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INDIRECT METHODS FOR MEASURING VARIATIONS OF THE SOLAR CONSTANT

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ABSTRACT

The various techniques thus far used to measure or infer variations of the solar constant, S, will be reviewed. The difference between the methods that measure δS, and those that measure variations in the solar luminosity, δL, is discussed. It is shown that the past practice of simply relating δS to δL by geometrical arguments is not valid because of anisotropy of the solar radiation. We conclude that direct techniques have proven the existence of short-term variability that is fully explainable in terms of the passage of active regions (spots and faculae) on the face of the Sun. These measurements, however, yield no conclusive evidence regarding variability on longer, climatically significant, time scales. The observations of changes in the solar diameter, on the other hand, support the existence of structurally induced variations of the solar luminosity on timescales of tens of years, which are clearly significant in our understanding of climatic variations.

INTRODUCTION

It has been common practice to use the concepts of solar luminosity, L, and solar constant or irradiance, S, interchangeably. L is the total energy output o the Sun per unit time, whereas S is the energy per unit time striking normally one unit area at the Earth's distance (and direction) from the Sun. If absorption can be neglected, and if the solar radiation is isotropic, these quantities are simply related,

$$L \quad 4\pi d^2 , \tag{1}$$

where d is the Sun-Earth distance*. Since until recently the simplifying assumptions required for equation (1) to be valid were unchallenged, the custom of referring to either L or S as equivalent concepts is understandable. We shall argue later on in this paper that the solar radiation is not isotropic. Since this invalidates relation (1), we shall hereafter clearly discriminate between S and L.

DIRECT METHODS

All direct methods for measuring the solar energy output involve determinations of S. This type of work was begun early in the century using ground-based detectors (ref. 1), and continued in the last two decades on the basis of observations carried out from various space-borne detectors (ref. 2). Of particular significance are the recent results from the ERB experiment on Nimbus 7 (ref. 3), and from the ACRIM experiment on the Solar Maximum Mission, SMM, (ref. 4) The importance of these two experiments, with overlapping measurements since February 1980, is that they both detected coincident variations of the solar constant, at levels of up to 0.2 percent, having timescales of days. These variations are now well explained in terms of active regions

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* In practice, S is always normalized to a Sun-Earth distance of 1 astronomical unit.

(spots and faculae) brought into view and out of view by solar rotation (ref. 5).

On longer timescales, changes of S have not convincingly been measured (refs. 1, 2). First of all, calibration difficulties have detracted significance from any detected small changes. Second, since S does vary with a few days timescales, differences at the few tenths of a percent level obtained from different rocket or balloon flights might not reflect more than these active-region induced changes.

A crucial outcome of the Nimbus 7 and SMM observations, followed by [illegible]'s interpretation, is that the solar radiation is not isotropic, since the radiation emitted in a direction where a particularly large spot is visible, for example, is less than that emitted in any direction where the spot is not visible.

INDIRECT METHODS

Indirect methods have been used to determine variations of both S and L. The δS determinations from indirect techniques apply to geological and biological data, and have the properties of (1) are not very sensitive, and (2) apply to timescales in thousands of years, where no other (more precise) data exist. An example of this type of work is the ice-core probing to determine migrations of the ice-caps on the Earth's polar regions. We shall not discuss these measurements any further in this paper.

The indirect measuring techniques which are of interest to us measure changes of L on timescales smaller than a few hundred years. The common feature in all of them is that they are based on the Stefan-Boltzmann law

$$L = 4\pi\sigma R^2 T^4 \tag{2}$$

which gives the total energy output per unit time of a blackbody sphere of radius R and temperature T.

The Sun is not a blackbody, and equation (2) is not strictly applicable; however, if we substitute T by T_{eff}, the effective temperature, then equation (2) is valid. It must be stressed that the only means of obtaining T_{eff} is through relation (2), i.e $T_{eff} = (L/4\pi\sigma R^2)^{1/4}$, and so the relation is not useful to determine L. Let us take derivatives.

$$\delta L/L = 2\ \delta R/R + 4\ \delta T_{eff}/T_{eff} \tag{3}$$

We can now determine variations of the solar luminosity by measuring the radius changes, as well as the variations of the effective temperature, which may be a quantity much easier to measure than T_{eff} itself. Livingston (ref. 6) attempted to determine δT_{eff} by measuring spectroscopic temperature changes δT_s, determined from the strengths of weak Fraunhofer lines which orginate in the same layers of the solar atmosphere (the photosphere) as the bulk of the solar irradiance. Then

$$\frac{\delta T_s}{T_s} = \frac{\delta T_{eff}}{T_{eff}} \tag{4}$$

He chose for this purpose the line λ 5380.3 from CI. More recent work (ref.

