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SOLAR PULSATIONS AND LONG-TERM SOLAR VARIABILITY<sup>1</sup>

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ABSTRACT

The seismology of the solar atmosphere is important in relating changes in luminosity to variations in other observables. This approach has already led to the identification of properties which were not previously observed or recognized. Equally important results from solar seismology are expected in the future.

INTRODUCTION

The relationship between variations in the sun's luminosity and long term variations in the earth's climate remains an open question in spite of considerable recent efforts to define it (see references 1 and 2 for a review). Various methods may be used to study the solar luminosity-terrestrial climate relationship. One approach to this study that is receiving serious attention is based on the observation of long-term variations of the solar diameter and related quantities. It is in establishing the relationship between these observables and solar luminosity where the study of solar pulsations can be important.

The fundamental measurements in a diameter-based program require a precise determination of the location of an edge of the solar disk. This location, as deduced from observation, depends on how the edge of the sun is defined. The edge obtained by any selected definition is sensitive, in general, to the shape of the solar limb darkening function. This function represents the decrease in the brightness of the sun as the limb is approached. The sensitivity of the edge location to time-varying whole-disk properties of this function was a factor in the misinterpretation of the Princeton solar oblateness measurements and later gave rise to equally serious questions concerning the reality of the solar oscillations reported at SCLERA<sup>2</sup>. The

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<sup>2</sup>SCLERA is an acronym for the Santa Catalina Laboratory for Experimental Relativity by Astrometry, a facility jointly operated by Wesleyan University and the University of Arizona.

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existence of these oscillations has now been corroborated (reference 3) but in so doing, new questions have surfaced regarding stellar pulsation theory at a fundamental level. For discussions of this topic, see reference 4 for a review on solar oscillations and references 5, 6 and 7 for reviews on solar oblateness.

The limb darkening function reflects the temperature gradient in the solar envelope which in turn is evidenced by an outward energy transport, i.e., luminosity. It is clear that a change in the solar luminosity and, hence, in the temperature gradient implies an accompanying change in the limb darkening function. Because the limb darkening function can also be studied with considerable accuracy, an examination of its long-term variation would be expected to be as useful a diagnostic of the solar luminosity as an intrinsic diameter study alone. In any case, if solar diameter variations are to be used to investigate solar luminosity, then the link between changes in the limb darkening function and the observed diameter must be understood at a basic level.

The relationship between changes in the limb darkening function and luminosity variations is likely to be complicated. This possibility makes advisable the use of an empirical procedure in which changes in the limb darkening function are examined for correlations with direct radiometric measurements of the solar constant. This approach ought to be sensitive to correlations in changes in the solar constant of about one part in 10,000 with periods on the order of days. This accuracy is fixed by the current level of reproducibility of direct radiometric measurements. However, the extrapolation of the empirical calibration from a period of days to a period of years to decades is probably not justified. Accuracy of the extrapolation would be fortuitous since there is no compelling reason to believe that the physical processes leading to short-term changes are the same as those underlying long-term changes. This empirical calibration would be useful in providing comparative data for more analytic work to follow.

Efforts have been made to identify the primary sources of possible luminosity changes by modeling various convection zone effects. The work described in reference 8 exemplifies this approach. Although this work is important, it models the solar envelope in only the simplest manner, in spite of the fact that it is in the envelope that the complicated manifestations discussed here are observed. A different approach is pursued here -- an empirical one in which the effect on observed quantities of a change in the rate of energy transport through the solar atmosphere is studied without concern for the origin of the change. Studying changes in the limb darkening function with time and luminosity would be representative of this type of approach. Determining the empirical parameters of the observables and identifying the important physical processes has been and remains a major thrust of the theoretical and its associated observational work at SCLERA. Studies of this type are described in references 6, 9, 10, 11, 12, and 13.

Reference 12 addresses the nonlocal character of radiative transfer in the solar atmosphere. The work shows that this nonlocal character is of primary importance in the treatment of perturbations of variables describing the solar atmosphere. This formalism can be used to calculate the effect of a

disturbance like a gravity wave on the limb darkening function and the luminosity.

