GODDARD GRANT
IN-92
CR
92583
P.12

An Investigation of Short Period Oscillations of the Solar Irradiance and Their Time Variations

NASA Grant NAG5-506

Final Technical Report

For the period 15 February 1985 through 14 December 1986

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August 1987

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

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The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics.

The NASA Technical Officer for this grant is Mr. Gilbert D. Bullock - Code 602, GSFC, Greenbelt, MD 20771.

(NASA-CR-180340) AN INVESTIGATION OF SHORT PERIOD OSCILLATIONS OF THE SOLAR IRRADIANCE AND THEIR TIME VARIATIONS Final Technical Report, 15 Feb. 1985 - 14 Dec. 1986 (Smithsonian Astrophysical Observatory) 12 G3/92 N87-27585 Unclas 0092583

AN INVESTIGATION OF SHORT PERIOD OSCILLATIONS OF THE SOLAR IRRADIANCE AND THEIR TIME VARIATIONS

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ABSTRACT

Measurements of solar irradiance fluctuations by the ACRIM instrument onboard SMM show variations on a time scale of about 5 minutes due to solar p-mode oscillations, as well as longer-term variations related to solar magnetic activity. Woodard (1984) showed that the 5- minute oscillations correspond to the well-known low-degree p-mode oscillations, with degree l=0,1,and 2. In this investigation we have studied the question whether the p-mode frequencies change with time as a result of changing solar structure associated with the activity cycle. The ACRIM data on SMM are particularly well-suited for this purpose, because the instrument operated continuously from February 1980 until December 1980 (near solar maximum) and again from May 1984 to the present (near solar minimum). The main activity in this investigation entailed a detailed study of the observational data to determine if a change in p-mode frequencies is evident from the time of solar maximum to that of solar minimum. We conclude that the measured eienfrequeancies were significantly higher, by about 1.3×10^{-4} (or 0.4 μHz) during the 1980 time frame than during the 1984-6 time frame. The validity of the 1984-6 measurements is particularly good, because there are a number of independent data sets. Unfortunately, the 1980 data set was relatively short, and we cannot absolutely rule out some unknown systematic error in those data, although we have found no evidence to that effect. Thus the conclusion that there is a significant change in eigenfrequency with the activity cycle remains only tentative, and needs confirmation from analysis of more data during the upcoming solar maximum.

A related activity, begun toward the end of this contract, was to develop theoretical models aimed at understanding how structural changes associated with the magnetic activity cycle could influence the observed p-mode frequencies. Also we began a search for signatures in the ACRIM data that may be due to g-modes. Both investigations are in their early stages, so conclusions are not yet available.

I. REDUCTION AND ANALYSIS OF ACRIM DATA ON P-MODE FREQUENCIES

The Active Cavity Radiometer (ACRIM) onboard the Solar Maximum Mission satellite (SMM) measures the solar constant with high accuracy, and with excellent long-term stability (Willson 1979, 1981). Irradiance variation have been detected on a variety of time scales. Most spectacular was the discovery of temporary decreases of irradiance associated with the passage of sunspots across the solar disk (Willson et al. 1981). The fact that large sunspots have a measurable effect on the irradiance indicates that the energy blocked by a sunspot is not immediately radiated away at some nearby location on the solar surface but rather is stored in the solar convection zone over time scales longer than the lifetime of the spots (see Spruit and Roberts 1983, Foukal, Fowler and Livshitz 1983). In combination with theoretical studies of sunspot blocking, the ACRIM observations thus provide us with useful information about the sub-surface structure of sunspots, and about energy transport in the solar convection zone.

Solar oscillations present another, quite different probe of the solar interior (Deubner and Gough 1984; Brown, Mihalas and Rhodes 1986). Woodard and Hudson (1983a,b) discovered short-period irradiance variations in the ACRIM data, and identified these variations with global solar oscillations, with periods near 5 minutes (also see Woodard 1984). The normal modes of a gravitating, gaseous sphere such as the sun can be classified according to the radial order n, degree l and azimuthal order m of the associated spherical harmonics. The modes that give rise to the observed 5-minute variability in the ACRIM signal are acoustic, pressure-driven modes (p-modes) with high order ($n = 15$ - 25) and low degree ($l = 0, 1, 2$). These modes have also been found in unimaged solar velocity measurements (Claverie et al. 1979, 1980; Grec, Fossat and Pomerantz 1980, 1983). The observed frequencies yield constraints on models of the solar interior (e.g. Christensen-Dalsgaard 1982).