7) indicates that the equivalent widths of different lines with diverse temperature sensitivities produce incompatible results. In fact, the current status of this particular problem requires a large amount of poorly understood modeling, and so for the time being we do not have a definitive way of measuring $\delta T_{eff}/T_{eff}$.

If one term of equation (3) cannot be determined, it would appear that the indirect techniques are useless to determine $\delta L/L$. We will show hereafter that such is not the case. In fact, changes of the solar structure (radius) are the cause of short-period luminosity changes, with δT_{eff} being but one of the consequences. It turns out, then, $\delta R/R$ can be directly related to $\delta L/L$ by means of numerical modeling. While our results are still model-dependent, they have advantages over the temperature model dependence in that (a) the modeling is better understood, and (b) it can be verified by observations.

THE RADIUS-LUMINOSITY RELATION

Let us assume that we have two stars of identical mass, age and initial chemical composition. Let us model them in the conventional manner (i.e. ignoring rotation, magnetic field, etc). Because of the nature of the equations of stellar structure and evolution, if we wish these stars to have a somewhat different luminosity, the only possible avenue is to use a different mixing length to model their envelope. This change will affect L, but also, and primarily, R. From this argument it was concluded that if the Sun is to acquire a different equilibrium value of its luminosity, it will do so at a different radius, and hence radius monitoring might be a sensitive means of monitoring changes of the solar luminosity (ref. 8). The trouble with this argument is that it cannot yield the relationship between R and L, since the timescales of interest do not always allow re-establishing total equilibrium (for example, the thermal timescale of the solar interior is $\gtrsim 10^6$ years), and the standard solar model does not contain all the physics that may lead to L changes on non-evolutionary timescales. By now extensive realistic numerical modeling of possible mechanisms leading to a quick luminosity change have been carried out (refs. 9, 10, 11). Contrary to our initial hope, it was found that the relationship between δL and δR is dependent on the mechanism that causes the changes, and more particularly, on the solar region where it primarily operates. If we define $W = \delta \ln R/\delta \ln L$, it is found that, in general, W is slowly time dependent. Three mechanisms have been examined to date, namely

1) α -mechanism: a sudden change of the mixing length on the solar convective envelope. This mechanism first proposed by Ulrich (ref. 12), has been examined extensively (refs. 9, 10, 11). The consensus is that $W \sim 6 \times 10^{-4}$, i.e. on short timescales the radius is very insensitive to $\delta\alpha$ which produce significant δL . The $\delta\alpha$, when applied to different regions of the convection zone, does not produce different results, since its effects are only important in the shallow super-adiabatic region (cf ref. 11).

2) β-mechanism : a layer at a given (variable) depth in the convection zone is perturbed by adding non-thermal pressure components (magnetic or turbulent pressure). Depending on the depth of the perturbation, this leads to a W that may reach $\sim .1$ (cf ref. 9).

3) core-perturbation: A sudden mixing event is arbitrarily induced within the partially nuclearly processed radiative core. In this case $W \leq .7$ (Sweigart, private communication).

Our current knowledge of W indicates that it depends strongly on the zone where the perturbation is effective, and to a lesser degree, on the size of the perturbation, and on the history and sequence of perturbing events (Endal, private communication). Further modeling is underway to better understand the sensitivity of W on the various parameters that may affect the Sun. It is now clear that the W value of the Sun, if indeed there is a unique value (say by the fact that one mechanism dominates the variations) cannot be determined from theory alone. Instead, we must determine W from simultaneous observations of δR and δL, after correcting δL for the modulation produced by active regions. The value of W thus obtained will allow us to determine δL for all times in which radius information is available, will identify the depth in the Sun where the changes originate, and finally, may identify the physical process responsible for the structural changes in the Sun.

