# Observations of the Sun at Ultraviolet Wavelengths: 1 to 400 nm

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**Abstract**

The solar spectrum peaks in the visible and is well represented as a black-body spectrum with an effective temperature near 6000 K. As we move from visible to ultraviolet wavelengths the radiation originates higher in the solar atmosphere: radiation at 400 nm originates near the base of the solar photosphere, at 200 nm near the top of the photosphere, from 100 to 160 nm from the chromosphere, and less than 100 nm from the transition region and corona. Examining radiation from higher and higher layers of the solar atmosphere, the variation steadily increases from far less than 1% at wavelengths longward of 300 nm, 10's of percent from 100 to 200 nm, and exceeding an order of magnitude at the short EUV and X-ray wavelengths. Such variability is now documented over all time scales: short- to intermediate-term variations, usually associated with the appearance and disappearance of active regions and modulated by the 27-day rotation of the Sun, to the much longer 11-year solar cycle variations.

## 1 Introduction

Solar radiation spans the entire electromagnetic spectrum from the shortest X-rays to long-wavelength radio waves. However, by far the greatest amount of the radiation falls in the visible, and the shape of the solar spectrum is quite similar to a black-body spectrum for an effective temperature near 6000 K, peaking near 500 nm. Figure 1 illustrates the solar spectrum from 200 nm in the ultraviolet to 2 $\mu$m in the near infrared - the integral of this spectrum accounts for roughly 94% of the radiant energy from the Sun. The smooth curve overlying this solar spectrum is the spectrum of a black-body with a temperature of 5770 K (simplified and without limb-darkening effects). The solar spectrum is quite smooth and continuous longward of its peak, but at the shorter wavelengths it is jagged and displays numerous absorption features, both lines and edges. The source of the emission of Figure 1 is diverse, with the visible originating in the lower photosphere. Moving to shorter and shorter wavelengths the emission comes from higher and higher layers of the solar atmosphere. The most comprehensive picture of the solar spectrum comes from the theory of stellar atmospheres, which uses opacity in establishing the shape of the spectrum of a star such as the Sun. The profusion of spectral lines and free-bound absorption edges of neutral metals (e.g., iron and titanium) provide structure to the solar spectrum, especially at wavelengths short of 400 nm.

When the Sun is observed from the ground, roughly half of the radiation has already been absorbed or scattered away by the atmosphere. Ozone is completely effective in removing all radiation short of 300 nm, and longward of about 1 $\mu$m large segments of the spectrum are removed by atmospheric water vapor. These and other absorbers, coupled with clouds and aerosols, are quite variable and preclude any hope of detecting from the ground changes in solar radiation unless the variation is quite large - say on the order of several percent. It is for these reasons that early attempts to establish solar variability were quite unsuccessful, and it was only with the advent of long-duration space missions that the first true measures of solar variability have now been achieved. Measurements from several spacecraft now span almost two complete solar cycles and from these we infer that the total solar irradiance, at least for the two most recent solar cycles, only changes on the order of 0.1%, certainly with some shorter term variations of a few times this value. The reader is referred to the observations that have been reported for the ERB instrument on NIMBUS-7 (Kyle at al., 1993), the ACRIM instruments on SMM and UARS (Willson, 1994), the ERBS instrument on the ERBE satellite (Lee, 1995), the VIRGO instrument on SOHO (Fröhlich, 1994), and several others.

For this discussion we will consider the record of total solar irradiance (TSI) only in the context of its constraint on the spectral measurements at ultraviolet wavelengths. That is, if we consider that the TSI varies by 0.1% we infer that the spectral band short of 400 nm, about 10% of TSI, cannot vary by more than 1% - or it would account for the entirety of the TSI variation. Likewise the band short of 300 nm, about 1% of TSI, cannot vary more than 10%. The following discussion will carefully consider what we presently know about the variation of the Sun in the ultraviolet, and what is yet to be measured and learned.

