

## THE RELATIONSHIP BETWEEN X-RAY RADIANCE AND MAGNETIC FLUX

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Received 2002 May 18; accepted 2003 August 7

### ABSTRACT

We use soft X-ray and magnetic field observations of the Sun (quiet Sun, X-ray bright points, active regions, and integrated solar disk) and active stars (dwarf and pre-main-sequence) to study the relationship between total unsigned magnetic flux,  $\Phi$ , and X-ray spectral radiance,  $L_X$ . We find that  $\Phi$  and  $L_X$  exhibit a very nearly linear relationship over 12 orders of magnitude, albeit with significant levels of scatter. This suggests a universal relationship between magnetic flux and the power dissipated through coronal heating. If the relationship can be assumed linear, it is consistent with an average volumetric heating rate  $\bar{Q} \sim \bar{B}/L$ , where  $\bar{B}$  is the average field strength along a closed field line and  $L$  is its length between footpoints. The  $\Phi$ - $L_X$  relationship also indicates that X-rays provide a useful proxy for the magnetic flux on stars when magnetic measurements are unavailable.

*Subject headings:* stars: coronae — stars: magnetic fields — Sun: corona — Sun: magnetic fields — Sun: X-rays, gamma rays

### 1. INTRODUCTION

What heats the corona on the Sun and other active stars? Different mechanisms of coronal heating has been proposed (for reviews, see Ulmschneider, Priest, & Rosner 1991; Fisher et al. 1998; Priest et al. 2000; Mandrini, Démoulin, & Klimchuk 2000), but the exact mechanism(s) remains unknown. A glance at an X-ray image of the Sun, along with a side-by-side full-disk magnetogram, leaves little doubt that magnetic fields must play the crucial role. X-ray emission is strongest between the poles of bipolar active regions, where the magnetic field is very strong, and is much fainter in the quiet Sun, where the magnetic field is weak. Tiny “X-ray bright points” have been shown to coincide with tiny magnetic bipoles. In spite of this observed qualitative connection, relatively little is known about the *quantitative* connection between magnetic fields and the amount of heat dissipated in the corona. A quantitative observational connection between energy dissipation and the magnetic field must be established before any coronal heating theory can be tested. The Sun contains magnetic structures on many different size scales: how does coronal energy dissipation depend on these size scales? Is there a different relationship between magnetic field and coronal heating in active regions versus that in the quiet Sun? How about the relationship between magnetic field in active stars versus their X-ray output?

Most of the previous studies on the subject of coronal heating were limited to a particular solar/stellar object, e.g., dwarf stars (Saar & Schrijver 1987; Schrijver et al. 1989), active regions and dwarf stars (Fisher et al. 1998), solar

active regions (Mandrini et al. 2000; Yashiro & Shibata 2001), and the quiet Sun (Wolfson et al. 2000). Although different authors derived different power-law dependences, considered collectively, their results suggest the existence of a “universal” relationship between total unsigned magnetic flux and X-ray spectral radiance.

The aim of this paper is to show that all closed magnetic field structures appear to obey a universal observational relationship between magnetic flux and the energy radiated in X-rays, and that this relationship is linear or nearly linear over 12 orders of magnitude (see Fig. 1). While there are significant fluctuations about this relationship, which are described in the paper, our work demonstrates that there is also a simple, overall observational law that any coronal heating theory must explain: the X-ray output of closed field structures is nearly linearly proportional to the unsigned magnetic flux that connects them. This discovery clearly and quantitatively links X-ray luminosity to the creation of a hot corona by magnetic fields and suggests that X-ray measurements are a reasonable proxy for the magnetic flux when magnetic measurements are unavailable.

### 2. THE DATA SETS

In the following discussion, we use the term “spectral radiance” instead of “luminosity,” since both solar and stellar X-ray measurements represent the flux integrated over a limited energy range only.