Woodard, in his thesis, obtained preliminary evidence for changes in p-mode frequencies, that might be related to solar activity. However, the data base then available (basically the first nine months of 1980) was too short for definitive conclusions. Nevertheless, the suggestive nature of these results inspired the present effort to explore possible time changes of solar acoustic eigenfrequencies in more detail, both observationally and theoretically.

Under this contract, Woodard spent five months in 1985 at CfA working with Noyes and others on the analysis and interpretation of more recent ACRIM data. Results were reported at the Cambridge NATO conference on *Seismology of the Sun and Distant Stars*, (Woodard and Noyes 1985a) and in *Nature* (Woodard and Noyes 1985b). In this work the 1980 data were re-analyzed, and data from May 1, 1984 (following the successful repair of SMM) through the end of 1984 were added. The treatment of data was as follows: Data were first detrended by applying a first-difference filter between successive data points. Data points were rejected if they deviated from the mean by more than seven times the rms deviation of the data from the mean. The data were binned on a time grid of constant sampling rate, and then subjected to a fast fourier transform (FFT). The overall data coverage was only about 42% due to orbital nighttime and other data gaps. Also, the binning width was one-fourth the 137.072 basic cadence of the data; thus most of the data points in the FFT were null and set equal to zero.

Comparison of the two data sets showed a small but significant decrease of the mean frequencies from 1980 (near solar maximum) to 1984 (near solar minimum). A number of statistical tests were performed on the data, including generating synthetic data strings each consisting of 75 individual oscillation modes patterned after the response of a damped simple harmonic oscillator to a random driving function. Each of the data strings was then passed through the window function for both the 1980 data and the 1984 data, and the mean frequency shifts were determined in just the same way as for the actual data. This process yielded a value for the spurious shift introduced by the window function, as well as the uncertainty introduced by the random nature of the input function. The shift, $\Delta\nu_{synthetic}$=0.06 $\pm$ 0.07 μHz, is consistent with no systematic shift introduced by the window function. The mean shift measured from the actual data was $\Delta\nu = 0.36 \pm 0.15$ μHz. We concluded that the measured eigenfrequencies for the 1980 data were systematically higher, by about 0.4 μHz, than those for the 1984 data. For details, see Appendix I.

Because of the expected availability of 1985 data, we sought and were granted a no-cost extension of this contract in order to carry on a similar analysis of the 1985 data. Analysis of these data was presented at IAU Symposium 123 in Aarhus, Denmark (Woodard and Noyes 1987), and indicated that the frequency shift persisted into 1985, but with only a very slight decrease between 1984 and 1985.

II. THEORETICAL CONSIDERATIONS

In the absence of magnetic fields, the frequencies of low-degree p-modes are approximately given by (Tassoul 1980):

$$\nu_{n,l} \sim \left(n + \frac{1}{2} + \epsilon\right)\Delta\nu,$$

where $\Delta\nu$ is the inverse of the sound travel time from the surface to the center and back,

$$\Delta\nu = \left[2\int_0^R \frac{dr}{c} \right]^{-1},$$

c(r) is the sound speed at radial distance r from the center, R is the solar radius, and ϵ is a correction term that depends on the stratification close to the solar surface. Magnetic fields may alter the mode spacing $\Delta\nu$ by changing the effective sound speed and/or the solar radius. Changes in the correction term ϵ may also be important.

The simplest explanation for the apparent decrease in eigenfrequency between 1980 and 1984-5 is that the radius of the sun increased during that interval by about one part in 10^4, or about 70 km. This could be associated with a change in structure of the convection zone that in turn is related to the solar activity cycle. Indeed, there is suggestive evidence that changes of convection behavior are associated with the activity cycle, based on observed changes in the properties of granulation and supergranulation seen at the surface. Thus, both the 1000-km scale granulation (Macris et al 1984) and the 30,000 km scale supergranulation (Singh and Bappu 1981) are found to be significantly smaller at sunspot maximum than at sunspot minimum. Some previous theoretical studies (e.g. Spiegel and Weiss 1980) have suggested that dynamo-generated magnetic fields deep in the convection zone could result in a decreased efficiency of convection. A decreased convective efficiency could produce a decrease in the radius of the sun, and and a consequent increase in p-mode eigenfrequencies, at solar maximum. It could also produce smaller supergranulation convective cells, if their mixing length spans a region where the convection is inhibited by magnetic fields. Similarly, surface fields at activity maximum could cause the characteristic size of granulation to decrease.