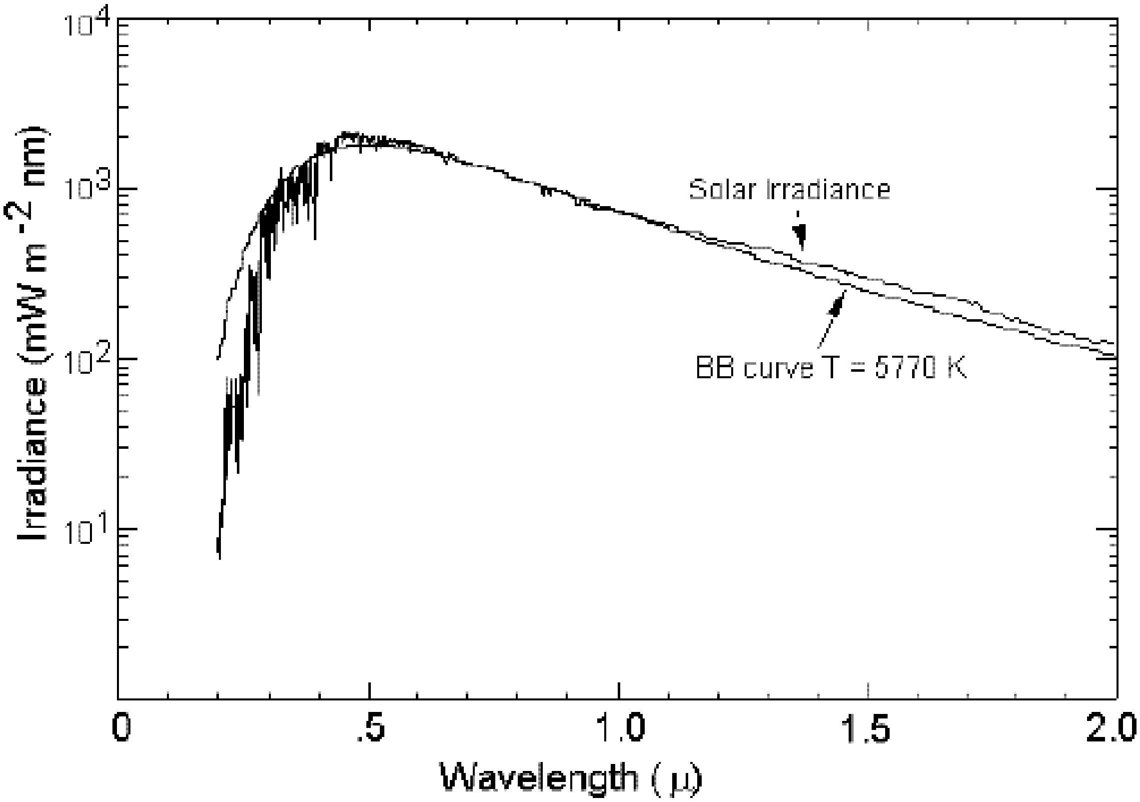


**Figure 1:** The solar irradiance spectrum from 0.2 $\mu$m to 2 $\mu$m. The smooth curve superposed is a black-body spectrum with an effective temperature of 5770 K.

## 2 Observations

The measurement of TSI had to be moved into space for the reason that its variation was much less than 1%, so small that it is masked by atmospheric effects as seen from the ground. Observations of the solar ultraviolet, on the other hand, can only be made from above the atmosphere, and therefore, these measurements were not even possible until the 1950's. In fact, the first twenty or so years of sporadic sounding rocket observations, some with film, some with photoelectric detectors, provide only meager information at a few select wavelengths (see White, 1977). It has only been during the past twenty years, from the peak of solar cycle 21 in 1979, through solar minimum in 1986, and through the entire solar cycle 22 that we now have measurements which piece together to provide a view of the ultraviolet Sun and its variation.

Figure 2 shows the ultraviolet portion of the solar spectrum from 120 to 420 nm that extends the data of Figure 1 (note that $10^9$ mW m$^{-3}$ of Figure 2 corresponds to $10^3$ mW m$^{-2}$ nm$^{-1}$ of Figure 1). This spectrum has been integrated to 1 nm spectral bins (effective resolution of 1 nm) but quite adequately illustrates the structure in the spectrum: the Fraunhofer absorption lines illustrated by the Mg II doublet near 280 nm, the typical absorption edges seen for example at 208 nm due to Al I, and the conversion to an emission line spectrum at the shortest wavelengths - notably Lyman $\alpha$ at 122 nm. In this spectral range we comment on these various features, for they become quite apparent when we examine solar variability discussed in the next section.

