USING THE BOUNDARY CONDITIONS OF SUNSPOTS AS A TECHNIQUE FOR MONITORING SOLAR LUMINOSITY VARIATIONS

by

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Abstract. Recent satellite observations of the solar total irradiance confirm that it is varying with at least on the 11 year time scale. Both blocking by sunspots and re-emission by faculae are components in this variation, but changes in the temperature of the solar photosphere may also be a contributing component. The satellite observations are as yet of insufficient length to answer the question of whether the sun is varying in luminosity on time scales longer than the 11 year sunspot cycle. This paper examines proxy methods of re-constructing these longer term luminosity variations, with an examination of secular changes in sunspot structure as one tool. Solar rotation changes and solar diameter changes are other parameters which may reveal information about solar luminosity variations. All three variables give remarkably similar conclusions. Over the last century the Earth's surface temperatures and the structure of sunspots have varied in a parallel manner. It is hypothesized that sunspots are embedded in a convective medium which itself is varying over long time periods. These variations in convective strength alter the boundary conditions on sunspots and hence cause their structure to vary. Simultaneous with the variations in convective strength, the solar luminosity will vary as well which, in turn, leads to changes in climate of the Earth. Variations in solar diameter and solar rotation support the hypothesis that solar luminosity has varied over the last century and reached a peak around 1925 to 1935. This evidence is reviewed along with a possible model of why sunspot structure may provide a good proxy measure of solar luminosity changes.

". . . . .the whole surface [of the sun] seemed to be a flat [i.e., penumbra] of immense extent." William Herschel (Feb. 12, 1800)

"I am much inclined now to believe that openings[sunspots], ridges[faculae], nodules, and mottlings[granules] may assist us possibly to expect a copious emission of heat, and therefore mild seasons." William Herschel (Jan. 15, 1801)

1. Introduction

Sir William Herschel observed the sun from 1785 to 1837, a period of 52 years, occasionally on nearly daily basis but at other times only after lapses of months or years. His notebooks from which the above two quotes are taken provide some of the most detailed observations of the sun in the period around 1800. Although he is noted for hypothesizing that the solar radiant output varied and that it affected climate as the second quote testifies, he also noted that the structure of sunspots varied. Unfortunately his observations of sunspot structure are not sufficiently detailed to deduce if there was any long-term variations in their structure. Day to day variations however were often noted. His notebooks are sufficiently detailed that they indicate a prolonged solar minimum from about 1806 to 1811-12. Perhaps it just a coincidence that the period 1810-1816 appeared to be markedly cold in many regions of the Earth (e.g., see Groveman and Landsberg, 1979).

Does the solar total irradiance vary on time scales longer than 11 years? Does sunspot structure provide a method of deducing what these longer term variation might have been? Are these longer term changes connected to long term changes in the climate of the Earth? This paper will review the hypothesis that there is a such a connection and provide further supporting physical and statistical reasons why the hypothesis that sunspot structure gives a proxy measure of solar luminosity variations is reasonable.

2. Review of the hypothesis

Although only an eleven year cycle in total solar irradiance variations have been identified so far (e.g., Hoyt and Kyle, 1990), there remains the possibility that longer term variations may exist. In 1979 Hoyt hypothesized that such longer term variations did exist and could be reconstructed through the use of measurements of secular changes in sunspot structure. The basic hypothesis is as follows: As the strength of solar convection increases, the solar luminosity increases. Sunspots which are embedded in the convective zone respond to the changes in convection with increased convection causing the penumbra of sunspots to be less extensive. Sunspot structure can be normalized by taking the ratio of the umbral areas to whole spot areas (u/w) or the ratio of umbra areas to penumbral areas (u/p). The time history of the variation of these ratios provides a time history of the solar convective strength and solar luminosity and therefore should be correlated with Earth temperatures. The original paper by Hoyt (1979) found a correlation to the Northern Hemisphere temperature time series of Budyko (1969) and Angell and Korshover (1975) of 0.57. More details are provided in that paper.

