X-RAY BRIGHT POINTS AND THE SUNSPOT CYCLE: FURTHER RESULTS AND PREDICTIONS

JOHN M. DAVIS
American Science and Engineering, Inc., Fort Washington, Cambridge, MA 02139, U.S.A.

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Abstract. X-ray images obtained during two rocket flights near the maximum of sunspot cycle 21 now allow the study of the variation of X-ray bright point number over an eleven-year period covering the maxima of the last two cycles. The new data are consistent with the earlier conclusion that the temporal variation of bright point and sunspot number are out of phase. The quantities are related through a power law with a negative exponent of 2/3.

1. Introduction

The current interest in solar variability and the solar terrestrial connection has focused attention on the Sun's magnetic activity cycle both as a source for, and as a baseline against which the variability of other phenomena can be compared. Recent studies have been wide ranging and have included the variation of the total UV flux (Cook *et al.*, 1980; Torr *et al.*, 1980), the large scale coronal structure and the solar wind (Sheeley and Harvey, 1978, 1981) and the polar solar wind (Coles *et al.*, 1980). Our efforts have been directed at understanding the behavior of regions of small scale flux emergence known as coronal or X-ray bright points (XBP). Their interest lies both in their direct relation to the solar magnetic field and in their identification as a possible source for the solar wind (Akasofu, 1983; Davis and Krieger, 1982; Mullan and Ahmad, 1982; Pneuman, 1983).

It will be remembered that bright points appear as small emission features in soft X-ray spectroheliograms. Comparison with photospheric magnetograms (Golub *et al.*, 1977) has revealed their bipolar nature and thus their similarity to ephemeral active regions (Harvey and Martin, 1973). However both this and a more recent study (Tang *et al.*, 1983) have indicated the lack of a one-to-one correspondence between bright points and ephemeral regions. For although all bright points can be directly associated with a magnetic bipole, the reverse is not true. The particular characteristics which distinguish those magnetic bipoles which are also coronal bright points from the general class of ephemeral regions remain unclear.

Davis *et al.* (1977) and Golub *et al.* (1979) have shown that the frequency of occurrence of coronal bright points is periodic and varies out of phase with sunspot number. The phase difference is close to 180°, i.e., the two quantities appear to be anticorrelated. This result was based upon X-ray observations made during the Skylab mission and during six sounding rocket flights covering the period 1970–1978. The Skylab data covering a six-month period in 1973, provided a continuous set of observations against which the single data points obtained during each rocket flight can be

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judged. Results are now available from two further rocket flights, launched on 16 November, 1979 and 13 February, 1981, respectively, during the maximum phase of sunspot cycle 21. The addition of these two points to the data set extends the coverage to an eleven-year period containing the maxima of cycles 20 and 21.

2. Results and Discussion

Representative images from the two flights are shown in Figure 1. Inspection shows that there are few coronal bright points and that the background corona appears brighter than found in images taken at other times of the sunspot cycle. The increased background emission is important because of the problem of obscuration (Golub *et al.*, 1976). This governs the difference in visibility of a small feature when viewed against a background of either the weakly emitting, large scale structure or the essentially emissionless background of a coronal hole. To eliminate this difference the standard procedure for counting bright points uses short exposures where the background is at or below the threshold of detection. Although this lowers the number of bright points that are observed, it removes the bias between regions containing different structures. For the Skylab data a 4 s exposure was used.

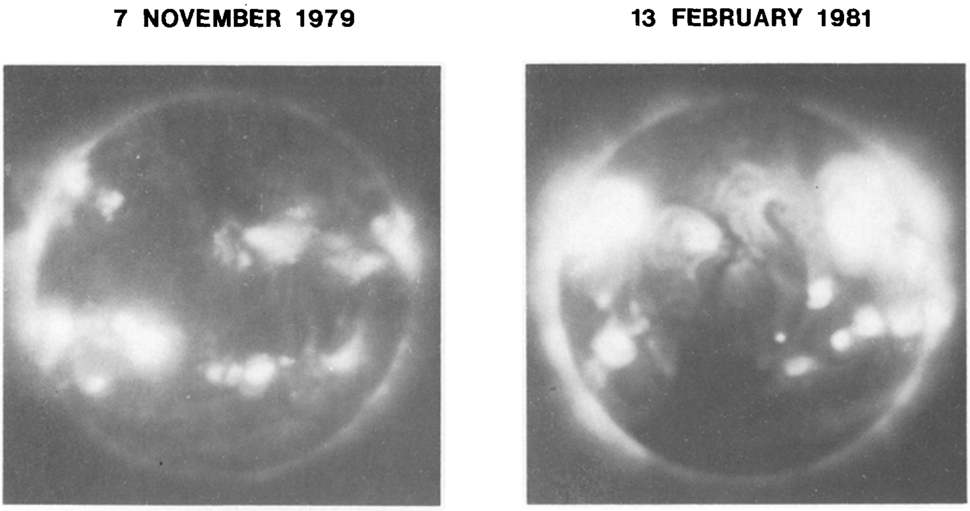

Fig. 1. Full-disk X-ray images recorded on 16 November, 1979 and 13 February, 1981.

