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Characteristics of the *N*- component of the heliospheric magnetic field observed by IMP and ACE over 46 years

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Abstract

We analyze the normal (*N*) component of the heliospheric magnetic field data observed by the IMP and the ACE spacecraft (and in some cases as a check, measurements by the WIND spacecraft) for the period 1973 to 2020. Parameters characterizing the frequency spectrum are calculated with a novel technique and benchmarked against synthetic data. This technique is based on variances calculated at incremental lags and yields the integral of a turbulence spectrum, formally from infinity to a specific frequency. While it can be used for lossy data, it can however only yield information about the energy and the inertial range for typical values of the spectral indices (−0.75 to −1.25 for the former and −2 to −1.5 for the latter). Correlation functions are calculated with a standard second-order structure function. We find that the yearly average for magnetic field magnitude for the period that includes$^{\pm}$the 2020 solar minimum is at a new low of ~4.2 nT, as is the variance ~4.4 nT^2. Overall the magnetic variance tracks the magnitude squared of the field very well, both showing a clear solar-cycle dependence. The ratio of the magnitude of fluctuations of the *N* component to the field magnitude has an average value of 0.52±0.02 for the whole data set, with an increase by about 10% in solar cycles 23 and 24 compared with cycles 21 and 22. The average value of spectral index of the energy range for the whole data set is −1.0±0.1 with some solar-cycle dependence, while that for the inertial range is −1.69±0.04 for the IMP/ACE data set. The spectral level in the energy range and in the inertial range both show a clear solar-cycle dependence. We also find a clear solar-cycle dependence for the e-folding correlation length, with a significant increase in values in solar cycles 23 and 24 compared with the previous two.

1. Introduction

- *Ab initio* modulation models require turbulence spectra as input, which this project aims to help provide.
- A novel data analysis technique yields integral of assumes three-stage power-law turbulence spectrum, with flat cutoff range at lowest frequencies to ensure finite energy density.
- *N*-component of magnetic field from IMP and ACE 1-minute resolution data analyzed for 46-year period from 1973 – 2020.
- Spectral indices, break between energy- and inertial range (bend-over scale), break between energy- and low-frequency cutoff range (cutoff scale), and level of spectrum, calculated for 27-day intervals and binned into yearly averages.
- Correlation lengths calculated with a second-order structure function.

2. Incremental-variances technique and the second-order structure

- Incremental-variances (IV) calculates variances of component B_j at incremental lags τ

$$IV(\tau) = \frac{1}{n(\tau/2 - \Delta t)} \sum_{i=1}^{n(\tau/2-\Delta t)} \left(B_{j,i} - \overline{B_j} \right)^2$$

- Here $\tau = [n(\tau)-1]\Delta t$ with Δt the time resolution of the data set, and n the number of data points in the subset used to calculate the IV for lag τ. The latter is evaluated up to the datapoint at ($\tau/2-\Delta t$).
- For large lags, $IV(\tau)$ approaches the variance of the data set.
- Turbulence spectrum

$$G(f) = C \begin{cases} f^{-k} \text{ if } f > f_{bo} & \text{Inertial range} \\ f_{bo}^{-k}\left(f/f_{bo}\right)^{-e} \text{ if } f_{co} < f < f_{bo} & \text{Energy range} \\ f_{bo}^{-k}\left(f_{co}/f_{bo}\right)^{-e} \text{ if } f < f_{co} & \text{No } f \text{ dependence} \end{cases}$$

- Value of the constants follow when the integral of the assumed spectrum is fitted to output from IV expression.
- Second-order structure function

$$D(\tau) = \frac{1}{N}\sum_{i=1}^{N}\left[B(t)_{j,i} - B(t+\tau)_{j,i}\right]^2 \equiv 2\delta B_j^2 - 2R(\tau)$$

- For large lags, the correlation function $R(\tau)$ approaches zero and $D(\tau)$ approaches twice the variance of the data set.