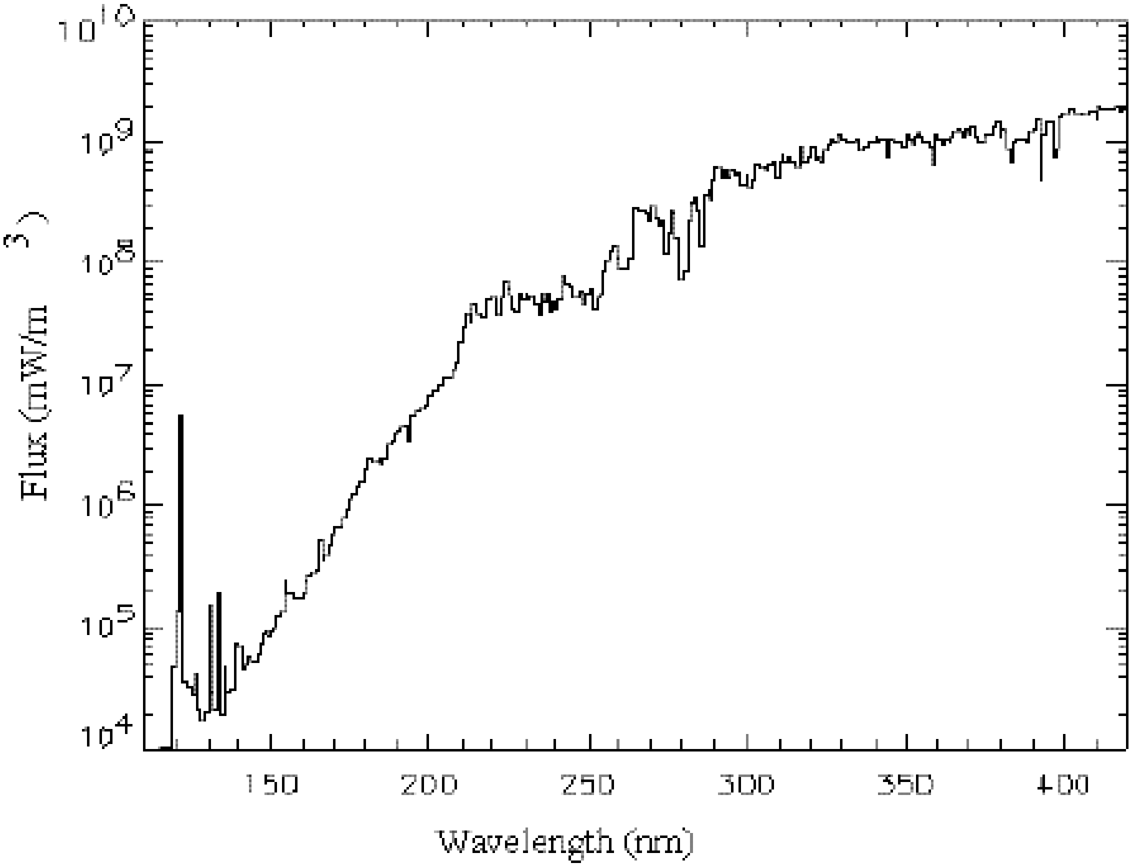


**Figure 2:** The solar ultraviolet irradiance from 120 to 420 nm at 1 nm effective spectral resolution.

The very shortest wavelengths, the extreme ultraviolet and X-rays, are not considered specifically in this discussion. This high-energy portion of the solar spectrum is dominated by emission lines originating in the solar transition region and corona, and as such it is highly variable. In the context of TSI - it is negligible, in the context of the Earth's atmosphere - it is especially important to the thermosphere and ionosphere above 100 km, in the context of stellar connections - it is of special relevance down to the Lyman edge at 91 nm and at the very short wavelengths where the interstellar medium once again becomes transparent. Unfortunately observation of the EUV Sun are quite sparse, especially during the past twenty years. AE-E (Hinteregger et al. 1981) observed the Sun from 1977 to 1981, but other than a few sounding rockets and the short duration San Marco satellite, no further observations have been forthcoming. This gap in the data set and in our knowledge of the Sun will be addressed by the SEE instrument (Woods, et al. 1994) to be flown on the TIMED mission with a launch in the year 2000. The Yohkoh satellite has provided irradiance observations at 4 to 40 Å since mid-1991 (Acton, 1996) and recent SOHO observations will provide limited irradiance measurements from late 1995 forward.