The relevant instrumental parameters for the two rocket experiments are collected in Table I. On each flight nominal exposure times of 1, 3, 9, and 27 s are available. To normalize the rocket data the bright points were counted on exposures where the product of the relative efficiency and exposure time approximates 4 s. The relative efficiency is defined as the product of the filter and prefilter transmissions and the mirror's effective collecting area at 44 Å. For these two flights 9 and 3 s images were selected and the values listed in Table I are the actual exposure times measured from the telemetry record.

Although an understanding of the origin of the increased background is not essential to this study, it is useful in providing a quantitative estimate for the obscuration correction. Analysis suggests that the background arises from the presence of extended, low density loops associated with, and having temperatures typical of, active regions. This conclusion is based upon interpretation of the images and a preliminary analysis of coronal spectra recorded during the second of the two flights. The spectra came from a 1 arc min^2 field centered at S 03 W 42. The field was located betwen three active regions and contained emission only from the large-scale structure. A line ratio analysis of various hydrogen-like and helium-like ions leads to a plasma temperature of 2.5×10^6 K. This is above the range of 1.5 to 2.1×10^6 K previously reported for the quiet Sun (Withbroe, 1975; Maxson and Vaiana, 1977; Mariska and Withbroe, 1978) and which has at other phases of the sunspot cycle formed the background against which the earlier bright point counts were made.

For X-ray telescopes the power emitted by a plasma in the temperature range 1 to 6×10^6 K, integrated over all wavelengths, reaching the focal plane is proportional to the second power of the electron temperature (see Vaiana *et al.*, 1977, Figure 32). Thus an increase in coronal temperature from 2.0 to 2.5×10^6 K will raise the detected emission by a factor of 1.5. That is, the background on a 4 s exposure from the rocket flights at solar maximum should be comparable to that on a 6 s exposure from the earlier period. This is found to be the case, and although this analysis is almost certainly an oversimplification, it has been used as the basis for correcting the data for the increased obscuration. The approach can be justified by noting that the temperature of the large-scale structure is likely to vary over the solar surface and will almost certainly be lower outside the active region zone. Thus the correction factor should be conservative. However one might also expect an accompanying increase in the amount of material at these temperatures with the increased background arising from a combination of both these factors. The increase in density of the large-scale structure must be rather modest for the emission measure, estimated from the spectrometer data, is not inconsistent with the results of Maxson and Vaiana (1977). Thus the higher temperature appears to make the dominant contribution to the increased background and applying the correction factor of 1.5 to the observations from the whole disk is more likely to cause the number of bright points to be over- rather than underestimated.

On balance the factor of 1.5 is believed to be a reasonable correction for the increased obscuration. Using this value the corresponding decrease in bright point visibility is approximately 30% (see Golub *et al.*, 1976, Figure 1). Therefore the measured values have been increased accordingly by a factor of 1.3. A final correction was applied to compensate for the fraction of the observable disk occupied by active regions at the time of the observations and which were therefore excluded from the area in which bright points were counted. The data are summarized in Table I.

The variation with time over sunspot cycles 20 and 21 of the corrected bright point counts is shown in Figure 2 where they are compared with the yearly averaged sunspot

TABLE I

Instrumental characteristics and bright point statistics

Date	Relative efficiency at 44 Å	Exposure (s)	$N_{\text{meas.}}$	Active region correction	$N_{\text{corrected}}$
16 Nov., 1979	0.433	8.94	9	1.16	13.6 ± 3.5
13 Feb., 1981	1.233	2.84	7	1.27	11.6 ± 3.4

number. The new data provide additional support to our previous conclusion that the temporal variation of large and small scale flux emergence is out-of-phase. Both sets of measurements have been normalized to their greatest values which occur for sunspots at the maximum of cycle 21 and for bright points at the minimum between the two cycles. It is possible that this presentation overemphasizes the single peak in the bright point data and the absolute amplitude of the bright point curve should be viewed with this in mind since we do not yet know whether the magnitude of the peak is typical of bright point behavior.

