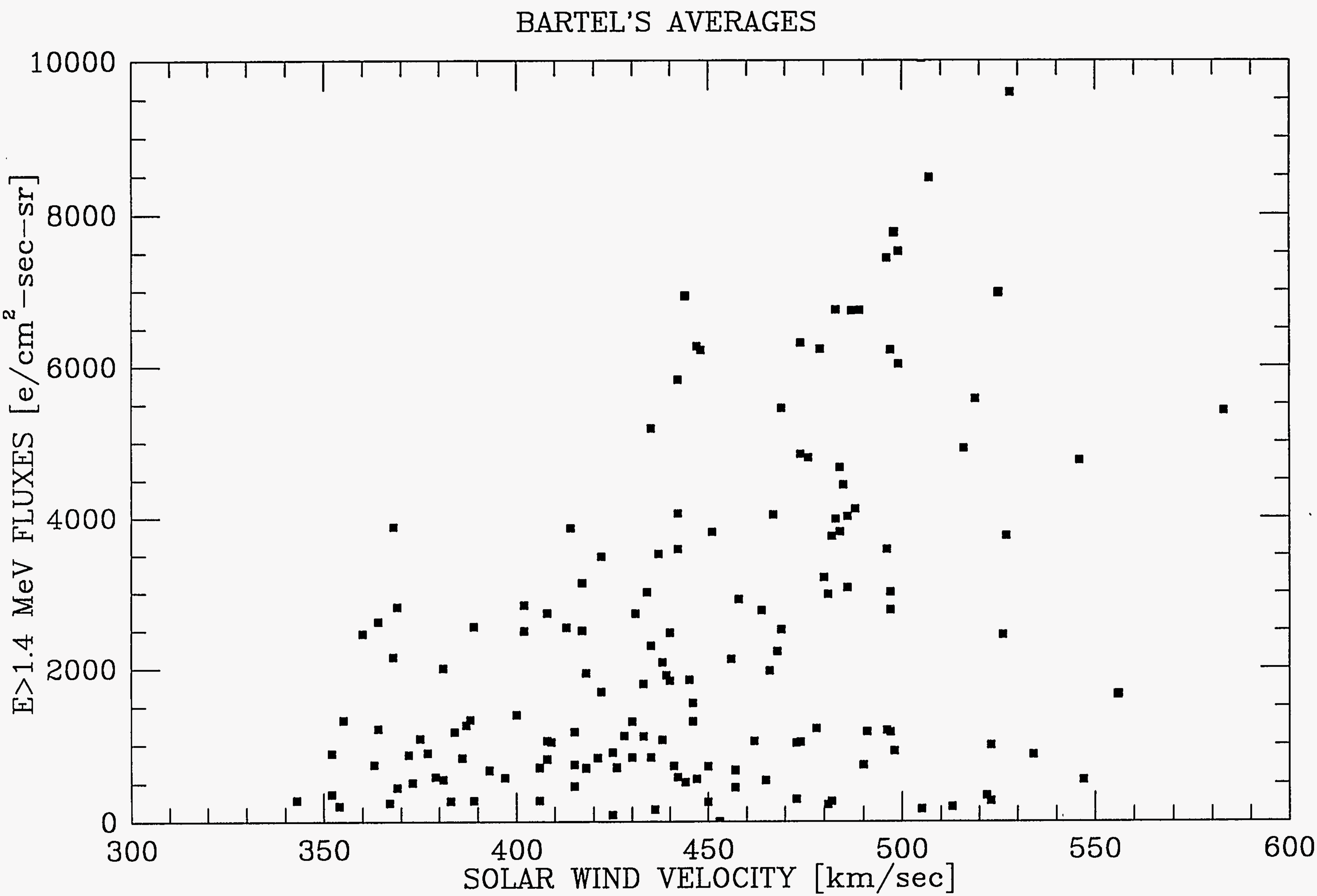

BARTEL'S AVERAGES
E>1.4 MeV FLUXES [e/cm^2-sec-sr]
10000
8000
6000
4000
2000
0
300
350
400
450
500
550
600
SOLAR WIND VELOCITY [km/sec]

Fig 7