In spite of the simple appeal of such a picture, the actual explanation of the apparent change of eigenfrequency may be very complex. Various models of the interaction between magnetic fields and solar p- modes have been discussed in the literature. Bogdan and Zweibel (1985) and Zweibel and Bogdan (1986) have studied the interaction of acoustic modes with a large-scale fibril magnetic field, using a wave-scattering approach. The assumption of a fibril state of the magnetic field is motivated by the fact that the field observed at the solar surface is highly intermittent, consisting of isolated magnetic elements surrounded by nearly field-free plasma (cf. Spruit and Roberts 1983). Bogdan and Zweibel find that reflection of acoustic waves off a region with numerous thin, intense, magnetic flux tubes is more effective than reflection off a diffuse field by a factor $\sim 1/f$, where f is the filling factor of the flux tubes. They apply their model to high-degree p-modes interacting with vertical flux tubes in the layers just below the solar surface. In this region the ratio of magnetic pressure and gas pressure in flux tubes is relatively large (of order unity), and frequency changes of order 0.3 percent can be expected, even for filling factors as small as 10^{-2}.

Roberts and Campbell (1986) consider the influence on both p-modes and g-modes of a stratified, horizontal magnetic field, via its effect on the propagation speed of these modes. In the presence of a magnetic field the propagation characteristics of sound waves are altered such that the waves propagate faster (the waves become magneto-acoustic modes). The magnitude of the effect depends on the geometry and strength of the magnetic field, and for low-degree p-modes (which travel nearly vertically within the convection zone) the effect is strongest when the field is horizontal. Magnetic fields throughout the convection zone may contribute to this effect. Roberts and Campbell find that the relative frequency change of p-modes is given by $(2\beta)^{-1}$, where β^{-1} is the average value of v_A^2/c^2 over the range $r = 0$ to R (v_A is the Alfven speed). Assuming that the magnetic field is located near the base of the convection zone, they require field strengths of at least 10^6 G to explain the frequency change observed by Woodard and Noyes (1985b). This is very large considering the strong buoyancy of such fields (Parker 1975).

Surface effects can also affect the observed eigenfrequencies, which depend on the precise temperature and density structure at the upper boundary of the resonant cavity, and specifically the nature of the chromospheric structure overlying the photosphere.The observed variation of chromospheric properties between active regions and the "quiet" sun is very substantial, and it might well be expected that even without changes in the interior structure, simply changing the fraction of surface covered by magnetic activity could have a measurable effect.

During the course of this work we have carried out a preliminary analysis of the problem and laid plans for a modelling effort to analyse explicitly the role of magnetic fields, both in changing the thermal structure of the convection zone and also in coupling p-modes to longitudinal mhd tube oscillation modes. This work will be completed in a separate study.

III. SEARCH FOR G-MODE SIGNATURES IN THE ACRIM DATA

Woodard (1984) undertook a preliminary search for g-modes in the ACRIM data. Also Froelich and Delache (1984; see also Froehlich 1987) have reported evidence for g-modes in the same data from an independent analysis. However the results are marginal. As of now, it is not clear that g-modes have been unambiguously detected, either in the ACRIM data or in any other solar data set. This is unfortunate, for as is well known, g-modes have the potential to provide us with the most definitive knowledge of the structure and dynamics of the very innermost regions of the sun, including the core. A definitive detection and measurement of g-modes will very substantially increase our understanding of the solar neutrino problem, and contribute greatly to our understanding of stellar structure and evolution.

Froehlich's analysis of the ACRIM data concentrated on the low- frequency range between 10 and 80 μHz, where the amplitude is expected to be largest on theoretical grounds. On the other hand, in this spectral region the lines are closely spaced and many of the lines are not expected to be resolved, so Frohlich carried out a statistical study, searching for excess power when the data are binned into regions with and without lines, as predicted by models with different values of buoyancy frequency N in the core, and different rotation rates. As already noted, this statistical study produced marginal results at best.