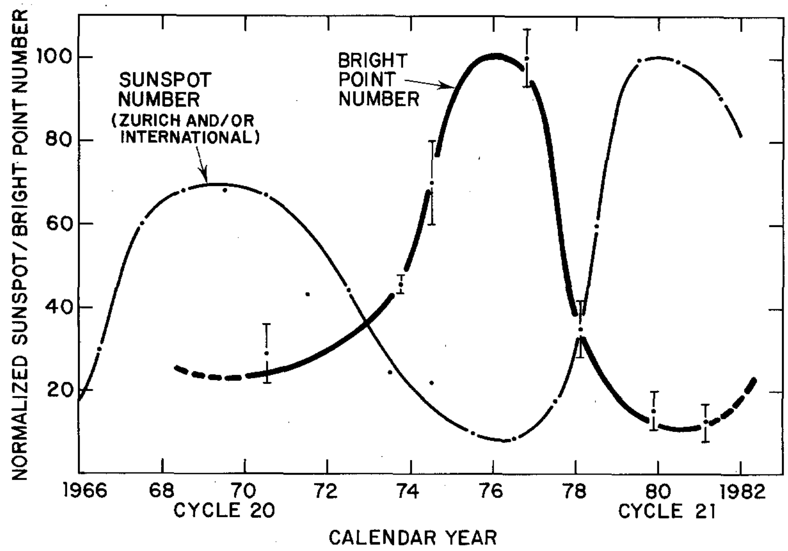

Fig. 2. Variation of the number of X-ray bright points over sunspot cycles 20 and 21.

To test for interdependence between these indicators of large and small scale flux emergence we have compared the corrected bright point counts with the weekly average sunspot number, centered on the day of the bright point observation (Figure 3). A weekly sunspot average was used to provide a measure of global, rather than local activity. The data fit a power law of the form

$$N_{\text{XBP}} = 421.1 N_{\text{SS}}^{-0.662} .$$

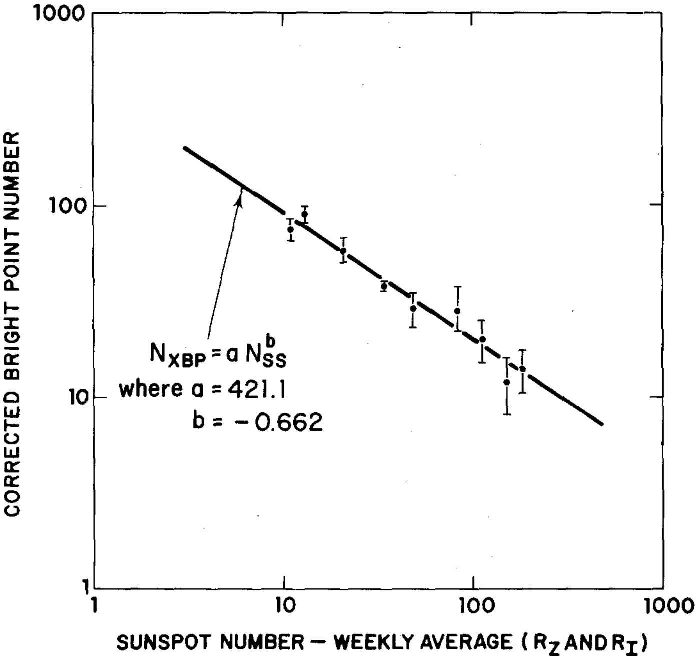

Fig. 3. The dependence of the number of bright points on the weekly average sunspot number.

The reduced χ^2 for the fitted curve is 0.9 and $P(\chi^2)$ is 0.5 indicating an acceptable fit to the data. The fact that the data points are from two sunspot cycles suggest that this relation could be used successfully as a first order predictor of future bright point behavior.

The anticorrelation of the small and large-scale components of the emerging flux spectrum has been interpreted as evidence of a constant pattern of flux emergence over a solar cycle (Golub *et al.*, 1979). This hypothesis has been questioned (Bonnet, 1981) in light of the result of Howard and LaBonte (1981) who find that considerably more flux is emerging during cycle 21, than emerged during cycle 20. However, the constant flux hypothesis was based on the observations over a single cycle, for which the result is still valid. It did not exclude inter-cycle variations in the total flux emergence. However, bright point data now exist from the maximum phase of two cycles. The comparison of these data show that the bright point minimum at the maximum of cycle 21 falls approximately a factor of 2 below the value at the previous maximum. Interpretation of this result in terms of the power law relationship suggests that the higher level of small scale flux at the cycle 20 maximum is compensating for the lower level of large scale flux and vice versa at the maximum of cycle 21.

The implication of this result is that the amplitude of the bright point maximum at the next solar minimum will depend more on the depth of the sunspot minimum than on the difference in the total flux between cycle 20 and 21. Since the 1976 minimum was not deep by historical standards, the observed numbers being over twice the mean of cycles 8–20, the possibility exists for even more dramatic XBP increases at future solar minima.

Finally, many aspects of the behavior of XBP remain enigmatic. The reason for the lack of correspondence, for instance, between the temporal behavior of bright points and ephemeral regions, which do not appear to show the dramatic out-of-phase variation with sunspots (Martin and Harvey, 1979), is still not known. All studies have shown that ephemeral regions are more numerous than bright points but no study has yet elucidated the particular characteristics which distinguish the two phenomena. We support the conclusion of Tang *et al.* (1983) that joint simultaneous, high spatial resolution, observations (soft X-ray and magnetograms) of several days duration are necessary to resolve this problem and suggest that the observation period provided by a space shuttle flight, scheduled late in the declining phase of the current cycle, would be ideal for this test.

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