- *In the following figures, open symbols denote IMP data and filled symbols, ACE data. Solid grey vertical lines indicate solar minimum periods, and dashed lines, solar maximum periods.*

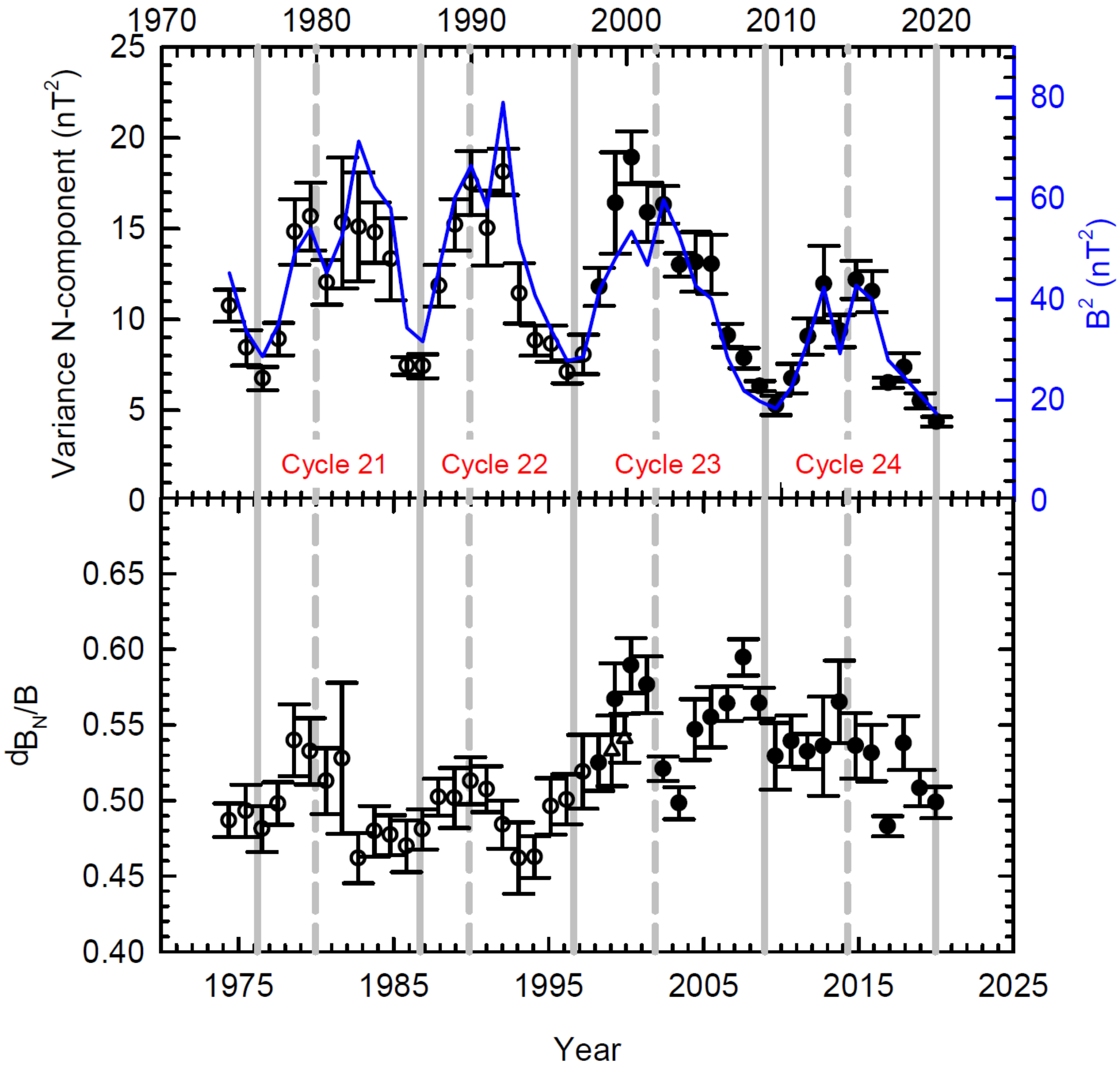

Fig 1 (top): Both variance and magnetic field magnitude squared show clear solar-cycle dependence with good correlation between the two. A significant decrease occurs in both from cycle 22 to cycle 24. Lowest value for magnetic field and variance is during 2020 solar minimum period, 4.2 nT and 4.4 nT^2 respectively.

Fig 1 (bottom): Ratio of magnitude of fluctuations to field magnitude has an average value of 0.52±0.02 for whole period. Increase of about 10% during cycle 23 confirmed by WIND data.

