GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 5, PAGES 655-658, MARCH 1, 1995

Correlated brightness variations in solar radiative output from the photosphere to the corona

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Abstract. Correlated brightness variations are shown to occur in time series of coronal soft X-rays exclusive of prominent active regions, chromospheric ultraviolet radiation, and the photospheric total solar irradiance corrected for sunspot effects. These temporal correlations suggest that upwardly extending magnetic fields may have a large scale impact on the solar atmosphere in addition to their demonstrable role of generating localized active regions. The correlations have implications for improving and extending solar spectrum variability models.

Introduction

The Sun emits much of its energy at visible wavelengths from near the base of the solar atmosphere, with the spectrum of a blackbody at 5770 K, the approximate solar surface temperature. Radiations at decreasing wavelengths are emitted from increasingly hotter and generally higher regions in the solar atmosphere, and with decreasing flux. For example, soft X-rays are emitted from regions at temperatures over two orders of magnitude higher than at the visible surface, with five orders of magnitude less energy than radiation at visible wavelengths.

Solar activity causes the entire spectrum to vary continuously, potentially influences the Earth's climate, modifies atmospheric ozone and dictates the thermospheric and ionospheric temperature and composition [*National Research Council,* 1994]. The largest percentage changes in solar radiative output generally occur at the shortest wavelengths formed in the hottest solar atmospheric regimes [see, e.g., *Lean*, 1991]. Coronal fluxes (excluding flares) can fluctuate by a factor of ten during the 27-day solar rotation and twice that amount throughout the 11-year activity cycle, whereas chromospheric ultraviolet (UV) radiation varies in the range 10 to 100 percent. Photospheric visible radiation is less variable still, changing only by a few tenths of a percent [*Willson and Hudson*, 1991]. An understanding of the origins of this spectral variability is needed to evaluate present solar terrestrial forcing, reconstruct this forcing in the past, and estimate future limits.

Growth, evolution and decay of local magnetically active regions (sunspots, plages, hot coronal loops) generate solar radiative output changes on all observed time scales by altering the density and temperature structure, and hence brightness, of the solar atmosphere. Compact, dark sunspots are the primary magnetic signatures in the photosphere where the gas pressure is large enough to balance the magnetic field strength. Higher, in the solar chromosphere, the dominant magnetic features are extended, bright plages in which magnetic fluxes are smaller than in sunspots, whereas in the upper solar atmosphere (the corona), gas pressure is reduced so much relative to the magnetic pressure that the magnetic field expands with some field lines forming bright loops and extended magnetic complexes, at times extending over much of the solar disk [see, e.g., *Zirin*, 1988].

Another brightness source, in addition to local magnetically active regions, apparently causes radiative output variations at a comparable level over the 11-year cycle. The nature and origin of this "missing" brightness source is obscure and controversial. It may simply be smaller scale active region remnants that are swept by convective flows to the boundaries of the chromospheric network [*Skumanich et al.*, 1984; *Foukal and Lean*, 1988]. Observational attempts to isolate this "active" network component in visible solar images are suggestive but inconclusive because quantitative analysis of weak, dispersed, small scale features is difficult [*Nishikawa*, 1990; *Foukal et al.*, 1991]. Global mechanisms unrelated to magnetic fields may be occurring instead, such as overall changes in solar diameter or surface temperature [*Kuhn and Libbrecht*, 1991; *Willson and Hudson*, 1991].

Solar monitoring by the Yohkoh spacecraft and the Upper Atmosphere Research Satellite (UARS) provides a unique opportunity to assess simultaneous variations in solar radiative output from widely separated solar atmospheric regimes, with the goal of better defining the brightness sources and their fluctuations. We analyze total irradiance, H I Lyman α spectral irradiance and full-disk soft X-ray images. Total solar irradiance brightness (obtained by removing the sunspot effect from measured total irradiance) has been shown to strongly correlate with mid-photospheric and chromospheric indices and H I Lyman α irradiance during 1981-1989 [*Livingston et al.*, 1988; *Foukal and Lean*, 1990], but the relationships have not been examined in the peak and descending phases of solar cycle 22. Yet to be established and characterized are well-constrained connections between coronal radiative output and either chromospheric or photospheric irradiances.

