SOLAR OSCILLATIONS OBSERVED IN THE TOTAL IRRADIANCE*

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Abstract. The total solar irradiance measurements obtained by the active-cavity radiometer on board the Solar Maximum Mission have been analyzed for evidence of global oscillations. We find that the most energetic low-degree p-mode oscillations in the five-minute band have amplitudes of a few parts per million of the total irradiance, and we positively detect modes with $l = 0$, 1, and 2. The distribution in l differs from that of the velocity spectrum, with relatively more power at lower l values. The individual modes have narrow line widths, corresponding to values of Q greater than a few thousand, or lifetimes of at least a week. We do not detect the 160-min oscillation in the power spectrum, and place an upper limit of 5 parts per million (99.9% confidence) on its amplitude.

1. Introduction

The new field of 'solar seismology' (e.g. Gough, 1980) is providing a tool to study the solar interior. The observational material consists of the solar global oscillations in three different period ranges: p-modes in the 5-min band (Deubner, 1975; Claverie *et al.*, 1979); the mysterious 160-min oscillation (Severny *et al.*, 1976; Brookes *et al.*, 1976); and the structure at periods of about 50 min or less reported by Hill *et al.* (1976). The mode identifications, amplitudes, frequencies, and general morphology of the oscillations will all contribute to our knowledge of solar interior structure and dynamics, as detailed in other papers from these proceedings.

The main results so far come from velocity measurements, namely the Doppler shifts of Fraunhofer lines. These measurements vary in their degree of spatial resolution; measurements of low-degree modes are more-or-less averages over the whole solar disk. We report here the first observations in integral solar irradiance (flux), using data provided by the Active Cavity Radiometer Irradiance Monitor (ACRIM; see Willson, 1979), on the Solar Maximum Mission (Willson and Hudson, 1981; Willson *et al.*, 1981). These data form a very long time series that will provide unsurpassed frequency resolution.

In this initial report we describe a preliminary time-series analysis of the ACRIM data in two period ranges: 5-min band (Sections 3 and 4) and the 160-min band (Section 5). To summarize briefly, we find that the 5-min modes are detectable and provide interesting information, while the 160-min mode is not but might not have been expected in this data set.

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* Proceedings of the 66th IAU Colloquium: *Problems in Solar and Stellar Oscillations*, held at the Crimean Astrophysical Observatory, U.S.S.R., 1–5 September, 1981.

Solar Physics **82** (1983) 67–73. 0038–0938/83/0821–0067$01.05.

2. Data

The ACRIM instrument provides bolometric measurements of the total solar irradiance. The thermal (pyrheliometric) detector responds accurately – at all solar wavelengths of any significance – to variations in the intensity. The instrument is aboard the Solar Maximum Mission spacecraft, launched on February 15, 1980. We have analyzed data from a 137-day interval: March 5 to July 20, 1980. The heart of the detector is a blackened conical cavity, whose rate of heat absorption is kept constant by servo-control (the thermal relaxation time is about 1.5 s). A mechanical shutter exposes the cavity to the full Sun during half of a 131.072-s cycle. When the shutter is closed the cavity is heated by an electrical coil. When the shutter is open, the Sun, of course, supplies part of the power input, hence the solar flux is recorded as the difference of the electrical heating rates on alternate halves of the cycle. The voltage across the heating coil is read (to 13 significant bits) every 1.024 s. Half of the readings cannot be used, because the thermal transients produced by the action of the shutter are much larger than any solar-induced voltage changes. We therefore ignore the 32 readings immediately following the opening or closing of the shutter and average only the succeeding 32 samples. To summarize, we sample the solar flux about once every two minutes, with a solar viewing time of about half a minute. The Nyquist frequency of the basic shutter cycle period is 3.815 mHz, placing it just above the main envelope of the 5-min oscillations (aliasing is apparently not a severe problem in our spectral analysis).

The orbital period of the satellite is close to 96 min (frequency = 0.174 mHz) but changes irregularly by about 0.1% during the observations. Periodic gaps occur in the data when the low-earth orbit SMM satellite is in the earth's shadow. We extrapolate the measured flux to one astronomical unit by making the standard earth-sun distance correction and by compensating for the effects of satellite orbital motion on the perceived irradiance.