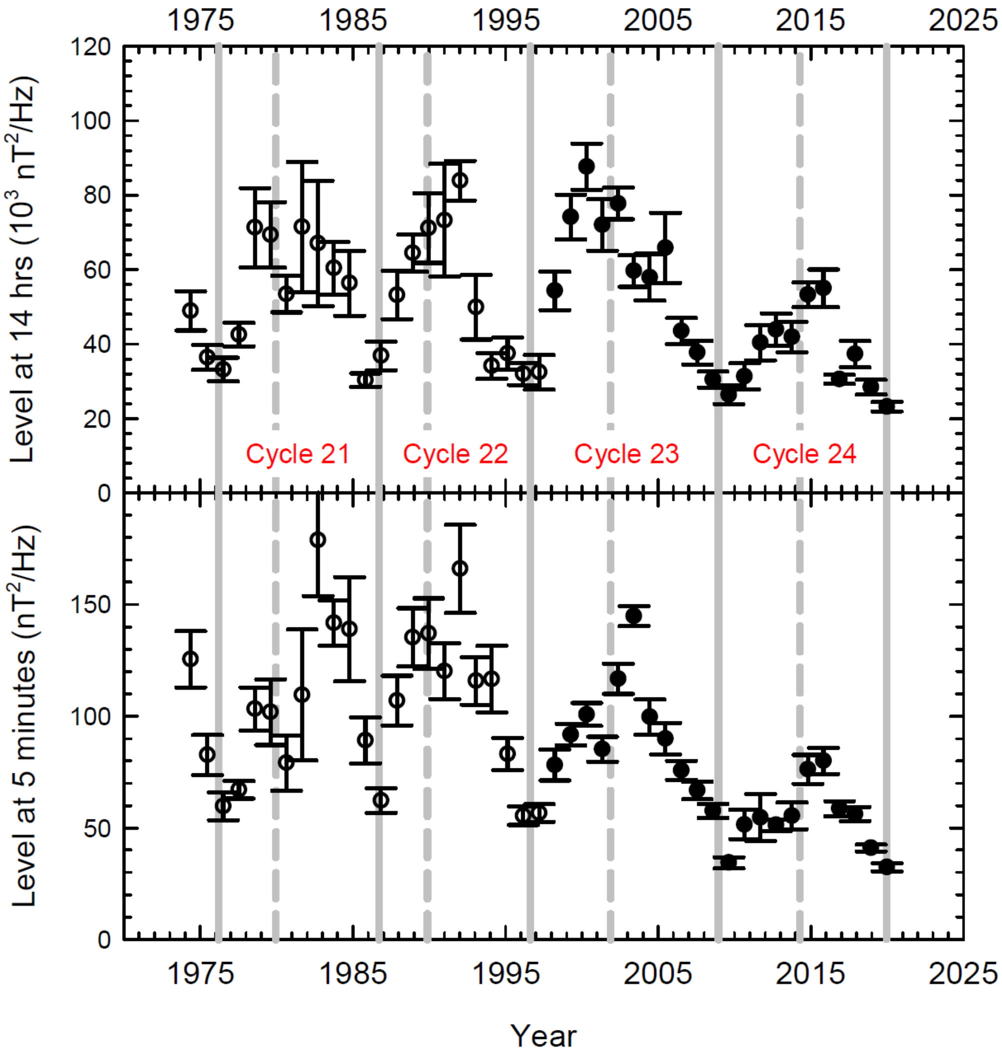

Fig 2: Spectral levels in the energy range (top) and in the inertial range (bottom) show a clear solar-cycle dependence. The behaviour of the ratio of the two levels indicates that the bend-over scale also has a solar-cycle dependence. As is the case for the magnetic field and the variance, there is a significant decrease in the levels over this period.