The longer wavelength spectrum of the Sun, in particular the spectral interval 120 to 400 nm, is now quite well studied. A number of instruments have provided, and continue to provide, spectra similar to that shown in Figure 2. Solar Backscatter Ultraviolet Instruments, SBUV, have been flow continuously since late 1978, first on the Nimbus-7 satellite and subsequently on a number of NOAA satellites (Cebula et al. 1994). These instruments operate in the spectral range 160 to 400 nm with a spectral resolution of about 1 nm. The Solar Mesosphere Explorer (SME) operated from 1981 through early 1989 and covered the spectral range 120 to 300 nm with a spectral resolution of 0.75 nm. More recently two instruments have operated on the Upper Atmosphere Research Satellite (UARS) since 1991. These two instruments, the Solar Ultraviolet Spectral Irradiance Monitor, SUSIM (Brueckner, et al. 1993) and the Solar Stellar Irradiance Comparison Experiment, SOLSTICE, (Rottman et al. 1993), have provided continuous coverage in the spectral range 120 to 420 nm with a spectral resolution varying from 0.1 to 1 nm. The GOME instrument on the European ERS-2 spacecraft (ESA, GOME Users Maual, 1995) has been operational since mid-1995, and covers the spectral range 240 nm all the way to 790 nm.

Woods et al. (1996) provide a very detailed comparison and validation of simultaneous observations obtained on two separate occasions by four separate instruments, the two on UARS and a SUSIM and SSBUV instrument flown on the Shuttle. This analysis implies that spectra as shown in Figure 2 are now known to an absolute accuracy (irradiance relative to the SI scale) of 2 to 5% (wavelength dependent with larger uncertainty toward the shorter wavelengths). The reader is referred to the Woods et al. (1996) article for a full discussion and a tabulation of the irradiance values.

# 3 Solar Variability

The present state of our understanding of the solar irradiance in absolute units, that is on a scale related to the SI standard of irradiance, has an uncertainty of approximately 2 to 5%. The reality of this fact is that if we compare two different observations of the Sun, from two different instruments, they may provide an estimate of true solar variability with an uncertainty of roughly 3 to 7%. This may be sufficient, although not altogether desirable, at certain wavelengths where the variation is much larger than these numbers. For example, such a capability would suffice at Lyman $\alpha$ where the solar cycle variation is about a factor of two. But such comparisons would be completely inadequate, providing ambiguous information near 200 nm where the solar cycle variation is only on the order of 10%. Therefore, our inability to calibrate irradiance instruments better than a few percent, limits the usefulness of intercomparing data sets from different instruments. Nevertheless, we have been fortunate in establishing long-term solar variations by using data from single instruments. As long as the observations continue for periods of several years, and as long as there is a credible technique to account for changes in the instrument sensitivity; then the data comparison becomes straightforward. For if we compare data from a single instrument, the ratio of any two measurements causes many terms to cancel - the area of the entrance aperture probably has not changed, the wavelength bandpass of the spectrometer likely has not changed, and so forth. The confidence in the amount of variation attributed to the Sun is related to the time base between the two measurements, and as mentioned above, to our ability to track changes in instrument sensitivity. Since 1978, the handful of instruments described above, ranging from the NIMBUS-7 SBUV to the present day UARS and ERS-2 instruments, have provided precise measurements accurate to perhaps a few tenths of a percent over time bases of two to three weeks, and one to two percent over time bases of several years.

## 3.1 27-day Variations

One of the dominant signals of solar variation is related to the 27-day rotation period of the Sun. As active regions appear and disappear on the solar disk, their occurrence is non-uniform. The resulting irregular distribution provides a striking signal modulated at the rotation period of the Sun. The amplitude of the signal is dependent on the summed strength of the activity on one side of the Sun, opposed by the signal on the other. This implies that in the unlikely occurrence of a near uniform distribution of activity, the 27-day signal could be quite small even for a very active Sun. Likewise, for a very non-uniform distribution - an active hemisphere and a quiet hemisphere could provide a strong 27-day signal even at moderate solar activity.