#### 2.1. *Quiet Sun*

We use full-disk images ( $4''95 \text{ pixel}^{-1}$ ) from the *Yohkoh* soft X-ray telescope (SXT; Tsuneta et al. 1991) and longitudinal daily magnetograms ( $1''14 \text{ pixel}^{-1}$ ) from the National Solar Observatory/Kitt Peak (NSO/KP; Jones et al. 1992) to compute total X-ray and magnetic fluxes for a quiet-Sun area  $4^\circ \times 4^\circ$  in size at the heliographic center (N00° W00°). To limit the effects of X-ray radiation scattered to quiet-Sun areas from distant active regions (Pevtsov & Acton 2001), we restrict this data set to 1995 January 1–1997 December 27 (near minimum of solar activity). For each day, we

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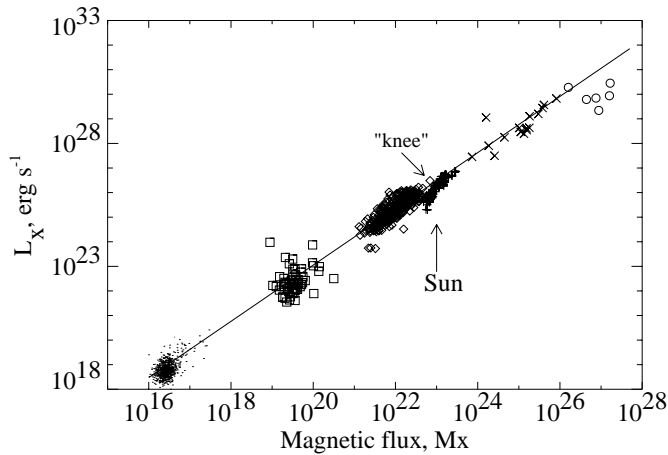


FIG. 1.—X-ray spectral radiance  $L_X$  vs. total unsigned magnetic flux for solar and stellar objects. *Dots*: Quiet Sun. *Squares*: X-ray bright points. *Diamonds*: Solar active regions. *Pluses*: Solar disk averages. *Crosses*: G, K, and M dwarfs. *Circles*: T Tauri stars. *Solid line*: Power-law approximation  $L_X \propto \Phi^{1.15}$  of combined data set.

identified pairs of images observed in two different filters, Al.1 and AlMg, within 600 s of each other. The median number of pairs is 16 with a maximum of 55 for a given day. The Al.1/AlMg filter ratio is used to compute coronal plasma temperatures. We convert X-ray emission into spectral radiance by integrating a thermal spectrum over the 2.8–36.6 Å (0.3–4.4 keV) wavelength range, with the limits corresponding to 1% of peak sensitivity through the Al.1 filter at *Yohkoh* launch. For this and subsequent radiance computations, we employ the spectral models of Mewe, Gronenschild, & van den Oord (1985) and Mewe, Lemen, & van den Oord (1986). The solar coronal abundances are adapted from Meyer (1985). Modeling of the SXT response to a multithermal coronal plasma has indicated that spectral radiance for the SXT passband derived in this way, barring unknown systematic errors, is accurate to about 10% (Acton, Weston, & Bruner 1999). The SXT fluxes were averaged over a given day and interpolated to magnetogram dates. There are 775 data points in this data set.

### 2.2. X-Ray Bright Points

Longcope et al. (2001) analyzed 285 X-ray bright points (XBPs) selected using the Extreme Ultraviolet Imaging Telescope (EIT; Delaboudiniere et al. 1995) and the Michelson Doppler Imager (MDI; Scherrer et al. 1995) observations. For each XBP, they estimated the temperature,  $T$ , and emission measure, EM, using the ratio of EUV fluxes in two (171 and 195 Å) spectral lines. The photospheric magnetic fluxes of associated bipoles were derived using MDI longitudinal magnetograms. To achieve spectral consistency, we use *Yohkoh* SXT data to measure soft X-ray fluxes for 59 of the XBPs analyzed by Longcope et al. (2001), for which reliable correspondence to SXT measurements is possible. The SXT observations have been converted into spectral radiance using temperatures from the EIT measurements of Longcope et al. (2001) rather than temperatures from the SXT filter ratios. Although the results from the two methods are within a factor of 3 on average, there is substantially less scatter using the EIT temperatures. The SXT filter-ratio technique has relatively large

experimental uncertainties for faint, cool, coronal plasmas. Typical XBP temperatures are  $T \sim 1.6$  MK.

### 2.3. Solar Active Regions

Fisher et al. (1998) used 333 vector magnetograms of solar active regions observed with the Haleakala Stokes Polarimeter (Mickey 1985) and cotemporal SXT images to compute the total unsigned magnetic flux and total X-ray radiance averaged over entire active region areas. The magnetic flux was determined using vertical (with respect to the solar surface) magnetic field. In this paper, the SXT count rates were converted into spectral radiance by assuming a coronal temperature of 3 MK and integrating a thermal spectrum over 2.8 and 36.6 Å, as described earlier (Fisher et al. used a 1–300 Å integration range).

