IMPORTANT OF MONITORING SOLAR GLOBAL PROPERTIES: LUMINOSITY, RADIUS AND OSCILLATIONS

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ABSTRACT

Space observations of solar irradiance (both bolometric and at various wavelengths) established conclusively that solar irradiance changes on time scales of minutes to the 11-year solar cycle. Surface brightness changes that correspond to effective temperature variations of less than one degree Kelvin have also been detected. Dynamical and thermal modulation of the Sun’s internal structure can be manifest at the surface as changes in irradiance and perhaps the solar radius. Solar imaging array experiments from space have demonstrated the possibility of measuring solar limb shape oscillations (corresponding to 5-min oscillations) at the level of 10 microarcseconds. Parallel monitoring and studying solar irradiance, radius and oscillations are essential to understand how and why the Sun is changing on human time scales. Understanding the origin of solar variability is essential to reconstruct and predict the solar induced climate changes. Combination of a solar imager with a state-of-the-art radiometer, like that currently flying on the SOHO/VIRGO experiment, will provide a valuable experiment to observe solar global properties.

Key words: solar total irradiance; solar radius, solar activity

1. INTRODUCTION

Study of the Sun’s variability has been of high importance for both astrophysics and solar-terrestrial physics. On one hand, the Sun, a fairly typical star, has the special advantage of proximity which allows the detailed study of a variety of phenomena important for stellar physics. On the other hand, the total radiative output of the Sun establishes the Earth’s radiation environment and it controls its temperature and atmospheric composition. Recent studies indicate that small but persistent variations in the solar energy flux may play an important role in climate changes (e.g. Eddy, 1977; Hansen et al., 1993; Reid, 1997).

Although the ultimate source of the solar energy is the nuclear reactions taking place in the center of the Sun, the immediate source of the energy is the solar surface. While the nuclear reactions are almost certainly steady on time scales shorter than millions of years, the mechanisms which carry the energy to the solar surface may not be. Indeed, observations of the solar radiative output integrated over the entire solar spectrum, hence total irradiance, obtained by space-based experiments over the last two decades have demonstrated that total irradiance varies on time scales of minutes to the 11-year solar cycle (Willson and Hudson, 1988; Fröhlich, 1994; Kuhn, 1996).

If the central energy source remains constant while the rate of energy emission from the surface varies, there must be an intermediate reservoir, where the energy can be stored or released depending on the variable rate of energy transport. The gravitational field is one such energy reservoir. If energy is stored in this reservoir, it will result in a change in the Sun’s radius. Thus, a careful determination of the time dependence of the solar radius can provide a constraint on models of total irradiance variations. Such measurements exist over 300 years, however, these measurements have provided very controversial results (Ribes et al., 1991; Kuhn et al., 1997).

2. VARIATIONS IN TOTAL IRRADIANCE AND SOLAR RADIUS

Continuous observational programs of total solar irradiance to detect its variability started about two decades ago from several space platforms (see summaries by Willson, 1994; Crommelynck et al., 1994; Fröhlich, 1994, 1998; Pap, 1997). The various irradiance measurements are summarized in Figure 1. These space observations have revealed variations in total irradiance over a wide range of periodicities. It has been shown that total solar irradiance varies in parallel with the solar cycle, being higher during maximum activity conditions. The long-term irradiance changes are attributed to the changing emission of faculae and the magnetic network (e.g. Foukal
and Lean, 1988). Short-term variations related to the evolution of active regions, are superposed on the long-term trend (Chapman, 1987). The effect of granulation, meso-, and supergranulation has also been recognized in solar irradiance on time scales of minutes to hours, while the rapid irradiance fluctuations in the 5-min range are due to the p-mode oscillations (Fröhlich, 1990).

Although considerable information exists on solar irradiance variations, the underlying physical mechanisms are not well-understood. Since we observe the Sun's irradiance from one direction in space, we have difficulty in determining whether the observed irradiance variations represent changes in the Sun's irradiance in all directions, i.e., true luminosity change, or are simply a result of a change in the angular dependence of the radiation field emerging from the photosphere. Comparison of the solar limb brightness and irradiance variations (Kuhn et al., 1988; Fröhlich, 1994) suggests that the solar-cycle-related long-term irradiance changes are real luminosity changes, while the short-term variations from days to months are caused by the active regions via the combined effect of dark sunspots and bright faculae (e.g. Kuhn, 1996).