Figure 3 is a typical variation of the Sun during a 27-day period (i.e., measurements separated by roughly 13 days) shown as a function of wavelength. The ratio is plotted twice, once for the scale at the left and then magnified by a factor of ten for the scale to the right. Notice how details of this curve correspond with the spectral features of Figure 2. All of the strong emission lines at the blue end of the spectrum have much higher variability than their neighboring "continuum." As our attention moves across the aluminum edge at 208 nm, the variation drops by a factor of two. The amplitude of the 27-day variation continues to fall toward longer wavelength, becoming only a small fraction of a percent with the exception of the strong

Fraunhofer lines of Mg II at 280 nm and Ca II at 390 nm. In fact, we notice that longward of about 300 nm the variation becomes negative. That is, the "active" phase is now dimmer than the "inactive" phase. This is reminiscent of measurements of TSI where often the more active Sun is accompanied by large sunspots which block more radiation than can be filled in by the surrounding bright faculae. Thereby, the ratio of the two irradiance values falls below "one," and we see the spectral signature of the "sunspot blocking" phenomenon. It should be noted that the 27-day variation shown in Figure 3 is typical, but by no means standard. Each rotation of the Sun will most likely provide a magnitude, and perhaps a shape, different from that shown in this figure.

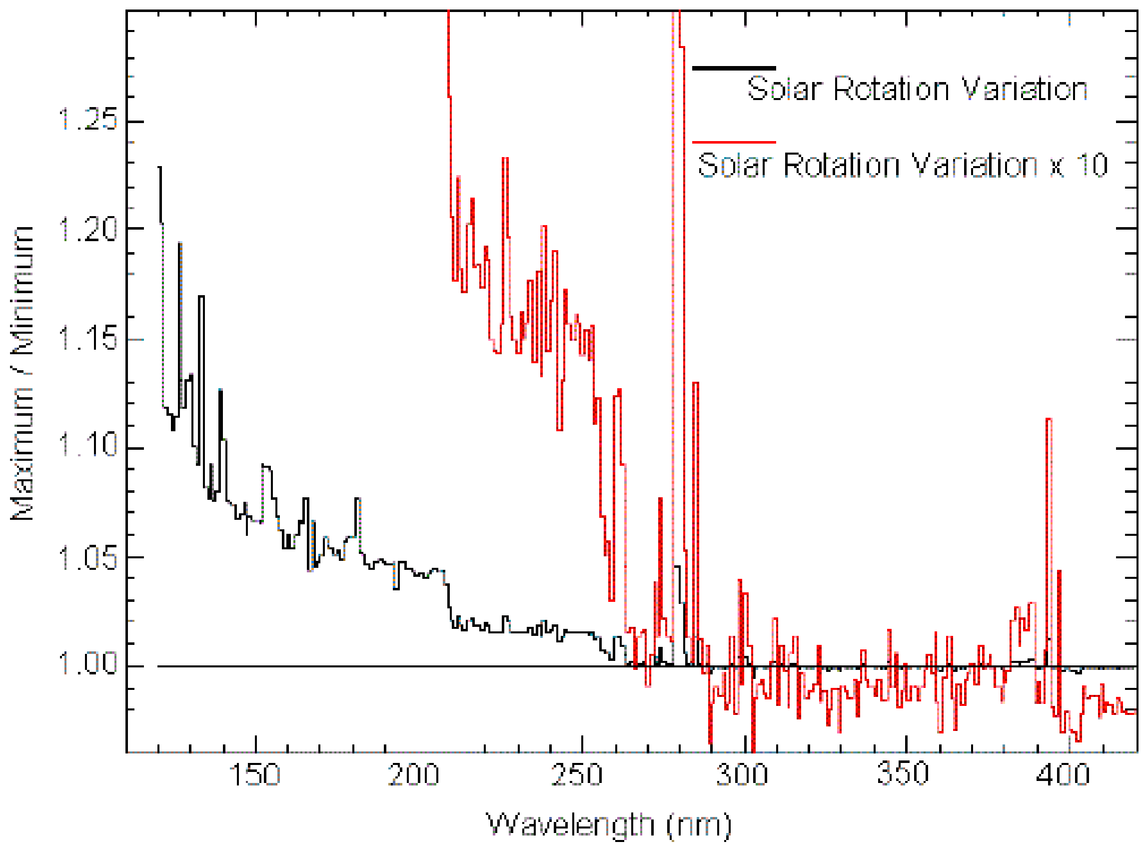


**Figure 3:** The amplitude of a 27-day variation of the Sun shown as a function of wavelength. This curve corresponds to a single rotation period in early 1992. Although this curve is typical of the 27-day modulation of solar radiation, it should not be considered "standard" in either amplitude or shape.