The  $L_X$  values from Fisher et al. (1998) were reduced by a factor of 4 to correct for an incorrect conversion of *Yohkoh* half-resolution images to full resolution in Fisher et al. (1998). This does not affect any of the correlation studies reported in Fisher et al. (1998).

### 2.4. Solar Disk Averages

We compute the total X-ray radiance and unsigned magnetic flux averaged over the visible solar hemisphere for the period from 1991 November 11–2001 December 15. Magnetic fluxes are computed using NSO/KP daily magnetograms. The daily averaged X-ray fluxes are computed using *Yohkoh* SXL (soft X-ray histogram log files, histograms of full-disk composite images). The coronal temperatures have been derived using the ratio of two SXT filters, and the conversion between the instrumental and physical units has been done using the same approach as for the quiet Sun. Typical solar X-ray disk temperatures are  $T \sim 2.5$  MK. To improve the signal-to-noise ratio, we excluded all pixels in the SXT frame beyond 1.1 solar radii. Furthermore, since some X-ray radiation is associated with the magnetic field at/behind the solar limb, we compute solar rotation (27.2375 days) averages of the magnetic and X-ray fluxes. The data set covers 127 solar rotations beginning at Carrington rotation number 1849.

### 2.5. Dwarfs and T Tauri Stars

Fisher et al. (1998) computed X-ray radiance and total magnetic flux of 16 dwarf stars (types G, K, and M) using X-ray surface flux, magnetic field strength, and magnetic filling factor published by Saar (1996). The magnetic flux was computed from the field strength and the filling factor by multiplying these two parameters by estimated surface area of each star. The X-ray spectral radiance was computed in the same way by multiplying the surface flux density by estimated stellar surface area. The X-ray data are composites of *ROSAT* (0.1–2.4 keV energy range), *Einstein Observatory* (0.2–4.5 keV), and *EXOSAT* (0.04–4.5 keV) observations. Thus, the stellar and solar X-ray observations cover approximately the same energy range. A similar approach has been applied to the T Tauri stars observed by Johns-Krull & Valenti (2000; BP Tau, Hubble 4, and T Tau) and Johns-Krull et al. (2000; DF Tau, TW Hya, and DK Tau). X-ray radiances for these stars are adopted from Walter & Kuhi (1981; DF Tau), Webb et al. (1999; TW Hya), and Neuhaeuser et al. (1995; BP Tau, DK Tau, Hubble 4, and T Tau).

3. ANALYSIS AND DISCUSSION

Table 1 gives the coefficients for each subset, fitted by  $L_X \propto \Phi^p$  (linear least-squares fit to logarithms) as well as the corresponding Spearmans rank correlation coefficients,  $r_s$ , and two-sided significance of its deviation from zero.

For comparison we also show  $p$  and the corresponding errors computed using bootstrap procedure (Press et al. 1992). Except for quiet-Sun data, the power-law indices derived using least-squares and bootstrap procedures are in good agreement. The bootstrap procedure, however, is applicable to an “identically distributed” data set (i.e., not “clusters” of data points), which is clearly not the case for quiet-Sun data.

With one exception (T Tauri), all objects show a statistically significant correlation between X-ray and magnetic flux. Deviation of five T Tauri stars from general  $L_X$ - $\Phi$  dependence might indicate, e.g., saturation of coronal heating on these stars, which appear completely covered by strong photospheric fields (Johns-Krull & Valenti 2000). However, given the limited sample, we cannot exclude other possible explanations, e.g., noise/selection effects or X-ray absorption in the wind of the classical T Tauri stars (5 of 6 are classical stars; see Walter & Kuhi 1981).

The power-law indices given in Table 1 (cols. [2] and [5]) show significant variation between different subsets. The errors (one standard deviation) are much smaller than the variations. Below we discuss some individual subsets and show that they may be affected by other factors that will significantly increase the uncertainties in  $p$ . Much larger uncertainties imply that individual subsets may or may not extrapolate into other groups and that, in some cases, only subset averages are important in revealing a global trend.