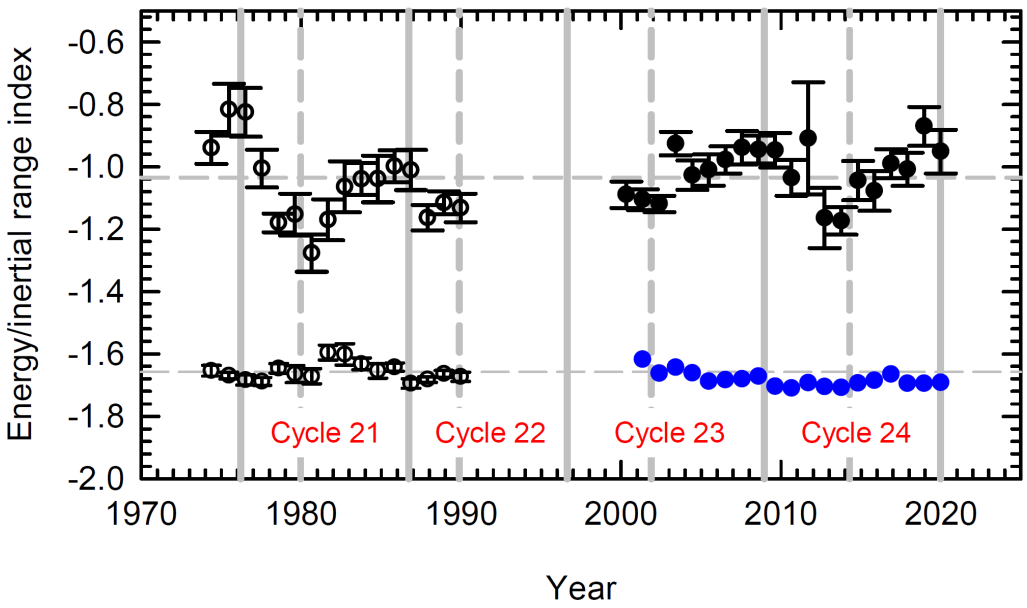

Fig 3: Data for the energy range spectral index are very variable during the period 1990 and 2000. If these are discarded, the remaining data show an 11.1 yr periodicity with a false-alarm probability of $p = 0.022$.
The inertial range spectral index is consistent with the Kolmogorov -5/3 value. There is a small difference between ACE and WIND data, here the latter is shown in blue.

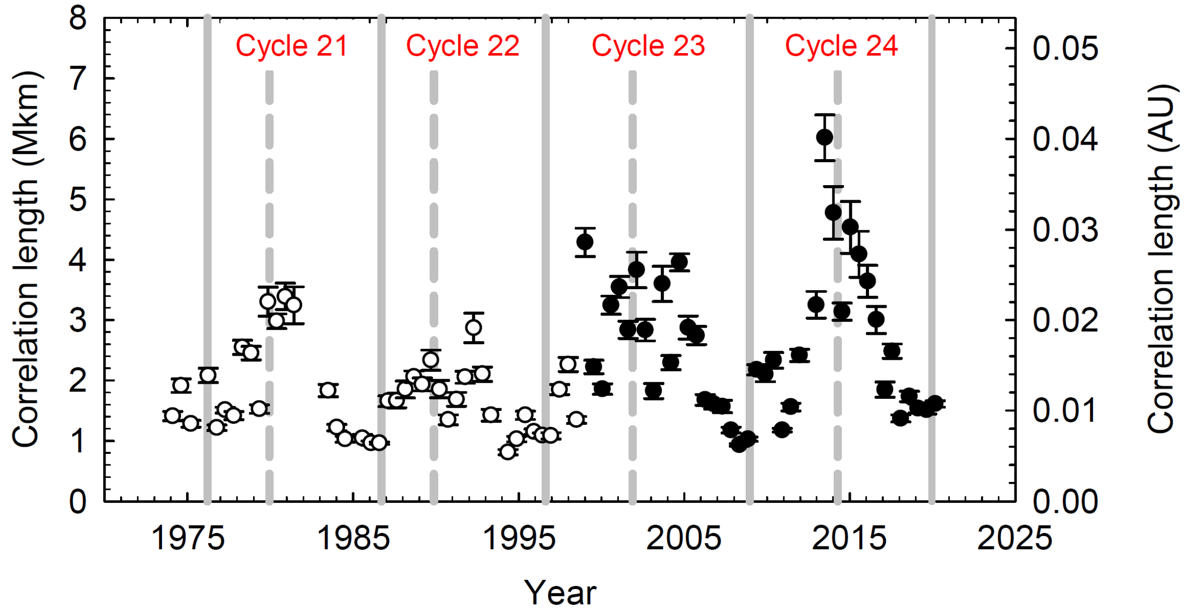

Fig 4: Correlation lengths calculated from the 2nd order structure function also show a clear solar-cycle dependence with a significant increase in values from cycle 22 to 24.

4. Summary and conclusions

- Both the magnetic field magnitude and the variance of the *N* component of the field reached their smallest values since 1973 during the period that includes the 2020 solar minimum, indicating that 2009 was **not** an unusual solar minimum.
- The magnetic field magnitude, variance of the *N* component, spectral levels in both energy- and inertial range, bend-over / correlation scale, and the spectral index of the energy range all show a clear solar-cycle dependence, with a maximum value for all six for a false-alarm probability of $p = 0.022$.
- Average value of the inertial range spectral index is -1.69 ± 0.04 consistent with Kolmogorov value of $-5/3$. No solar-cycle dependence.
- Average value of the energy range spectral index of -1.0 ± 0.1 consistent with a $1/f$ spectrum.
- There is a significant drop in turbulence energy levels in solar cycles 23 and 24 compared with cycles 21 and 22 and a concurrent increase in correlation lengths.

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