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LETTER

Letter to the Editor

Long-duration cosmic ray modulation from a Sun-Earth L1 orbit

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Abstract. We analyse cosmic ray hits impacting the detector system of the Coronal Diagnostic Spectrometer aboard the Solar and Heliospheric Observatory spacecraft. These observations allow us to study the modulation of cosmic rays over a 4 year period (1996-2000) running from solar minimum to maximum, from a Sun-Earth L1 Lagrangian orbit. The modulation, at the 45-50% level is consistent with cosmic rays of energy 1 GeV.

Key words: Sun: activity – Sun: atmosphere – Sun: UV radiation – ISM: cosmic rays

1. Introduction

The Coronal Diagnostic Spectrometer (CDS) on the European Space Agency/NASA Solar and Heliospheric Observatory (SOHO) comprises two extreme ultraviolet spectrometers (Harrison et al, 1995). One of these, the Normal Incidence Spectrometer (NIS) has a detector consisting of a Tektronix 1024x1024 pixel (21 micron), cooled, microchannel plate-intensified CCD. Two solar spectra, covering the wavelength ranges 308-380 Å (NIS1) and 517-633 Å (NIS2) are imaged simultaneously onto the CCD. The instrument has been used to explore the topology, evolution and plasma characteristics of the solar atmosphere through the study of emission characteristics of the extreme ultraviolet emission lines detected (see, e.g. Harrison et al., 1997). However, the data taken from the NIS detector are affected by cosmic rays, which deposit charge in one, or usually more, pixels. This charge is then counted as signal when the detector is read out.

For most operations of the CDS instrument, the cosmic ray hits are ignored or cleaned from the data. However, CDS has been in space in a Sun-Earth L1 Lagrangian orbit since early 1996. For the first time, we present an analysis of the cosmic ray hit data for this instrument. Comparing data from the early mission through to the present day, we are able to examine aspects of the cosmic ray environment for a period from solar minimum to maximum.

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2. The observations

In normal operation, because of telemetry constraints, CDS data telemetered to ground are selected on board to encompass only the wavelength range of a few emission lines of interest for the current observation in either or both of the NIS wavelength bands, i.e. we do not normally return data from the entire exposed detector area. However, since the start of SOHO science operations in April 1996, the CDS operations team have performed a number of regular monitoring programmes, and one of the monitoring observations takes a 50 second exposure at a sequence of ten closely spaced locations and each complete spectrum is downlinked. This observation has been performed regularly once or twice a week for the lifetime of the mission. This regular operation allows a 'synoptic' view of the cosmic ray hit characteristics.

Early in the mission the Sun was remarkably quiet and the spectrometer slit in this observing sequence was directed to an area of 'quiet sun'. As the solar activity has increased, an increasing number of the observations have included brighter features and many active region observations have been made.

Several computer programs have been developed to detect and alleviate the effects of cosmic rays in the data. These programs are used either to flag affected pixels as 'missing' data or to replace affected pixels with data interpolated from nearby pixels. Since the first stage of any of these programmes is to detect cosmic ray-affected pixels by their anomalous data value, they are also useful for monitoring the rate at which the data are affected by cosmic rays. We have used the CDS_NEW_SPIKE program written by Peter Young to perform this task. This routine checks each pixel in the dataset for significant deviation from the median of surrounding pixels. The ability to do this in the three dimensions of the dataset (SolarX,SolarY,Wavelength) greatly enhances the reliability of the detections over that achievable in simple 2-dimensional images. It also naturally ignores effects due to defective CCD pixels, as can be seen in Fig. 1.

An example of part of a typical exposure is shown in Fig. 1. The upper image shows the cosmic ray-affected raw data together with a few weak emission lines and the lower image shows those pixels identified as being affected by cosmic rays.

