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Can we predict when the next solar cycle is about to take off?

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Abstract.
In investigating the long-term variability in the solar soft X-ray flux, we discovered a sudden increase ("the step") at the onset of Cycle 23. This step occurred in August 1997 when the X-ray emission observed by the Yohkoh SXT instrument increased within two rotations of the Sun from some of the lowest values seen during solar minimum to about 30% of the rate seen at the following maximum. This was not the result of the emergence of one or two active regions but seemed to be a global phenomenon. Further, there was a north-south asymmetry in the step, activity in the northern hemisphere of the Sun emerging first followed a month later by activity in the south. The strong-field magnetic flux shows the same rapid increase in activity. Preliminary results from prior cycles indicate similar step functions but the data are sparse and will need considerably more careful relative calibration and analysis before we can draw firm conclusions. This result imposes new constraints on the prediction of solar activity from any combination of magnetic dynamo and flux transport models.

Key words. Sun: solar cycle – Sun: X-rays – Sun: magnetic field

1. The X-ray Data

The Yohkoh Soft X-ray Telescope (SXT; Tsuneta et al. 1991) accumulated over 144,000 full-disk, half-resolution images in its 3-50 Å thin aluminium filter during its 10 years of operation. We summed the pixel rows and columns of the CCD images and plotted the resulting data points as a function of time (see Fig. 1).

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The most surprising feature of the resulting lightcurve was a sudden increase in the integrated X-ray flux by about a factor of 6 in 1997; after the step, the intensity rose gradually to its maximum value around the peak of the activity cycle. We could not attribute the step increase to any change in the operation or calibration of the SXT. The SXT AlMgMn composite filter showed the same step function behavior. Further, the 5-min summed, 1-8 Å data from the GOES X-ray Sensor also had a similar step (with a 50% larger amplitude) at the

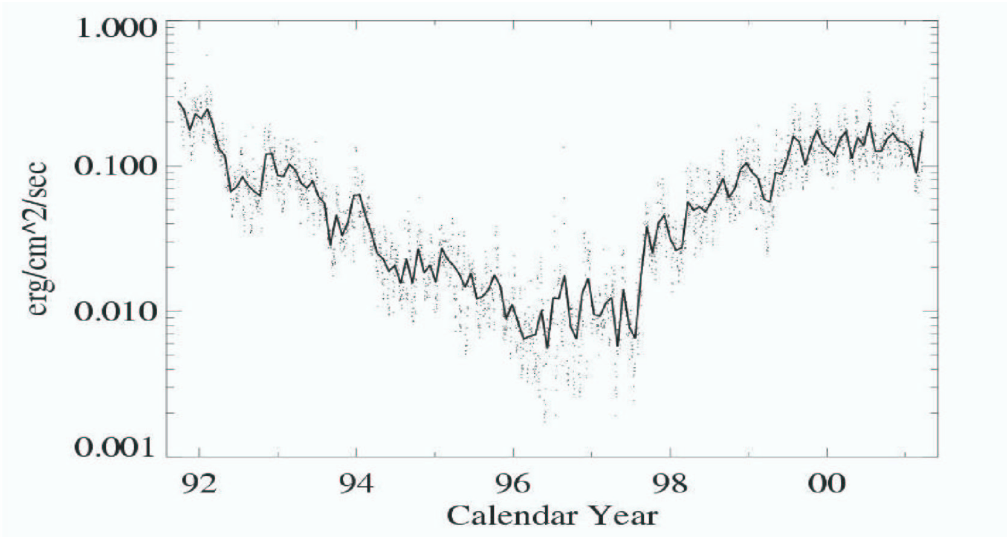

Fig. 1. The Yohkoh SXT lightcurve shows a sudden increase in integrated X-ray intensity during Carrington Rotation 1926 (August 1997). The dots show individual data points and the solid curve shows a 27-day running average.

same time. So we concluded that the step feature was of solar origin. The sequence of SXT images showed that the step was the result of an outbreak of activity primarily in the northern hemisphere, followed by a similar outbreak in the south a rotation later (see Fig. 2, bottom row).