It is extremely important in the context of the Earth to know whether the observed irradiance changes, especially for the long-term, are luminosity changes or results of energy distribution by active regions. In addition, this is an important and not yet resolved problem in solar physics. Since the variations in the solar energy flux—persistent over long periods of time—may trigger climate changes, it is fundamental to understand the underlying physical mechanisms and thus the possibilities for a solar forcing of climate on time scales of decades to centuries. Therefore, implementation of a state-of-the-art radiometer on STEREO, as currently flying on SOHO/VIRGO, to measure solar total irradiance from two spacecraft at large angular separations from Earth would complement the current irradiance monitoring experiments. An irradiance monitoring experiment on STEREO would be able to answer the important question: are the observed irradiance changes real luminosity changes?

It has been shown that empirical models of total irradiance, solely based on magnetic effects, cannot explain all the aspects of irradiance changes (e.g. Fröhlich and Pap, 1989). Identification of the cause of the residual discrepancy is a difficult problem since temporal changes in differential rotation in the interior of the Sun, the solar dynamo magnetic field near the base of the convective zone (Fröhlich, 1986), large scale mixing flows or large scale convective cells (Ribes et al., 1985; Fox and Sofia, 1994), photospheric temperature changes (Kuhn et al., 1988) and/or radius changes (Delache et al., 1986; Ulrich and Bertello, 1995) may all produce changes in solar luminosity. The problem is further complicated by active regions emergence and the fluctuation of p-mode oscillation frequencies. Although the p-mode frequency changes are correlated with some magnetic field variations, it is not clear what the causal relationship is between the magnetic and thermal mechanisms.

Simultaneous studies of total irradiance, p-mode oscillations, and radius are essential to better understand the underlying physical mechanisms of irradiance changes. In order to measure the solar radius, one needs to establish the position of the solar limb with maximum accuracy. The solar limb is, potentially, a sharp spatial reference with which we can hope to detect the effects of (1) solar oscillations (both p- and g-modes); (2) the gravitational quadrupole moment (or the solar oblateness), and changes in the solar radius (Kuhn et al., 1997, 1998). Both the solar radius and shape measurements help to determine the solar luminosity. Ground-based attempts to measure the solar radius and limb shape have a long history, however, corresponding space observations are almost nonexistent.

The major problems we face when measuring the solar radius are that the solar limb is intrinsically fuzzy, which is worsened by the atmospheric seeing effects, and there is evidence that latitude- and time-dependent temperature variations may cause significant variations in the shape of the limb-darkening function (see summary by Ribes et al., 1991; Kuhn et al., 1997, 1998). The historical observations of solar radius over the last 300 years may provide an estimate of the past luminosity changes and their possible climate effects (Sofia et al., 1979). Analysis of the historical radius data indicate that the Sun was larger during the Maunder Minimum (Ribes et al., 1987). For example, Eddy and Boornizian (1979) claimed that the Sun was contracting at the rate of 0.1%, or one arc sec in the angular diameter per century, which turned out to be an unlikely large value. However, one could not rule out a few tenths of an arc sec. variations of the solar radius on time scales of decades.