3.1. Solar Disk Averages

The power-law index for the full-disk points (considered by themselves) is about 2, and thus is higher than corresponding values for the active regions and dwarf stars. The power-law index  $p$  will be lower if we account for a difference in X-ray radiance between unipolar fields and areas of mixed polarity. The integrated magnetic flux of unipolar areas (coronal holes) may be comparable with mixed polarity areas of the quiet Sun but have much lower X-ray flux. Harvey, Sheeley, & Harvey (1982) estimated that fluxes from a low-latitude coronal hole is  $(2-5) \times 10^{21}$  Mx during

solar minimum and  $10^{22}$  Mx during solar maximum. From the same study, the flux of a polar hole is  $3 \times 10^{22}$  Mx (minimum) and  $10^{22}$  Mx (maximum), respectively. During a period in 1979 (during the rise phase of a solar cycle) the magnetic flux from the recurrent coronal holes was about  $(1-2) \times 10^{22}$  Mx and accounted for more than 80% of the Sun’s magnetic flux (Harvey et al. 1982). On the other hand, the X-ray flux from coronal holes is almost below the detection level of the *Yohkoh* SXT. This suggests that we might find a change in the power-law index if we attempt to subtract an estimate for the magnetic flux in coronal holes, namely,  $2 \times 10^{22}$  Mx. Doing this decreases the power-law index from 2 to 1.61.

The  $L_X$ - $\Phi$  dependence for full-disk averages shows a change in power-law index, i.e., strong magnetic and X-ray fluxes have a power-law index close to unity, while the weak fluxes exhibit much higher  $p \simeq 2$ . A similar “knee” in the  $L_X$ - $\Phi$  dependence was recently reported by Benevolenskaya et al. (2002). One can see this “knee” as further indication that the presence of the coronal holes in periods of low sunspot activity may distort the correlation between total magnetic and X-ray fluxes. However, the change in slope (“knee”) might have some instrumental component. Over a period of years beginning in late 1992, different sections of the SXT entrance filters failed, increasing the response of the telescope at long wavelengths (i.e., lower temperatures). Prior to the first SXT filter failure (1992 November 13) the power-law index  $p = 1.62 \pm 0.15$ . After 1998 January 24 (last failure),  $p = 2.22 \pm 0.15$ . The level of solar activity was somewhat similar in these two periods, so the change in power-law index might be due to a change in the instrumental response. On the other hand, the “knee” in the  $L_X$ - $\Phi$  dependence is present in the data from 1992 November 13–1995 August 16, when the SXT filter state was the same. Thus, we believe that while the variation in the SXT response may affect the  $L_X$ - $\Phi$  dependence, it does not play a dominant role.

We also note that the locus of these full-disk averages is wholly consistent with extrapolating the main-sequence dwarfs ( $p = 0.98$ ) to the relatively low activity level of the Sun as a star. These late-type dwarf stars, as well as some T Tauri stars, are also in good agreement with solar active regions and solar disk averages, which may indicate that the same mechanism(s) that operate on the Sun also heat the coronae of active stars.

TABLE 1  
POWER-LAW INDICES ( $L_X \propto \Phi^p$ ), SPEARMANS RANK CORRELATION COEFFICIENT ( $r_s$ ), AND TWO-SIDED SIGNIFICANCE ( $s$ ) OF ITS DEVIATION FROM ZERO

Object (1)	$p$ (2)	$r_s$ (3)	$s$ (4)	$p_{\text{bootstrap}}$ (5)	$p_{\text{real}}$ (6)
Quiet Sun.....	$0.93 \pm 0.06$	0.31	0.00	$0.67 \pm 0.08$	$1.06 \pm 0.31$
Quiet Sun, 27 days avg. <sup>a</sup> .....	$1.84 \pm 0.26$	0.72	0.00	$1.82 \pm 0.34$	$1.26 \pm 0.43$
XBPs <sup>b</sup> .....	$0.89 \pm 0.19$	0.48	0.00	$0.87 \pm 0.24$	...
Solar ARs.....	$1.19 \pm 0.04$	0.83	0.00	$1.20 \pm 0.04$	...
Sun.....	$2.02 \pm 0.07$	0.95	0.00	$2.10 \pm 0.11$	$1.78 \pm 0.83$
Sun-CH <sup>c</sup> .....	$1.61 \pm 0.05$	0.95	0.00	$1.67 \pm 0.08$	...
Dwarfs.....	$0.98 \pm 0.19$	0.83	0.00	$1.17 \pm 0.27$	...
T-Tauri.....	$-0.08 \pm 0.51$	0.26	0.62	$-0.10 \pm 0.88$	...
All data.....	$1.15 \pm 0.00$	0.85	0.00	$1.10 \pm 0.01$	$1.13 \pm 0.05$

<sup>a</sup> Quiet Sun, 27.2375 days averaged.