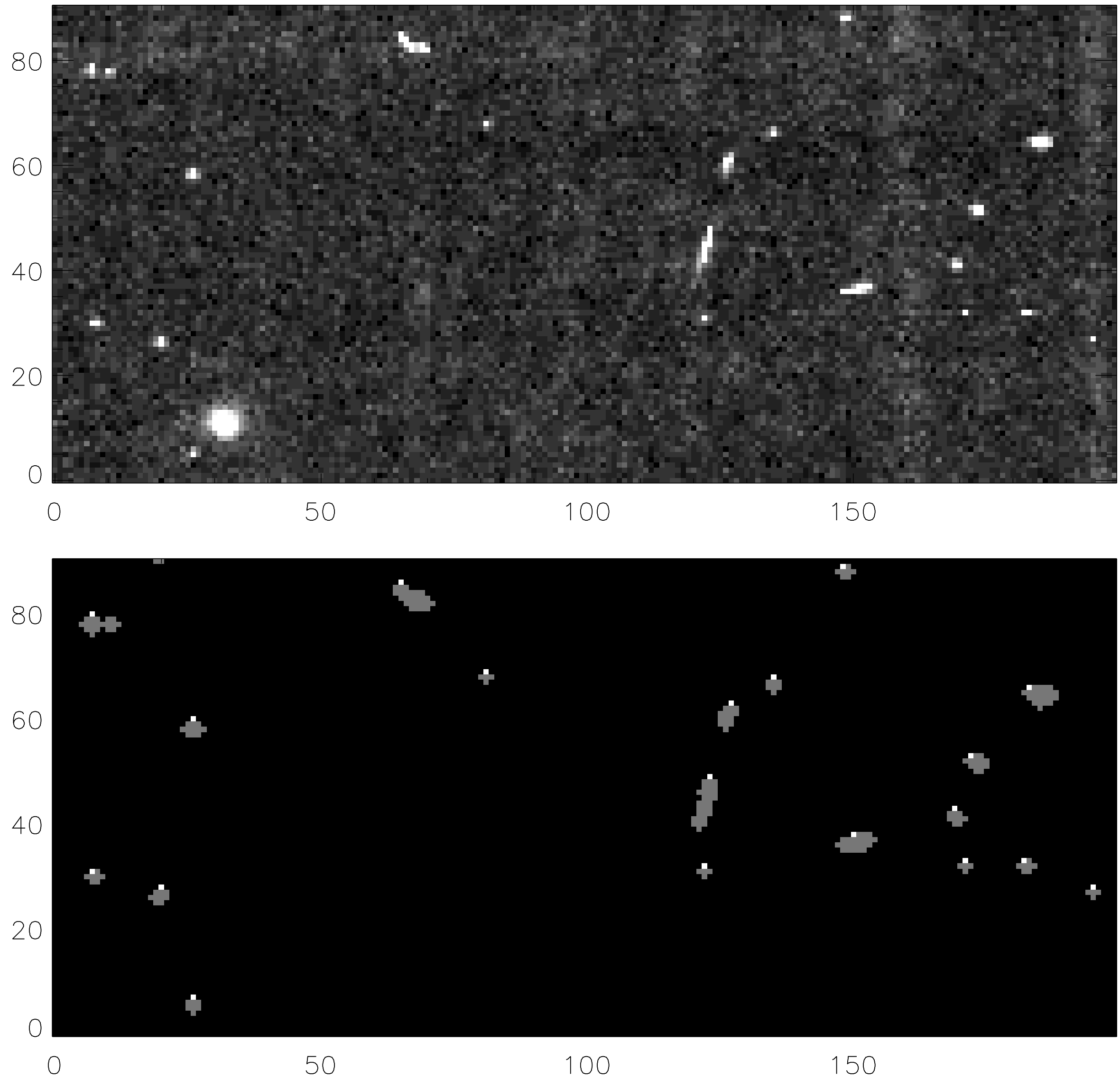

Fig. 1. The upper panel shows a portion of a raw image on the CDS detector. Although the image is scaled to highlight the cosmic rays, some weak emission lines can be seen. The lower panel shows, for the same image, the pixels identified as containing excess counts from cosmic ray hits. For each group, one pixel (white) is indicated by the software for individual cosmic ray hit counting.