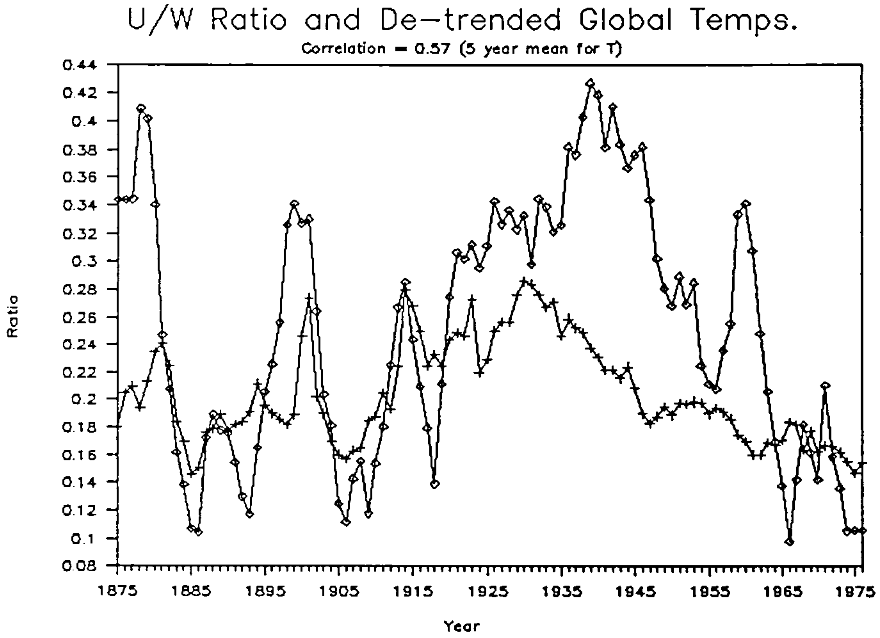

Figure 1. A plot of the Greenwich Observatory sunspot structure (u/w) and the five year running mean smoothed Hansen and Lebedeff global temperatures with 0.6 C added to place the two plots on the same scale. The correlation of the two curves is 0.57.

Using the global temperature values of Hansen and Lebedeff (1987), the correlation to u/w equals 0.26. Spencer and Christy (1990) show that the Southern Hemisphere surface temperatures are not reliably measured so it is not surprising that the correlation would drop by going from Northern Hemisphere data set to a global data set. If the global temperature is de-trended to remove a trace gas and/or urban warming effects and five year running means of temperature are used (see Figure 1), the correlation is 0.57. The solar forcing hypothesis only explains variation in the temperature of a long-term nature. The short term variations are arising largely from internal chaotic behavior in the climate system such as El Ninos (e.g., see Spencer and Christy) or interannualar cloud cover fluctuations (Hoyt, 1976).

The trends in sunspot structure shown in Figure 1 persist no matter what subset of the total sunspots used. Sunspots stratified by size, by type, or by Greenwich observer all have the same characteristic long-term variation shown in the figure. A comparison of one Greenwich observer to another using one-way analysis of variance techniques shows that in all but one case out of 82 observers the Greenwich observers derive the same sunspot structure. A typical one standard deviation uncertainty in yearly mean u/w values is about 0.003 whereas the mean values range from about 0.15 to 0.25 or 33 standard deviations. There is no reason to believe that sunspot structure does not change with time.