<sup>b</sup> Excluding seven points that significantly deviate from general dependence.

<sup>c</sup> Sun visible hemisphere with (estimated) coronal holes magnetic flux subtracted.

### 3.2. Quiet Sun

Pevtsov & Acton (2001) studied the correlation between magnetic and X-ray flux in three quiet-Sun areas  $4^\circ \times 4^\circ$  in size centered at N00° W00°, S50°, W00°, and N50°, W00°. They found that  $L_X$  and  $\Phi$  are weakly correlated and suggested that enhanced X-ray emission in quiet-Sun areas may be due to additional energy deposited from the large-scale relaxation process in the solar corona triggered by the evolution of distant active regions. In addition, the presence of the coronal canopy (e.g., transequatorial loops, active region expansion with height) might distort the  $L_X$ - $\Phi$  correlation in some quiet-Sun areas. Thus, one can question the use of quiet-Sun radiances in the current study. Recently, Aschwanden et al. (2002) discussed the contribution of two different mechanisms—active region magnetic loops and network nanoflares—to the heating of the quiet-Sun corona. They found that the network component contributes a constant flux of  $\sim 1$ – $2$  data numbers (DN)  $s^{-1} \text{ pixel}^{-1}$  (Yohkoh SXT), which is independent of the presence of active regions. We believe that daily averages of  $L_X$  and  $\Phi$  significantly reduce effects of the coronal canopy and large-scale relaxation in the quiet-Sun data used here, and hence, better represent local magnetic field and X-ray radiance. To decrease the influence of active region heating and the coronal canopy, we restrict the quiet-Sun data set to a 3 yr period near solar minimum (1996). With all these precautions, we believe that we measure the true (“baseline”) emission of the quiet-Sun corona observed by Aschwanden et al. (2002). Averaging quiet-Sun X-ray and magnetic fluxes over a solar rotation (27.2375 days) significantly increases the correlation between  $L_X$  and  $\Phi$  (Table 1). The solar rotation averages of quiet-Sun fluxes (not plotted) follow the same general dependence, although the power-law index is quite different from the daily quiet-Sun averages.

Like the full-disk averages, the quiet-Sun data also exhibit a change in the power-law index with SXT filter failures. For example, solar rotation-averaged (nonaveraged) quiet-Sun data obtained before 1995 August 16 are fitted by  $p = 1.20 \pm 0.62$  ( $p = 1.17 \pm 0.10$ ). For the next two periods of fixed filter configuration (1995 August 16–1996 August 24 and 1996 August 24–1998 January 24)  $p = 0.83 \pm 0.44$  ( $p = 0.71 \pm 0.09$ ) and  $p = 1.85 \pm 0.41$  ( $p = 0.70 \pm 0.09$ ).

### 3.3. Estimating More Realistic Uncertainties

The uncertainties of individual power-law indices shown in Table 1 (col. [2]) are based on statistical properties of each subset and may not correctly represent nonstatistical errors due to, e.g., a change in instrument response or physical conditions in solar atmosphere. To assess a more realistic uncertainty in  $p$  (shown as  $p_{\text{real}}$  in col. [6] of Table 1), we use the following approach. First, we recall that the data observed during periods of different SXT filter configurations may follow a different power-law dependence. Second, a  $p$  coefficient may change when one subtracts an estimated flux of coronal holes (full-disk solar data). For quiet-Sun data, we also computed  $p$  excluding points with very weak magnetic flux (i.e.,  $\Phi < 3 \times 10^{16} \text{ Mx}$ , which corresponds to a random noise level of  $\sim 5 \text{ G pixel}^{-1}$  of a typical full-disk NSO/KP magnetogram). By averaging the  $p$  indices for the same object computed under various constraints, we derive a more realistic estimate of possible uncertainties in  $p$ . The  $p$  coefficients computed that way are in agreement with  $p$

computed by other methods, but the uncertainties are significantly larger.

Finally,  $p_{\text{real}}$  for all six data sets was computed by dividing the data into groups of two, three, and four subsets (in all possible combinations). The power-law index fitted to different groups varies from 0.97 to 1.22, with average  $p = 1.13 \pm 0.05$ .