2. The Magnetic Data

The enhanced coronal activity originates in concentrated magnetic field so the step should be reflected in the magnetic data. We accumulated line-of-sight magnetic images from the Michelson Doppler Imager (MDI; Scherrer et al. 1995) on SOHO (see Fig. 2, top row) and from the National Solar Observatory at Kitt Peak (Harvey & Worden 1998). The MDI team created a database of synoptic charts charts, linear in longitude vs. sine latitude, which map the solar magnetic flux accumulated over a Carrington rotation (27.2 d) in 3600×1080 pixels. The online NSO/Kitt Peak archive (see **http://nsokp.nso.edu/dataarch.html**) provides synoptic charts at lower resolution, with 360×180 pixels. We analyzed the temporal evolution of the magnetic flux at successive Carrington rotations using several different breakdowns of the data, in particular:

- Total unsigned flux
- Northern vs. southern hemisphere
- Latitudes 0-15, 15-40, 40-60 degrees
- Weak vs. strong field.

We restricted the latitude bands to ± 60 degrees to reduce systematic errors from low signal-to-noise data (J. Harvey, private communication, 2003) and we used a strong-field flux threshold of 25 G as defined by K. Harvey (Rabin et al. 1991). By inspection, in this time interval the $\pm$ 15-40 degree latitude band corresponded to the range of new-cycle active regions, while old-cycle regions were almost always within ± 15 degrees. Before summing the MDI data, we divided the fluxes for each row in a chart by the cosine of the latitude, to convert the line-of-sight values to radial values for an assumed radial field; the Kitt Peak charts already have cosine latitude factored in. To compute weak-field fluxes, we used Kitt Peak data rather than MDI data, because the weak-field MDI data appeared to have lower signal-to-noise. The strong-field fluxes are less subject to

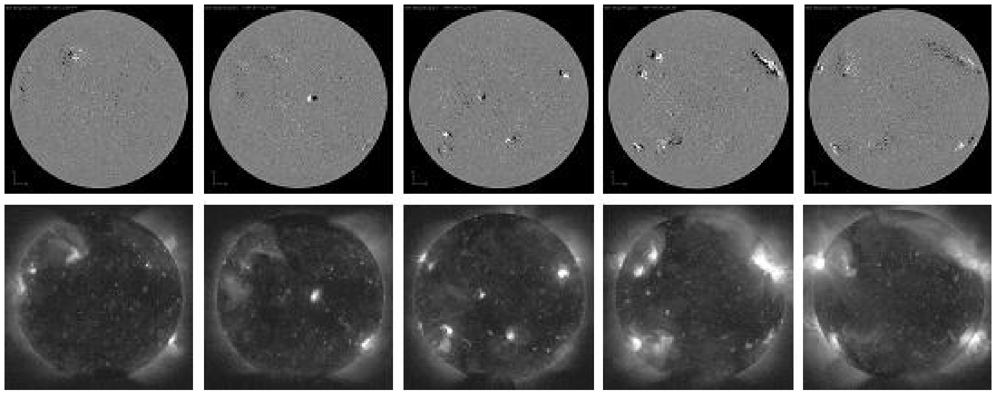

Fig. 2. A sequence of monthly solar images from SOHO MDI (top) and Yohkoh SXT (bottom), from June to October 1997, shows that the outbreak occurs over a wide range of longitudes.

noise, and the temporal behaviors of the MDI and Kitt Peak data appeared very similar.

Figure 3 shows histograms of the MDI strong-field flux and the Kitt Peak weak-field flux plotted for Carrington Rotations (CR) 1911 through 1936. The CR axis is shown at the top of the graph; the corresponding time in the two-year period from 1996.5 through 1998.5 is shown at the bottom of the graph. The dark shaded bar graph shows the strong-field flux for the active region belt in the northern hemisphere, which jumps by a factor of ~2.5 during CR 1926, the same time as the SXT X-ray step. The light shaded bar graph shows the strong-field flux in the active region belt for the northern and southern hemispheres combined, and indicates that the magnetic flux step in the southern hemisphere occurs one rotation later (cf. de Toma et al. 2000). The dashed lines show the Kitt Peak weak-field flux for the northern and southern hemispheres combined, for the active region belt (lower curve) and the total latitude band considered (± 60 degrees). In the active region belt, the weak-field flux dominates before the step but is overtaken by the strong-field flux at the time of the step. The weak-field flux in the ±60 degree band has the same general shape as in the active region belt and about a factor of 2 higher intensity. It crosses over the (active region) strong-field flux about a year after the step (cf. de Toma et al. 2000).