Spacecraft Monitoring of Solar Radiative Output

Full disk, coronal soft X-ray images (in a spectral band from about 0.3 to 4 nm) are recorded many times per day by the Soft

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Paper number 95GL00114
0094-8534/95/95GL-00114$03.00

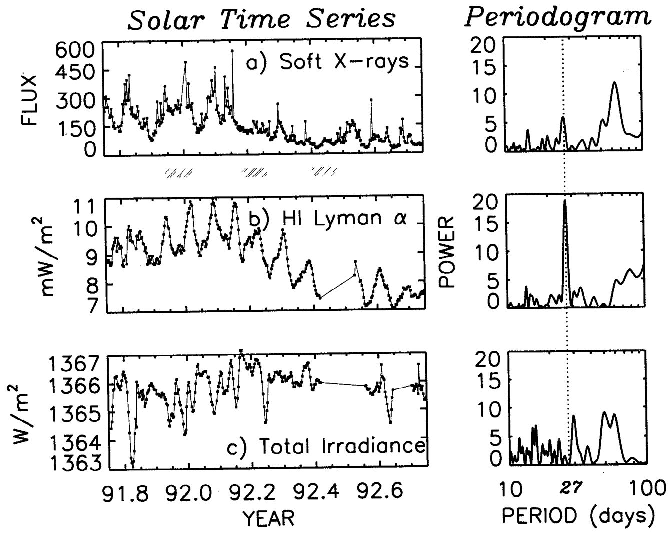

Figure 1. Shown in the left panels are variations in a) the coronal soft X-rays recorded by the Yohkoh SXT, b) the chromospheric ultraviolet H I Lyman α spectral irradiance measured by the UARS/SOLSTICE, and c) the photospheric total solar irradiance measured by ACRIM II, also on the UARS. Shown in the panels on the right are the respective modified periodograms, calculated using 265 points for which data are available simultaneously for the three time series.

X-ray Telescope (SXT), launched on the Japanese Yohkoh satellite in August 1991 [*Acton et al.*, 1992]. Onboard the UARS, launched in September 1991, the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) monitors full disk photospheric and chromospheric UV spectral irradiance at wavelengths from 120 to 430 nm [*Rottman et al.*, 1993; *Woods et al.*, 1993] and the Active Cavity Radiometer Irradiance Monitor (ACRIM II) records the total (spectrally integrated) solar irradiance composed primarily of photospheric radiation. The UARS observations succeed, but without overlap, earlier measurements of solar UV and total irradiance made by the Solar Mesosphere Explorer (SME) [*Rottman*, 1988] and

Table 1. Correlations among disk integrated coronal X-rays, chromospheric Lyman α and photospheric total irradiance. Correlation coefficients above the diagonal were derived using UARS/ACRIM II total irradiance data. The entries below the diagonal were derived using Nimbus 7/ERB total irradiance data over the same period.

Solar irradiance	X-rays	Lyman α	Total irrad.	Total irrad. minus spots	Mod. bright X-rays
X-rays	1	0.75	-0.38	0.51	0.82
Lyman α	0.73	1	-0.08	0.78	0.92
Total irrad.	-0.31	0.22	1	0.3	-0.14
Total irrad. minus spots	0.61	0.84	0.26	1	0.66
Moderately bright X-rays	0.81	0.90	0.23	0.78	1

ACRIM I on the Solar Maximum Mission [*Willson and Hudson*, 1991]. A Nimbus-7 Earth Radiation Budget (ERB) spacecraft radiometer also monitored the total solar irradiance until 1992 [*Hoyt et al.*, 1992].

Markedly different temporal variations occur in the fluxes of soft X-rays, Lyman α and total radiation, as evidenced in Figure 1 by the time series and their modified periodograms [*Horne and Baliunas*, 1986] and the linear cross correlation coefficients in Table 1. Shown in Figure 1 are disk-integrated fluxes from one desaturated (combination of long and short exposures) SXT image per day obtained using a thin Aluminum filter [*Tsuneta et al.*, 1991]. Approximately 65% of the signal arises from coronal radiation at wavelengths between 1 and 2 nm. Lyman α SOLSTICE data are daily mean values of the integrated irradiance of the 121.57 nm line profile [*London et al.*, 1993] and ACRIM II total irradiances are daily mean values of spectrally integrated radiation from the full solar disk. In-flight instrument sensitivity changes are removed from the Lyman α and total irradiance measurements by comparisons with emissions from bright ultraviolet emitting stars and redundant optical channels, respectively. Although no onboard radiometric standards are available for comparison in the case of SXT, there is no evidence of significant degradation in sensitivity after 3 years in orbit. The exposures required to observe the faintest features in the X-ray corona and the brightest parts of flares are unchanged since launch.

Modified periodograms for the one year of unevenly spaced data in Figure 1 were calculated after first subtracting the mean value from each time series and applying a split bell cosine window to taper 20% of the ends of the time interval. According to the false alarm probability, peaks with power greater than 10 have a roughly 1% likelihood of arising from chance alone assuming that the data are pure noise [*Horne and Baliunas*, 1986].