The various measurements of the solar radius and their results are summarized in detail by Ribes et al. (1991). In this paper we show the preliminary results of the intercomparison of the CERGA and the Mt. Wilson radius data. The CERGA astrolabe measurements started in 1976 and measurements are regular from 1978 (Laclace, 1983). The Mt. Wilson radius values have been derived from the observations in the neutral iron line at 525.0 nm (Ulrich and Bertello, 1995). The CERGA radius measurements, as example, are plotted on the upper panel of Fig.
Figure 2 (dotted line) for the time interval of 1978 to 1994. The solid line shows the composite total irradiance (Fröhlich and Lean, 1998) for the same time interval. The Singular Spectra of the composite total irradiance and the CERGA and the Mt. Wilson radius measurements are shown in the mid-panel. The long-term trends derived from the first eigenvalues of the Singular Spectra are plotted on the lowest panel. As can be seen, both radius data show considerably higher noise level than the total irradiance and only a few oscillatory components can be identified from their spectra. Note that Delache et al. (1985) and Gavryusev et al. (1994) have reported significant peaks in the power spectrum of the CERGA measurements at 1,000 and 320 days. A strong annual variability is also present in the Mt. Wilson data, however, it does not seem to be associated with the 320-day periodicity in the Mt. Wilson data. As can be seen from Figure 2, the CERGA measurements show an anticorrelation with the long-term variation of total irradiance, while the Mt. Wilson observations indicate a positive correlation. We note that the radius measurements performed by Brown (1987), using HAO’s Solar Diameter Monitor, show no significant variation in the solar radius at all.

These controversial results indicate that further efforts are required, using more sophisticated techniques and free from the atmospheric seeing effects, to determine whether this important astrophysical quantity changes with solar activity. The difficulty of ground-based observations of the solar radius due to the distorting effects of the Earth’s atmosphere has been recognized by Sofia and his collaborators in their development of the Solar Disk Sextant (Sofia et al., 1994). The Sextant instrument has already provided measurements from balloon flights. However, observations from balloons still have some atmospheric contamination, and provide only infrequent measurements which cannot give the detailed information necessary to discover the relation between luminosity and radius variations.

Recently Kuhn et al. (1997, 1998) reported results of solar limb measurements using the images from the Michelson Doppler Imager (MDI) experiment on SOHO at the Earth-Sun Lagrange point (Scherrer et al., 1995). Although the SOHO/MDI experiment was not designed for astrometric imaging or photometric observations, it has been proven to be effective for measuring small changes in the solar limb position (Kuhn et al., 1998). It has been shown that when the SOHO spacecraft is “rolled” for calibration, it is possible to measure solar limb shape and size changes at the $10^{-6}$ pixel level for oscillations, and at the $10^{-3}$ level for static shape and size changes. The MDI experiment was primarily designed as a heliometric experiment to provide full disk Doppler images of the Sun with a 1-min cadence. Limb pixel data are returned with a 12-min cadence. MDI has a 1024 × 1024 CCD camera to obtain full-disk and higher resolution Doppler images of the Sun near the 676.8 nm Ni I line.

The solar radius is the hardest measurement to extract from the MDI data. However, by rolling the spacecraft, and therefore the MDI optics, the static solar shape can be extracted from much larger instrument distortions. Figure 3 shows the residual solar shape (which rotates as the SOHO spacecraft

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3. CONCLUSIONS

A quantitative understanding of the parametric description of the solar irradiance variability can only provide partial insight into important questions like, “Could the solar irradiance change by a larger amount during the next cycle?” or more to the point, “Are the catastrophic climate changes observed in the prehistoric isotopic records related to changes that occur in the Sun?” (see papers in a special JGR 102, 1997 issue). We lack the fundamental understanding of the physical mechanism beneath and in the solar convective zone that causes the solar luminosity variations. This issue, namely how entropy is transported through the convective zone, is a longstanding problem of solar and stellar physics.

The solar radius and shape observations are needed to understand exactly how the Sun’s convective envelope changes in response to the emergent energy fluctuations. The determination of this outer boundary condition on the limb shape is essential for the correct physical interpretation of solar luminosity and irradiance effects. Since the ground-based radius measurements lead to rather controversial results, space observations are required to reveal the variations in the solar radius. As the SOHO/MDI observations show, the exceedingly small solar shape fluctuations are readily measurable from outside the atmosphere. The MDI solar shape data reveals how the convective envelope responds to acoustic oscillations. Our goal is that the radius and shape observations enable a new set of helioseismic solar “shape” diagnostics of the radiative and convective interior. These measurements, together with the space irradiance measurements, will help to achieve our ultimate goal: to understand how, why and what mechanisms govern the changes in the solar energy flux and related potential climate changes.

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