Work at SCLERA and the Sacramento Peak Observatory has resulted in a new observational technique to study the properties of pulsations in the solar envelope (reference 13). Use of this technique has led to the discovery of five-minute-period traveling waves in the photosphere which are probably gravity waves. This discovery is important because these waves may significantly affect the relationship between the solar limb darkening function and the luminosity. The technique utilized in this work determines the frequency and vertical, rather than horizontal, spatial characteristics of a disturbance by employing the observed Doppler shift of a spectral line as a function of position in the absorption line.

Intensity and displacement fluctuations arise in the essentially adiabatic interior of the sun, but are observed in the nonadiabatic atmosphere. In the photosphere, radiative damping should be the most important nonadiabatic process, directly affecting the properties of global oscillations in the photosphere where they are observed and, for instance, greatly affecting the propagation of traveling disturbances which may be responsible for heating throughout the atmosphere. It is therefore necessary to determine what types of disturbances occur in the photosphere and to be able to theoretically treat the radiative damping of such disturbances in detail.

#### RADIATIVE EFFECTS

The theoretical treatment of a disturbance in the atmosphere entails the study of the appropriate wave equation. Radiative damping enters the wave equation through the first law of thermodynamics as the heat gained by the system. Locally, this heat gain per unit time is given by the divergence of the radiative energy flux,

$$-\vec{\nabla} \cdot \vec{F}_R = \int_{4\pi} \kappa_\lambda \rho (J_\lambda - S_\lambda) d\lambda \quad ,$$

where  $\vec{F}_R$  is the radiative flux,  $\rho$  the density, and  $\kappa_\lambda$ ,  $J_\lambda$ , and  $S_\lambda$  the opacity, the mean intensity, and the source function, respectively, at wavelength  $\lambda$ . The opacity and source function are determined locally while the mean intensity is affected by other regions of the atmosphere. Reference 12 describes a method for addressing this problem and demonstrates the inadequacy of the standard (and local) Newtonian cooling law and the Eddington approximation. This inadequacy is manifest in their considerable failure to predict the radiative damping of perturbations in the photosphere, the place where such effects should be most important in the limb darkening function.

The method given in reference 12 shows that the nonlocal character of the mean intensity, in conjunction with the presence of line blanketing, leads to a wavelength dependence of the opacity that is also important in the calculation of radiative damping incorporating changes in the opacity. This nonlocal

approach yields more realistic spatial properties of disturbances in the solar atmosphere, allowing an improved comparison between the luminosity and limb darkening function variations. The calculation of these spatial properties is being pursued at SCLERA.

### MECHANICAL EFFECTS

Mechanical energy flux has been observed in the photosphere (reference 13). The flux may be of consequence to the relationship between variations in the limb darkening function and luminosity.

The observations discussed here were performed at the Sacramento Peak Observatory. The data are high resolution line profiles of the 5434 Å Fe I line, which is a nonmagnetic line spanning the photosphere. By examining the Doppler shifts closer and closer to the bottom of the absorption line, the velocities of the disturbances are resolved at nine successively higher altitudes in the photosphere. These velocity data are filtered to examine power in the five-minute-period window.

Calculations using the filtered data reveal that there is a disturbance in the five-minute-period window in addition to the well-known five-minute-period acoustic mode. The secondary disturbance is found to be traveling waves which have ingoing and outgoing phase velocities. For both the ingoing and the outgoing traveling waves, power is observed for vertical wavelengths which are about 4/3 times the height of the atmosphere spanned by the observations. Longer wavelengths may be present but the current work has considerably reduced sensitivity in that region. Taking the height of the photosphere spanned by the observations to be 400 km, the vertical wavelength for both ingoing and outgoing phases is approximately 530 km. The period of these traveling waves is  $278 \pm 41$  seconds and their vertical phase velocity is about 2 km/sec.

If the observed traveling waves comprise only a small portion of their spatial spectrum or if the waves are not localized, the group of waves which they represent may provide an important net vertical energy flux to the lower chromosphere. This flux, which may be as large as  $10^7$  ergs/cm<sup>2</sup>/sec, could have implications for the relationship between the limb darkening function and solar luminosity. The horizontal extent of the traveling waves reported here is currently under investigation.

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