For each of the ten exposures in all of the over 400 observations with this study, the location and strength of the affected pixels were recorded. In general for each cosmic ray event several surrounding pixels are associated with that event. The distribution of raw data values for affected pixels therefore shows a preponderance for low data values and the recorded count of affected pixels is considerably larger than the actual total of incident cosmic rays. The number of pixels associated with one cosmic ray hit is a sensitive function of the detection algorithm parameters, as well as the path of the particle at the detector. We have therefore used the algorithm described by Thanisch et al. (1984) to count groups of connected pixels to give a truer estimate of the actual number of hits. Very close hits are sometimes counted as single hits as can be seen from Fig. 1 where one pixel from each affected group of pixels is highlighted. The bright patch at pixel (32,10) in the upper panel is a detector defect. Since it is constant from exposure to exposure is not identified as a cosmic ray hit.

The first conclusion drawn from the statistics was that those observations taken of active regions generally showed a much reduced count rate. This is because of the slightly increased background continuum and much stronger emission line intensities which inhibit the flagging of many of the low intensity impacts. In order to maintain the homogeneity of the data we have therefore only retained observations (approximately 400) from quiet Sun regions. The second notable effect was that the count rate changed abruptly after June 1996. At this time, the read-out mode of the CDS CCD was changed. Once again that change affected the ability of the software to flag discrepant, low intensity level pixels and so only post-June 1996 data have been retained.