Although the theory of sunspot structure remains poorly explained, some idea of what is going on may be deduced from the sunspot model of Pizzo (1986). Figure 2 from that paper shows the contours of equal sunspot opacity and equal temperature. The two contours are nearly parallel so a small change in temperature, for example, would lead to a relative large change in sunspot structure. The location of the outer sunspot boundary is defined by the intersection of the optical depth equals one contour and a temperature contour. It would appear therefore that the change in sunspot structure is caused mostly by a change in the penumbras with little effect on the umbras. Thus, the outer boundary conditions on the sunspot apparently provide information on solar convection and luminosity. Each sunspot can be viewed somewhat as a thermometer embedded in the sun. Although no one sunspot provides a good measure of the convection, when large numbers of sunspots are used, the state of the convective strength can be monitored. That there do appear to be changes in the convective strength are supported by the works of Livingston (1982) using solar line bisectors and Kuhn et al. (1988) using limb brightness data.

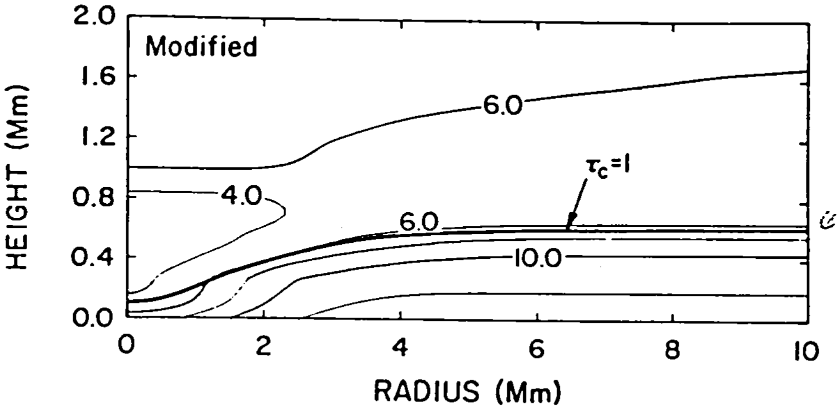

Figure 2. A model for sunspot structure from Pizzo (1986). The closely parallel contours of temperature and optical depth suggest a small change in photospheric temperature or solar luminosity will manifest itself as a large change in sunspot structure.

3. Variations in solar luminosity longer than 11 years?

There are several solar parameters which vary on the time scale of 70 to 90 years which may be associated with luminosity variations on the same time scale. Besides sunspot structure, there are variations in solar diameter (Gilliland, 1982) who deduced there was a maximum in solar luminosity in 1930 (close to the 1932 peak deduced from sunspot structure). In addition the solar rotation became most like a rigid body for the 1924-1935 solar cycle. The slowest equatorial rotation rates occurred in the 1912-24 solar cycle. The Gleissberg cycle of 80-90 years, the Maunder minimum (Eddy, 1976), and ice core oxygen isotope variations (e.g., Hibler and Johnsen, 1979) all suggest that solar luminosity variations longer than 11 years may be present.

Consider variations in solar rotation. Using single sunspots whose positions were measured at the Royal Greenwich Observatory (RGO), the solar differential rotation can be calculated for each solar cycle and for each hemisphere of the sun. The results of this analysis are summarized in Table 1. The equatorial rotation rate in degrees per day shows long term variations with a minimum around 1924-34. The differential rotation also reached a minimum meaning the sun appeared to rotate more like a rigid body then at other times. The differential rotation is arising in some as yet not fully understood manner from the interaction of

Table 1. The differential rotation of the sun in degrees per day assumed to be of the form a + b * cos (lat) for each solar cycle and for Northern Hemisphere and Southern Hemisphere single spots. N is the number of pairs of observations used.