Analysis of Variability Sources

Dissimilarities among the data in Figure 1 occur because separate variability sources affect radiative output in different solar atmospheric regimes. Dark sunspots (where magnetic fields block convective transport to the photosphere) cause pronounced decreases in total irradiance during some solar rotations (e.g., Sept/Oct 1991) [*Hudson et al.*, 1982] whereas during the same rotations enhanced emissions from bright magnetic plages can cause UV flux increases. Enhanced X-rays are emitted from regions on the solar disk associated with both photospheric sunspots and chromospheric plages.

The periodograms in Figure 1 reflect the relative importances of these distinct active region variability sources. The strong 27-day peak in the periodogram of the Lyman α data is a direct result of rotational modulation of active region plage emission [*Lean and Repoff*, 1987]. Significant power at 27 days is absent in both the coronal soft X-ray and photospheric total irradiance data. In the case of total solar irradiance this absence is the result of competing modulation by dark sunspots and bright faculae during solar rotation [*Foukal and Lean*, 1986]. Although difficult to discern in white light images except near the limb of the solar disk, photospheric faculae occur in the vicinity of the Ca K chromospheric plages, and rival sunspots in modulating total solar irradiance.

Isolating the soft X-ray variability sources is more difficult. The distributions of soft X-ray brightnesses on the entire solar disk, shown in Figure 2, demonstrate that the brightest regions are the most variable. However, at certain times during

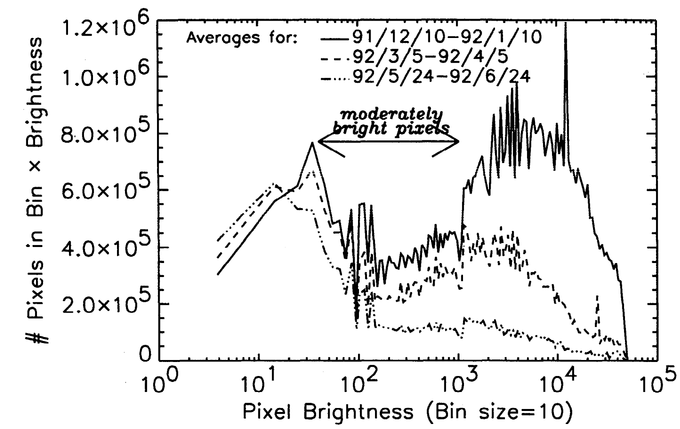

Figure 2. The mean distribution of pixel brightness in soft X-ray solar images for three different levels of solar magnetic activity indicated by the hatched time intervals in Figures 1 and 3. Pixel brightness is measured as photons/sec recorded by the SXT detector.

rotational minima, these brightest pixels (typically associated with very active regions) contribute less to the disk-integrated X-ray signal than do the moderately bright pixels of the "general corona" (identified in Figure 2 with brightnesses in the range 40~1000 photons/sec, measured by SXT's detector) which are more heliocentrically dispersed, and persistent over monthly time scales [*Hara*, 1993].

When the sunspot blocking is removed from the total solar irradiance, the correlation of the residual total irradiance with Lyman α irradiance is 0.78 (increased from -0.08) for ACRIM, and 0.84 (increased from 0.22) for ERB. (The sunspot blocking function was determined from information about sunspot locations and areas obtained from white light solar images [*Foukal*, 1981].) Using a time series obtained as the disk integral of only the moderately bright regime of the X-ray data increases both the correlation with Lyman α, from 0.75 to 0.92, and the correlation with the residual total solar irradiance brightness, from 0.51 to 0.66 for ACRIM (and from 0.61 to 0.78 for ERB).

Similarities among the moderately bright soft X-rays, Lyman α and the residual total irradiance (i.e., minus spots) resulting from the above analysis are evident in Figure 3. Power at 27 days is now significant in each case. Thus, we conclude that removing the contributions of the most pronounced magnetic active region variability sources in total and X-ray solar fluxes (i.e., the dark sunspots and brightest X-rays, respectively) reveals mutually correlated variations in coronal, chromospheric and photospheric brightnesses. This suggests a common brightness source for the variations, connected with the bright magnetic structures seen in Ca K images which are already known to be associated with Lyman α irradiance variability [*Lean and Repoff*, 1987].