## 3.2 Solar Cycle Variations

As we extend our observations of the Sun over a longer and longer time base, we hope to establish correspondingly longer time scales of solar variability. If a single instrument has been used to make the measurements, we must establish any and all changes in the instrument sensitivity before we can extract from the data the inherent variation in the Sun. The two UARS instruments, SOLSTICE and SUSIM, were both designed with the specific goal of measuring long-term solar variations. SUSIM uses standard lamps as in-flight calibration source; and moreover, it uses redundant lamps and optical channels to confirm all instrument changes. SOLSTICE uses a completely different calibration technique relying on bright blue, early-type stars as in-flight calibration standards. This unique approach relies on the assumption that the stars are very stable (inherent variability of a small fraction of one percent over time periods of thousands of years), and that the ensemble average of twenty or so stars form an even more stable reference standard. The validation paper by Woods et al. (1996) documents the initial comparisons of these two instruments, and additional comparisons are in progress. Both techniques appear to work well, and the six and one half year data record from either, or both instruments will be accurate to better than one percent. The UARS time period spans conditions from near solar maximum in early 1992 through solar minimum in 1996, and now on toward the next solar maximum. Both instruments together with the entire UARS spacecraft are working well, and there is every reason to believe that the mission will continue through the maximum of cycle 23.

Figure 4 provides a preliminary estimate to the solar cycle variation from early 1992 to late 1996. Similar to Figure 3, it is the ratio of the maximum Sun to the minimum Sun, and it is interesting to see the similarity of this curve to the rotational variation of Figure 3. We note the strong variation - as much as a factor of two in Lyman $\alpha$ and in the other strong chromospheric lines short of 140 nm, and generally stronger than the neighboring continuum. The amount of variability steadily decreases toward longer wavelengths where again we see a drop of about a factor of two moving across the aluminum edge at 208 nm. At the present time we feel that these data sets have a precision and relative accuracy (uncertainty in the ratio of two values) limited at one to two percent, and therefore as we move toward longer wavelengths, especially at 250 nm and above, we are becoming limited by the observations. It is encouraging to see the Mg II doublet at 280 nm rising from the noise floor, but as we move on to 300 nm and above the present state-of-the-art is just not up to the task of resolving true solar variability. Both the SUSIM and SOLSTICE Science Teams continue to refine their data processing algorithms, and we are optimistic that in the final analysis the detection limit for solar variability will be at, or slightly better than, the one percent level. This precision and relative accuracy will hopefully be adequate to establish solar variability at wavelengths less than 300 nm. At wavelengths longward of 300 nm it appears that the solar variation will remain hidden below our present detection limits, and will await the next generation of solar irradiance techniques.

### 3.3 Flare Enhancements

Short-term solar variations in particular flares are very dramatic when observed in the ultraviolet, and these transient occurrences have important stellar counterparts. Brekke et al., (1996) discuss an observation of a Class 3B solar flare for which the emitted flux density from the entire solar disk increased by more than an order of magnitude for many of the chromospheric emission lines in the spectral range 120 to 170 nm. Such a flare phenomenon would be easily detected in other stars. For example, if a star is observed in the Si IV line at 139 nm during the impulsive phase (approximately 5 minutes) of a large stellar flare, its brightness may be expected to rise a factor of ten or more.

## 4 Future Observing Programs

We now have a record of the variation of total solar irradiance, and of the variation of its ultraviolet spectral component, over two complete solar cycles. However these observations represent only a snapshot of the long term behavior of the Sun, and it is essential that such measurements be continued. This extended data base will allow us to more fully understand the nature of the Sun and the physically processes underlying its variability. However, the spectral knowledge that we have of solar variability is limited to wavelengths short of 300 nm. In the visible and near infrared we can place upper limits on solar variability, limits set for the most part by observations of total solar irradiance. Since TSI varies only on the order of 0.1%, it is difficult to reconcile spectral changes much different than this value. It is just as unlikely that the spectral character of the variations is "white" and invariant in wavelength. Theories and modeling of solar radiation speak to a structured solar variation, and to address and constrain such theories will require visible and near infrared observations.