	Northern Hemisphere					Southern Hemisphere				
years	N	a	s.d.	b	s.d.	N	a	s.d.	b	s.d.
1879-89	1286	14.533	0.027	-3.08	0.298	1625	14.514	0.022	-2.88	0.269
1889-02	1545	14.563	0.023	-2.98	0.262	1664	14.565	0.023	-3.20	0.251
1902-11	972	14.552	0.036	-3.63	0.484	992	14.514	0.031	-2.79	0.437
1912-24	1704	14.423	0.021	-2.64	0.252	1574	14.420	0.022	-2.35	0.245
1924-34	1610	14.402	0.020	-2.44	0.199	1363	14.392	0.018	-2.56	0.188
1934-44	1825	14.405	0.017	-2.96	0.156	1860	14.432	0.017	-3.14	0.165
1944-54	2313	14.416	0.017	-3.06	0.175	2284	14.430	0.017	-2.52	0.158
1954-65	2560	14.376	0.014	-2.64	0.103	1892	14.459	0.018	-3.31	0.146
1964-76	2473	14.414	0.017	-2.63	0.164	1853	14.405	0.018	-2.56	0.197

Table 2. The equatorial rotation of the sun using single spots observed between +5 and -5 degrees solar latitude of the equator. The single spots are further selected to be within 60 degrees of longitude of the central meridian.

years	N	deg./day
1879-1889	673	14.586
1889-1902	824	14.588
1902-1911	728	14.511
1912-1924	751	14.453
1924-1934	715	14.482
1934-1944	763	14.492
1944-1954	1153	14.462
1954-1965	1054	14.536
1965-1976	1050	14.479

convection and viscosity. If the surface rotation is varying, the convection strength is probably also varying and therefore the luminosity would be varying as well. Using single sunspots within 5 degrees of the equator as tracers (Table 2), the equatorial solar rotation reached a minimum for the century one cycle earlier than the minimum in differential rate (i.e., 1912-24). Also within each 11 year cycle, the solar rotation appears more like a rigid body toward solar maximum which recent satellite observations indicate is time of maximum solar luminosity.

To show that the change in equatorial rotation was not an artifact of the fitting procedure, the single sunspots within 5 degrees of the equatorial were used to calculate the solar rotation rate. Table 2 shows that the same time history as the other analysis.

4. Predictions of the hypothesis and tests for its validity

This paper has presented some reasons why the hypothesis that variations in sunspot structure could provide a proxy measure of solar luminosity variations. If true, then other consequences will follow. For example, if one solar hemisphere is persistently more active then the other hemisphere for an extended time period, u/w would be greater for that hemisphere. As another example, if one assumes the hypothesis is true, then for times of high solar luminosity, the penumbras would shrink relatively. As a consequence the fraction of large spots to all spots could be expected to decrease during these times (such as the early 1930's). Finally consider stars cooler than the sun such as K and M stars. Cool stars could be expected to have less convective pressure on sunspots then the sun, so these star-spots should have extended penumbras. For sufficiently cool stars, the whole surface may appear to be mostly penumbra with the consequent chaotic fields and absence of highly polarized light.

5. Concluding remarks

Variations in sunspot structure, solar diameter, solar rotation, and Earth surface temperatures have all shown a parallel behavior over the last century. One plausible connection between these time series is that the solar convective strength and hence solar luminosity is varying on these time scales as well. Indeed it would be hard to imagine how sunspot structure could change without any accompanying change in other solar parameters, particular luminosity. Kuhn et al., Livingston, and others have presented supporting evidence that there are changes in the convective strength of the sun.

A picture of long-term solar variations could be constructed as follows. Convective strength and solar luminosity increased from the late 1800's to a peak around 1930-35 and decreased steadily until at least 1976. Near the peak in solar luminosity, sunspots had their least extensive penumbras, the solar diameter was decreasing at its maximum rate, the sun was rotating more like a rigid body then at other times, and the equatorial rotation rate had just recently had its slowest rate of the century. Shortly thereafter the surface temperatures of the Earth reached a maximum.

Sunspot structure could be measured for sunspots after 1976 when the RGO stopped measurements. Older measurements may also provide a mechanism to extend the time history of sunspot structure. There are ample tests which could be performed to test the hypothesis that sunspot structure can be used as a proxy to measure long-term solar luminosity variations. Many of these tests were presented in the earlier paper (Hoyt, 1979) and as yet have not been tested.

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