We have recently begun a different approach, in which we used a CLEAN algorithm to rid the data of effects of the window spectrum, and to search for prominent peaks in the data due to individual g-modes. The result of our first analysis is that the ACRIM power spectrum (based on 1 May 1984 to 11 April 1986 data) is consistent with pure white noise in the frequency range 20-80 μHz. This conclusion is derived from the appearance of the cumulative distribution--the log of the number of requencies for which the power density exceeds a given threshold, vs. threshold--of the spectrum. Since the cumulative distribution has not yet been analyzed quantitatively we do not yet have an upper limit on g-mode amplitudes.

The spectrum from which the cumulative distribution was calculated is based on a time string of individual shutter cycles. The time string itself has been detrended and deglitched at JPL prior to our analysis at CfA. The detrending was accomplished by removing Fourier components of the original time series with periods longer than a day. The specturm ws found to contain peaks at the diurnal (11.57 μHz) frequency and its harmonics, and at the orbital frequency of the SMM satellite (~ 177 μHz). In addition to these peaks, there are sidebands, due to the orbital gaps, of the diurnal peaks. We found that only the orbital aliases of the diurnal frequencies were reduced by the CLEAN program, a fact which indicates that the CLEAN algorithm is working well, (as tests with simulated data confirm) but that the diurnal and orbital power must actually be in the time series. The diurnal harmonics were removed from the spectrum by hand prior to computing the cumulative distribution.

Further work is planned, in connection with Dr. Philip Scherrer, to analyze the ACRIM data jointly with Stanford data obtained concurrently. Because both data sets contain suggestive, but not definitive, evidence for g-modes, it may be possible to verify or refute their existence through a correlative study.

REFERENCES

Bogdan, T.J., and Zweibel, E.G. 1985, *Ap. J.*, **298**, 867

Christensen-Dalsgaard, J. 1982, *Mon. Not. Roy. Astron. Soc.*, **199**, 735

Claverie, A., Isaak, G.R., McLeod, C.P., van der Raay, H.B., and Roca Cortes, T. 1979, *Nature*, **282**, 591

Claverie, A., Isaak, G.R., McLeod, C.P., van der Raay, H.B., and Roca Cortes, T. 1980, *Astron. Astrophys.*, **91**, L9

Deubner, F.L., and Gough, D.O. 1984, *Ann. Rev. Astr. Astrophys.*, **22**, 593

Foukal, P., Fowler, L., and Livshitz, M. 1983, *Ap. J.*, **267**, 863

Froehlich, C., and Delache, P. 1984, in *Solar Seismology from Space* (Snowmass conference), NASA-JPL Froehlich, C., 1987, in *IAU Symposium #123* (in press)

Grec, G, Fossat, E., and Pomerantz, M. 1980, *Nature*, **288**, 541

Grec, G, Fossat, E., and Pomerantz, M. 1983, *Solar Phys.*, **82**, 55

Macris, C. J., Muller, R., Rosch, J., and Rouddier, T. 1984, in *Small-scale Dynamical Processes in Stellar Atmospheres*, ed. S. Keil (Sacramento Peak: Sunspot), p. 265

Parker, E.N. 1975, *Ap. J.*, **198**, 205

Roberts, B. and Campbell, 1986, preprint

Singh, J., and Bappu, M.K.V. 1981, *Solar Phys.*, **71**, 161

Spiegel, E. A., and Weiss, N. O. 1980, *Nature*, **287**, 616

Spruit, H.C., and Roberts, B. 1983, *Nature*, **304**, 401

Tassoul, M. 1980, *Ap. J. Suppl.*, **43**, 469

Willson, R.C. 1979, Active cavity radiometer type IV, *J. Appl. Opt.*, **18**, 179

Willson, R.C. 1981, *Solar Phys.*, **74**, 218

Willson, R.C. 1981, Gullkis, S., Jannsen, M., Hudson, H.S., and Chapman, G.A. *Science*, **211**, 700

Woodard, M. 1984, Ph.D. thesis, Univ. California at San Diego

Woodard, M., and Hudson, H.S. 1983a, *Solar Phys.*, **82**, 67

Woodard, M., and Hudson, H.S. 1983b, *Nature*, **305**, 598

Woodard, M. and Noyes, R.W. 1985a, in *Seismology of the Sun and Distant Stars*, NATO Conference, Cambridge England

Woodard, M., and Noyes, R.W. 1985b, *Nature*, **318**, 449

Woodard, M., and Noyes, R.W. 1987, *IAU Symposium #123*, (In Press)

Zweibel, E.G., and Bogdan, T.J. 1986, *Ap. J.*, **308**, 401