## 4. CONCLUSIONS

Figure 1 shows the relationship between total unsigned magnetic flux and X-ray spectral radiance for all 6 data sets.<sup>7</sup> Considered together, the combined data reveal a single power-law relation between integrated magnetic flux and X-ray radiance with  $L_X \propto \Phi^{1.13 \pm 0.05}$ . Fisher et al. (1998) showed that their data follow the same functional dependency ( $L_X \propto \Phi^{1.19}$ ) as the Alfvén wave heating model and the “minimum current corona” model, although the heating rate in the Alfvén wave heating model may be insufficient. Our data are fitted by  $L_X \propto \Phi^p$  with  $p = 1.13 \pm 0.05$ , in agreement with Fisher et al., and hence support their constraints on possible heating mechanisms.

The left side of Figure 1 is comprised of spatially resolved objects (i.e., active regions, X-ray bright points, and quiet-Sun areas). On the right side are unresolved surfaces of stars. The fact that the integrated stellar coronae follow the same trend as the resolved solar objects suggests that the stellar coronae are heated by structures such as active regions that may be larger in size but similar to those on the Sun. The solar features follow the same (within uncertainties)  $L_X$ - $\Phi$  dependence, which, in our opinion, supports a predominance of one heating mechanism in all solar features. However, we cannot exclude a possibility that other mechanisms may still have some contribution to the coronal heating in all these objects. The assumption that stellar coronae are a sum of discrete magnetic objects implies a linear proportionality between  $L_X$  and  $\Phi$ . Schrijver et al. (1989) suggested that a small nonlinearity may be explained as a combination of the magnetic filling factor and the effectiveness of the heating mechanism on the closeness of flux tubes. As noted in the previous section, the individual power-law indices in many cases are probably affected by selection effects and systematic errors: it is only by using the huge dynamic range of the different observations that these systematics fall out. We regard the full data set as the most reliable; despite all the possible complications (coronal holes, canopy effects, etc.) and the difference in power-law indices in individual subsets, the combined data follow one simple relationship. Over a great diversity in spatial scales and magnetic flux densities, the X-ray output of coronal plasma is roughly proportional to the unsigned magnetic flux threading the solar or stellar photosphere. The relationship clearly breaks down in detail within certain unipolar structures, such as sunspot umbrae and coronal holes, but these situations are not dominant when one considers the Sun or a star as a whole. The simple, nearly linear relationship suggests a common heating mechanism, although the level of scatter about that relationship suggests that other magnetic parameters, such as the detailed morphology, also play an important role.

<sup>7</sup> Active regions and the dwarf stars were previously shown by Fisher et al. (1998) in their Fig. 9.

Assuming that the physical relationship between X-ray radiance and magnetic flux is truly linear, we suggest that the average volumetric heating rate  $\bar{Q} \sim \bar{B}/L$ , where  $L$  is the length of the field line separating its photospheric footpoints and  $\bar{B}$  is the average field strength along that field line, is consistent with that relationship. This relationship also appears to be consistent with earlier studies of the heating of individual coronal loops (Porter & Klimchuk 1995). The nearly linear relationship suggests that X-rays will provide a useful proxy for magnetic flux estimates on stars when magnetic data are unavailable.

We thank Peter Sturrock and another anonymous referee for their helpful comments. G. H. F. acknowledges support from the Supporting Research and Technology program of the NASA Sun-Earth Connections Theme, The Sun-Earth Connections Theory Program, the NASA Astrophysics

Theory Program, NSF, and the DoD MURI grant, “Understanding Magnetic Eruptions on the Sun and their Interplanetary Consequences.” He also acknowledges that part of the work was carried out at the Institute for Theoretical Physics at UCSB. The work of L. W. A. was supported through contract NAS8-00119 with NASA Marshall Space Flight Center. C. J.-K. has been supported by NASA through grant NAG5-8098. NSO/Kitt Peak magnetic data used here are produced cooperatively by NSF/NOAO, NASA/GSFC, and NOAA/SEL. *Yohkoh* was a mission of ISAS in Japan. The SXT instrument was a collaboration of the University of Tokyo, the National Astronomical Observatory of Japan, and the Lockheed Martin Solar and Astrophysics Laboratory. The National Solar Observatory (NSO) is operated by the Association of Universities for Research in Astronomy (AURA, Inc.) under cooperative agreement with the National Science Foundation (NSF).

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