By studying the polarity and latitude of each emerging region, we determined that all of the new activity at the step and after was the result of the emergence of new-cycle (Cycle 23) regions.

3. Discussion

We have established that the Sun suddenly increased its coronal activity at the onset of Cycle 23 as a result of the emergence of a series of new-cycle active regions, first in the north, then about a rotation later in the south.

These results lead to a number of questions which we are currently endeavoring to answer:

• **Do other activity indicators show the same phenomenon?** Initial results indicate that the rate of flaring and the monthly sunspot area also show a clear step but the monthly sunspot number, CME rate, and total solar irradiance do not.

• **Has this happened before?** Initial results for previous cycles suggest that there were comparable but less significant steps at the onsets of Cycles 21 and 22. If the ~ 10.5-year time interval between the steps in the last three cycles persists, then the step for Cycle 24 should occur in January 2008 (±2 months).

• **Why is there a step?** (I.e., why is there a sharp step-like increase rather than the expected ramp up?) How can the slowly varying or invariant processes that generate or transport the solar magnetic field (i.e., the dynamo, dif-

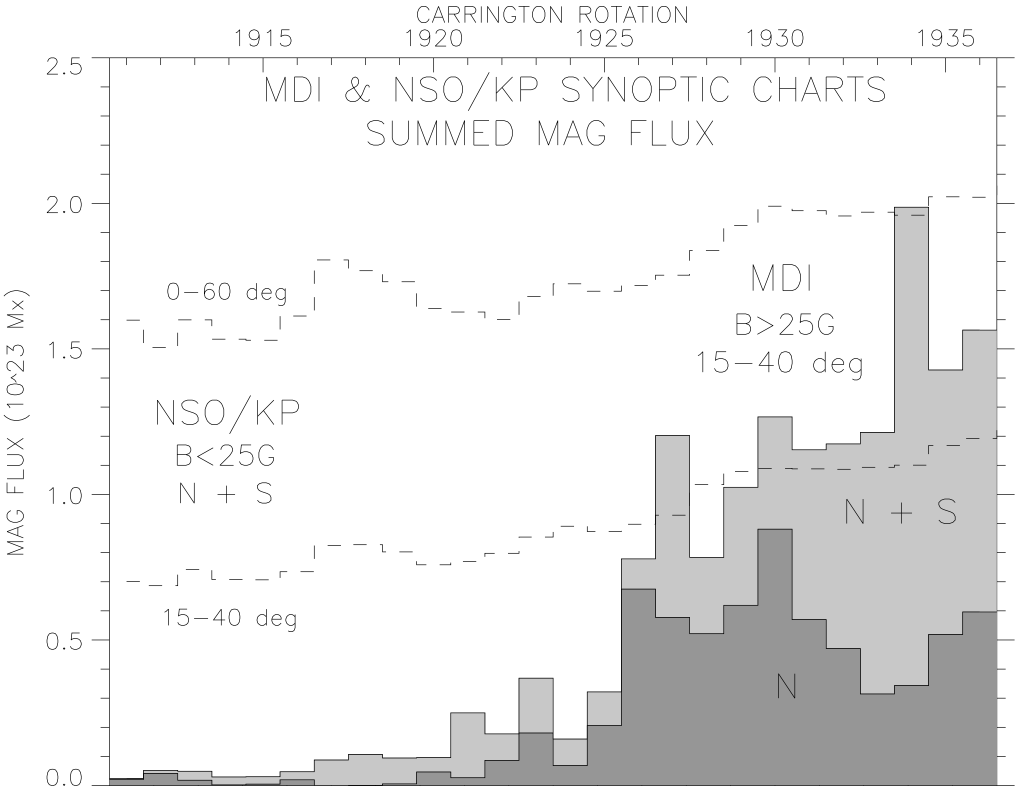

Fig. 3. The (MDI) strong-field flux shows the increase in activity in both hemispheres compared to the (Kitt Peak) weak-field flux that initially dominates. The weaker half of the Carrington chart with lowest intensity was used to estimate background in each case.

ferential rotation, convection, and meridional flow) produce a large, abrupt step-function increase in intensity? Are we seeing the result of an instability or loss-of-equilibrium? Where? What is its nature?

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