The reason that more is presently known about the ultraviolet variability is not that the UV measurements are better, but only that their solar variations are so much larger. Past spectral observations have been up to the task of measuring one to a few percent changes, but they not been able to record long term changes

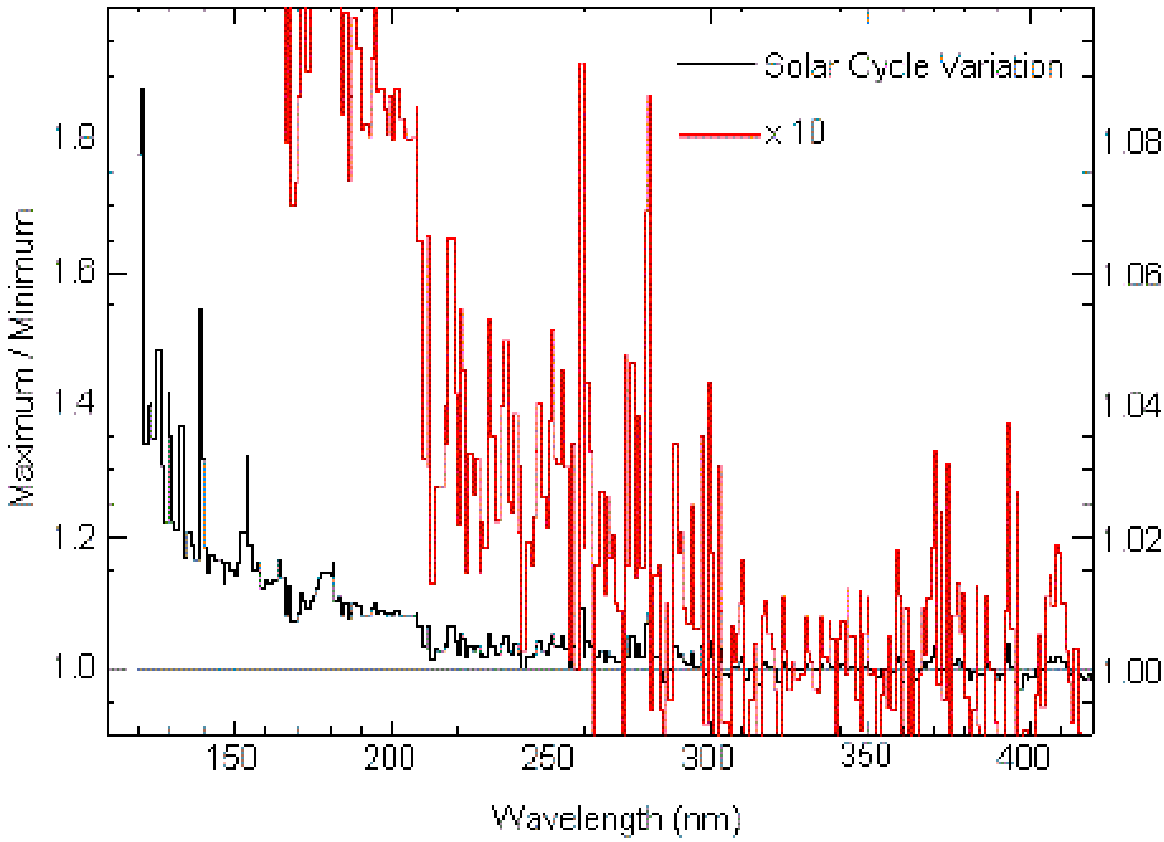


**Figure 4:** The amplitude of solar cycle variation (early 1992 divided by 1996) as a function of wavelength. Estimate of the uncertainty in this ratio is 1 to 2%, and there is presently only an upper limit (<1%) of solar cycle variations at wavelengths longer than about 300 nm.

at the fraction of a percent level. This is the challenge for future observations, and techniques based on super-sensitive electrical substitution radiometers (ESR's) will soon be applied to these observations. The next generation of irradiance instruments should provide the spectral details underlying the envelope of the TSI.

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## Discussion following Gary Rottman's talk

Wade: You didn't discuss much about what goes on between the Lyman edge and 911 Å; is that an instrumental limitation?

Rottman: Yes, it's difficult to make the measurements as you move further and further into the UV. But also, we are allowed to do Ly $\alpha$ with UARS only because of its importance to water vapor in the atmosphere. To go next step, you've got to make convincing arguments about why you need to make these measurements. Now, the solar physics community has ample reason; we would love to do the whole Lyman series, Ly $\beta$ especially. The TIMED SEE instrument (Tom Woods, PI) will do that; the TIMED community recognizes the importance of this spectral range because of their atmospheric interest above 100 km. But this is a constant struggle, trying to justify *why* we need to make these kinds of observations.