CHANGES OF THE SOLAR RADIUS

It is convenient to separate measurements of the solar radius in two groups: those carried out in the past, and those currently underway or planned for the future. To date, three types of measurements carried out continually in the past have been identified which yield information on the solar radius. They are: (1) transit or meridian circle observations (refs. 13, 14), (2) timings of the transits of the planet Mercury in front of the Sun (refs. 15, 16), and (3) timings of total solar eclipses (refs. 16, 17). Because of the effect of the observer's personal equation (refs. 13, 14) and other unknown difficulties, the transit instrument timings cannot be literally taken as measurements of the solar radius. The transits of Mercury provide data apparently free of systematic errors, but the error of each individual measurement is $\sim\pm 1''$ (refs. 15, 16). Consequently, while they can successfully disprove large secular changes of the solar radius, they cannot provide any information regarding non-secular radius changes of amplitude $<$ few arc seconds. Finally, two types of solar eclipse timings have been proposed, namely (a) timing measurements carried out in the middle of the path of totality (ref. 16), and at the edge of the path of totality (ref. 17). Reasons have been stated (ref. 18) indicating that the path-edge observations, while fewer in number, provide the more reliable means of monitoring changes in the size of the Sun (ref. 19). The results of applying this technique thus far obtained are given in ref. 18. Of particular significance are the eclipses of 1925 and 1979, since they were observed by a large number of observers who were very near the edge of the path of totality (the timing error is negligible), whose location was extremely well documented (ref. 18), and three of the observed contacts occurred in the same lunar features, so that the derived radius change is independent of lunar profile errors. This shows that between 1925 and 1979 the solar radius differed by $>$ 0.5.

Future measurements should include edge timings to link all future results to past results. In addition, however, measurements by more modern techniques will be carried out. In particular, the SCLERA telescope should be able to detect radius changes at the milli-arc second level, a factor of 50 better than the edge timing observations (ref. 20). Additional instrumentation is currently planned at the High Altitude Observatory and at Sacramento Peak Observatory.

IMPLICATIONS OF THE SOLAR RADIUS CHANGES

Timing observations near the edge of the path of totality have shown that the solar radius changes by approximately 0.5 in timescale of tens to hundreds of years. This implies that solar luminosity variations of structural origin having similar timescales have taken place. Notice that these changes would, in addition, undergo the activity-induced modulation described in ref. 5. In fact, the occurrence of structurally induced changes will show up as a secular growth in the residuals of the analysis given in ref. 5. To estimate what 0.5 change corresponds to in terms of solar luminosity change, we must know the mechanism responsible for the variation. The occurrence of such large radius changes already eliminates the α-mechansim, since it would imply a $\delta L/L > 80$ percent, a value clearly excluded by the history of the Earth's climate. If the change originated by events occurring in the solar core, the implied luminosity change would be at the 0.03 percent level, thus negligible for most climatic purposes. However, it is difficult to visualize interior mechanisms acting on timescales as short as tens of years. A more probable origin of the solar variations resides in a β-mechanism associated with the variable magnetic field produced at the base of the convection zone by the solar dynamo. In this case, $\delta L/L$ may be of the order of 0.5 percent, a value neither excluded by the climatic history of the Earth, nor negligible. In fact, the size of the climatic effect would strongly depend on the duration of the changes, and this cannot be currently assessed on the basis of only 5 radius values with rather uneven time-distribution (ref. 18).

SUMMARY AND DISCUSSION

From direct measurements carried out by detectors on board NIMBUS 7 and SMM, it has been found that the solar irradiance varies with timescales of days to months. Such variations can be fully explained in terms of flux modulation caused by the passage of active regions on the visible solar hemisphere, and reflect the directional dependence of the energy deficit caused by the sunspots and the re-emission of the energy by the faculae. The measurements do not require (or support) variations of the solar luminosity during the six months of high-precision observations carried out by the SMM.

Indirectly, solar luminosity changes with timescales of tens to hundreds of years can be inferred from structural changes in the Sun as revealed from past radius measurements. While the factor relating radius changes to luminosity changes, which depends on the mechanism that produces the variations, is not known with complete confidence, the currently favored interpretation (a β-mechanism) supports luminosity variations having an amplitude of $< 0.5\%$. These variations, if long-lived, have important climatic consequences.

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