Discussion

Correlated chromospheric and photospheric brightness variations are identified that persist into the corona. Whereas photospheric facular "footprints" of chromospheric plages are well known, and provide a physical explanation for mutual chromospheric/photospheric variability, the correlated coronal variations evident in Figure 3 are unexpected, based on observations of the abrupt disappearance of the chromospheric network at the base of the corona [*Reeves*, 1976]. Furthermore, the correlations are not confined to rotational time scales, for which modulation by localized active regions dominates, but persisted during the reorganization of the overall magnetic structure of the Sun around mid 1992 [*White et al.*, 1994], when the level of solar activity dropped significantly as a prelude to the upcoming solar minimum.

That the brightness sources of both total and UV irradiance variations are also responsible for coronal emission variations suggests a magnetic origin. This is true for the local plage regions and the additional brightness component. That it has nevertheless proven difficult to detect and quantify co-spatial fine scale bright features common to the photosphere, chromosphere and corona may signify the presence of unresolved fine structures associated with the large scale magnetic field [see, e.g., *Feldman*, 1983].

Our results demonstrate that the correlation of total solar irradiance brightness and H I Lyman α spectral irradiance previously identified in solar cycle 21 has persisted in cycle 22. We use this relationship to cross-calibrate UARS/ SOLSTICE with the earlier SME UV observations that terminated in 1989, prior to the launch of the UARS. The correlation between nine years of SME Lyman α and Nimbus 7/ERB total irradiance data (corrected for sunspot blocking) predicts a mean Lyman α irradiance of 6.8 mW/m² for October 1991-September 1992 (the time interval shown in Figure 3). Using the ACRIM II data normalized to ACRIM I by overlapping Earth Radiation Budget Experiment observations, the predicted Lyman α irradiance is 5.8 mW/m². These two estimates differ because of differences in the Nimbus 7/ERB and ERBE long term trends [*Lee III et al.*, 1995] but both are significantly less (by 23% and 34%, respectively) than the mean value of 8.8 mW/m² measured for the Lyman α irradiance by SOLSTICE during the same period. The differences between SME and SOLSTICE may therefore be radiometric, rather than

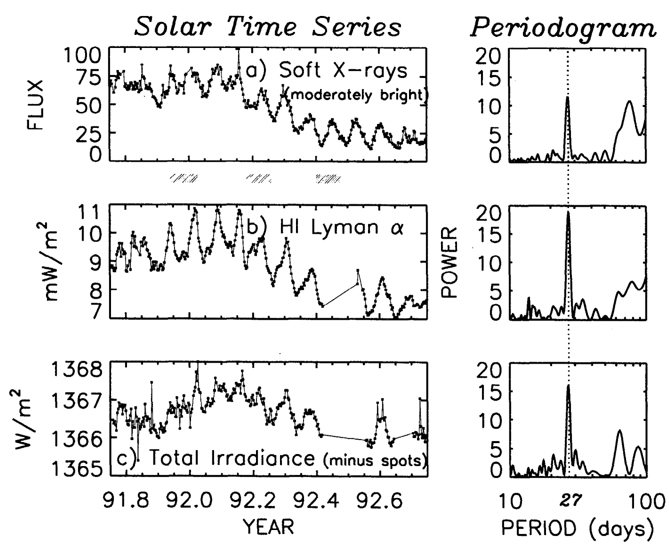

Figure 3. Shown in the left panels are variations in a) the coronal soft X-rays from the moderately bright sources identified in Figure 2, b) the UARS/SOLSTICE chromospheric ultraviolet HI Lyman α spectral irradiance, and c) the photospheric total solar irradiance measured by UARS/ACRIM II, with the sunspot blocking removed according to *Foukal* [1981]. Shown in the right panels are the modified periodograms of the time series on the left.

anomalously high activity in solar cycle 22 [*Hoegy et al.*, 1993].

Having identified correlated brightness variations in radiative output formed throughout the solar atmosphere, we expect that in the future a detailed analysis of Yohkoh and Ca K images and magnetograms will provide new insights, not only to coronal radiative output variations, but for the variability of the entire solar spectrum. This new knowledge will facilitate construction of improved, physics-based solar variability models for use in solar terrestrial research to interpret spacecraft data and reconstruct solar-terrestrial forcings in the absence of direct observations.

Acknowledgments. The SERDP and NASA W-18,410 provided partial support for J.L.L. NASA contract NAS8-37334 with MSFC and Lockheed supported K.T.S. and L.W.A. The SXT experiment is a collaboration of the National Astronomical Observatory of Japan, the Lockheed Palo Alto Research Laboratory and the University of Tokyo. U. Feldman provided helpful comments.

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(Received November 30, 1994: accepted December 15, 1994.)