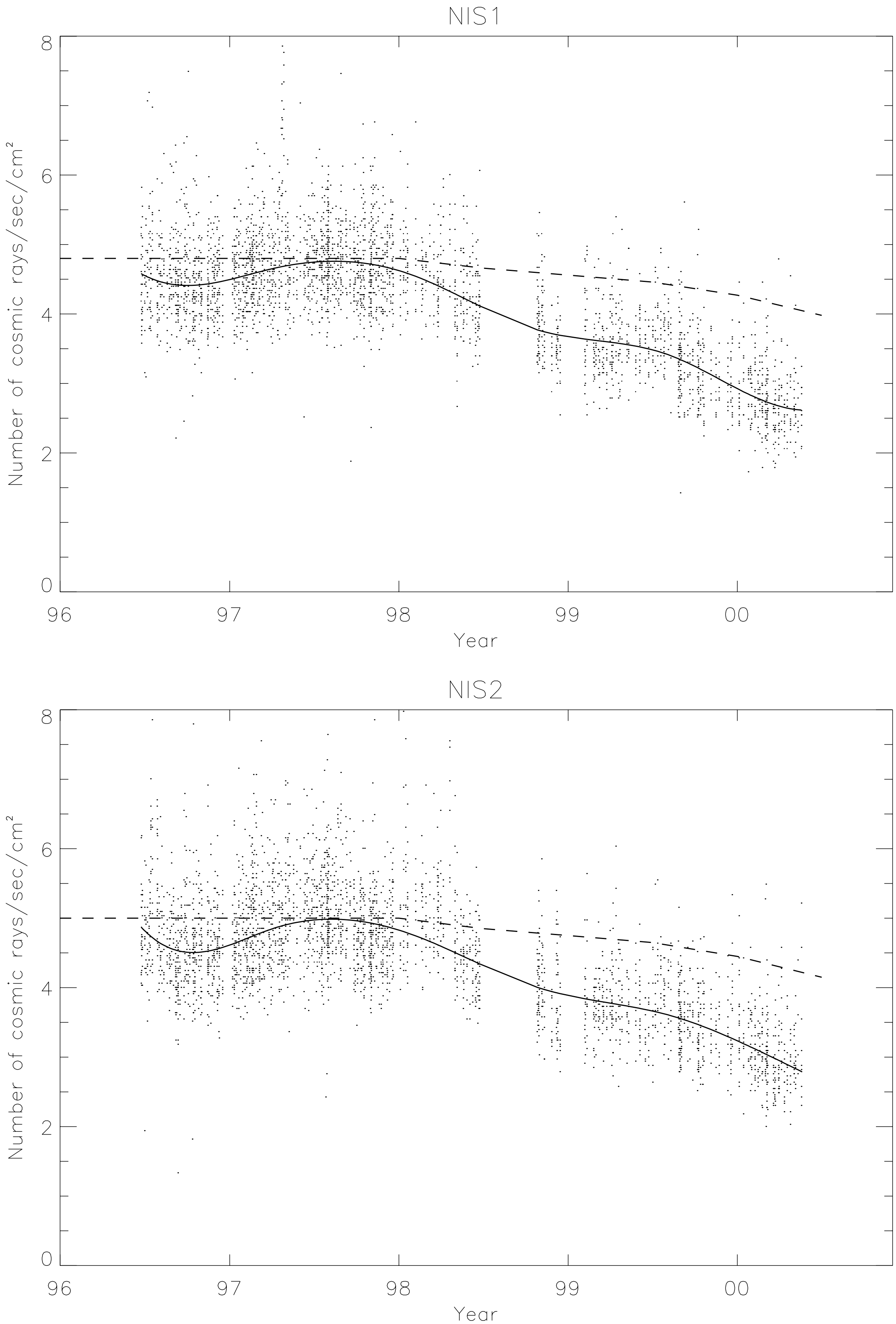

Fig. 2. For the two CDS NIS detector ranges the number of cosmic ray hits is plotted against time. A spline fit to the data is shown, indicating a 45-50% decrease in cosmic ray hits from solar minimum (1996-7) to maximum (2000). For comparison, the dashed curves indicate the profile detected at the Climax neutron monitor for the same period.

3. The data

The derived count rates for the regions of the detector covered by both CDS/NIS spectral bands are shown in Fig. 2. As expected these show very similar results. The most significant feature in both plots is the 45-50% relative decline in count rate from late 1997 to the present day.

The basic picture is a decline in cosmic ray hits from solar minimum to maximum and this is a confirmation of results given for various spacecraft (see e.g. Kunow et al., 1991) which suggest that the cosmic ray flux is modulated by the intensity of the solar magnetic fields, in this case over a 4 year period in a Sun-Earth L1 orbit 1.5 million km sunward of the Earth.

The NIS detector system is subject to the occasional bombardment from particles of solar origin during solar storms, but the principal trend shown in Fig. 2 is anti-correlated with solar activity as is to be expected if the source of the cosmic rays is beyond the solar system.

Kunow et al (1991) review comic ray modulation as a function of cosmic ray energy (the most energetic particles are least affected by the heliospheric field). Their Fig. 11.3 shows that energies above about 5 GeV show almost no solar cycle variation but that energies of 2 Gev, 1 GeV and 100 MeV show variations of order 40% 45% and 80% respectively. This suggests that the energy of the majority of the cosmic ray particles being detected using CDS is approximately 1 GeV.

For comparison, we consider the cosmic ray hit profile as indicated using the University of Chicago Climax neutron monitor which is sensitive to particles of energy $>$3 GeV. Over the CDS observation period, the Climax data show a decrease of about 15% with a peak in 1997. An indication of the Climax profile is given in Fig. 2. This is for higher energy cosmic rays than those which we believe to be detected using CDS and thus the smaller decrease is consistent with our expectations.

4. Summary

We have shown that cosmic ray hits on a solar extreme ultraviolet spectrometer detector system located at a Sun-Earth L1 Lagrangian orbit over the period 1996-2000 show modulation of order 45-50%. This modulation is in anti-phase with the solar cycle and is consistent with the majority of particles being detected of energy 1 GeV.

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