Wade: The irony of it is, of course, that *Voyager* has been looking at objects other than the Sun for years, in just that region, although not specifically for variability in solar-like stars.

Rottman: Well, TIMED will do it also, and there are a few rocket flights recently that cover that spectral region, but these provide only snapshots of the Sun, with no reliable synoptic data to establish solar variability.

Ayres: You kind of glossed over the extreme UV, particularly the 10 to 30 nm region. While it is true that this is a very difficult region to observe for most stars, there is a horizon that varies in depth from a few parsecs to tens of parsecs for which it is possible to observe stars, as has been done with EUVE. It's an extremely useful spectral region, because it contains a variety of ionization states, particularly for iron. But I think it's fair to say that our knowledge of the stars from 10 to 30 nm is better than our knowledge of the Sun, because we don't have solar measurements of even moderate spectral resolution in this region. This lack of information for the Sun makes it very difficult to interpret the stellar measurements.

Rottman: There have been infrequent observations in this area, especially back toward the beginning of Cycle 22, but I think they were troubled with their short duration and troubled with calibration problems. It's certainly an area that needs attention, though I don't see any hope for it before the TIMED mission. It is our point of view that to really understand then Sun we will need uninterrupted data sets in all of these wavelengths.

White: The irony of it is, Tom, that TIMED is really driven by the needs of the upper atmosphere folks, and the band you're talking about is important to them. But, we can't get the solar folks in space physics to recognize we need these solar data.

Ayres: And the Harvard spectrometer on SMM, which would have looked at this region in some detail, with fairly good resolution and in time for the solar maximum, was dropped. Gary, let me make one more comment – actually two more comments. One on the X-ray region, and the tremendous dichotomy between solar physics and stellar physics. There are people like Loren Acton who have worked for a long time with the YOHKOH experiment, who see these spectacular changes from solar minimum to maximum, largely because YOHKOH's bandpass is pretty hard compared to that of its stellar counterparts. So as you were saying, as you go to shorter and shorter wavelengths, you see more and more variability across the cycle. It's a factor of 100 in $L_x$ across the cycle in the YOHKOH data. But if you go to the somewhat softer bands that are typically observed with the stellar instruments, like EINSTEIN, or BEPPOSAX, or even AXAF when it goes, you find a variation over the cycle that's more like 5 or 10. So a lot of stellar folks look at the solar community, and they say, what's going on in the Sun that there's this tremendous variation being quoted, yet we don't see anything like this in the solar proxies we have in our stellar data?

I won't even show a viewgraph, at risk of running over my time [laughter] – or of running over your time, actually [laughter], I'd like to make one more comment concerning the absolute accuracy of these missions. I know that with SOLSTICE, you've taken a lot of pains to observe ensembles of hot stars regularly, to track the degradation of the instrument with time. And I know it's very difficult to take an absolute measurement in the laboratory and ensure that it's carried to orbit. But there are stellar targets, like hot white dwarf stars, that are known to be very stable in their luminosity, and very predictable in their energy distributions, that might be useful as radiometric calibrators. They'd essentially give you absolute calibrations, to the extent that you know the distribution. So they might be useful as standards for the solar observations, if one could design an instrument that could observe these very faint objects.

Rottman: Well, it took lot of work to bridge the brightness gap between the Sun and these bright blue stars. To go even further to the stars you're suggesting would require careful consideration. Perhaps you could use HST, and go from those standards to our blue stars. But each time you do a step like this, and transfer the calibration from one data set to another, you introduce at least a 1% error. It doesn't take very long before you're back at our present capability of 3 to 5%.

Wade: Well, clearly the problem is that the Sun is too bright, so you ought to send your laboratory to Pluto and observe from there [laughter].

Rottman: You know, the more I work in this area, the more it seems phenomenal to me that the Sun is as stable as it is. When you talk about a tenth of a percent over time periods of five years – we can't do that in the laboratory; we cannot make standard sources that stable. So from many standpoints, the Sun is a more reliable source than any other we have, so *maybe* [laughter] we ought to be using the Sun to calibrate our lab standards!