Large, slow variations in the data reflect the development of solar active regions (Willson *et al.*, 1981). In searching data for global oscillations, we view these long-term drifts as a source of noise. We describe in the following sections the filtering that we have used to minimize this noise. Slow drifts in the instrument itself are quite small and have negligible effects on the analysis of high frequencies.

3. Observations of Low-Degree *p*-Modes

The basic tool in our analysis of the short-period oscillations is spectral analysis via the fast Fourier transform. Because of the periodic data gaps mentioned above, the spectral power cannot be straightforwardly estimated from the direct transform of the time series, even with some crude estimate of the missing data. However the sunlit portion of the satellite orbit is long enough that a continuous, unbiased auto-covariance function can be calculated and transformed into a spectral estimate. In practice we need some high-pass filtering, so we first calculated the power spectrum of the difference time series (the differences of adjacent two-minute samples), then restored the power spectrum of the original data by the appropriate frequency attenuation factor.

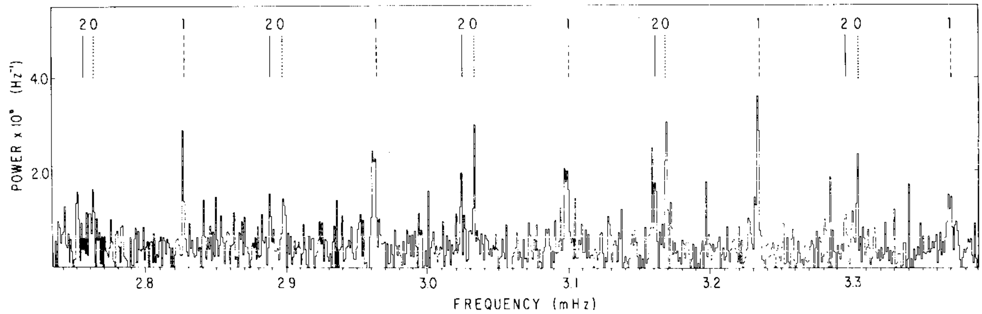

Fig. 1. Portion of the power spectrum of 137 days of total irradiance data from the ACRIM instrument on board the Solar Maximum Mission. The text describes the analysis technique in detail. The modal frequencies measured by Claverie *et al.* (1981) are shown for comparison, along with their mode identifications (*l* values).

We have analyzed eleven non-overlapping contiguous data intervals, covering the period March 5–July 20, 1980, as described. The resulting periodograms were averaged into a power spectrum of moderate frequency resolution ($\Delta\nu = 0.931$ μHz, corresponding to 2^{13} shutter cycles or ~ 12 days). Figure 1 shows a relevant high-frequency portion of this spectrum along with a set of comparison frequencies. For each of the 12-day intervals the auto-covariance function was calculated for positive lags and extended symmetrically to negative ones (2^{14} lags total, lag = shutter cycle). A symmetrical triangular envelope was applied to the function to reduce the influence of badly estimated lags near the ends.

To judge the significance of the spectral estimates we have isolated the frequency interval 2.688 to 3.517 mHz, in which oscillations have been detected in velocity. We assume that the individual points are χ^2-distributed and use the mean and scatter of the spectral points to determine the effective number of degrees of freedom. We assume the mean power in the chosen frequency band fits a straight line. We obtain ~ 4 degrees of freedom by this method; smaller than the nominal value, ~ 11 (which takes data gaps into account). The discrepancy confirms our impression that the underlying power spectrum is not as smooth as we might desire; a better model must be devised (naturally, the normal modes themselves contribute to an anomalously large scatter). We regard a spectral feature as real if it lies within 2 μHz of an already published frequency, and if its likelihood of occurring by chance (in this small frequency range) is less than 5%. For each significant point or group of points we calculate a mean frequency. We compare our observed frequencies with those of the Birmingham group (Claverie *et al.*, 1981) in Table I, and find no significant discrepancies. Table I adopts the mode classification of Grec *et al.* (1980). The power spectrum of Figure 1 is much noisier than the spectra of the best velocity measurements, but there seem to be additional significant frequencies in this plot besides the ten listed in Table I, probably because the number of degrees of freedom has been conservatively underestimated.

Following Grec *et al.* we have performed a summed-frequency analysis (but with a best folding interval of 135.25 μHz), and display the result in Figure 2.

TABLE I

Observed p-mode frequencies, μHz (Claverie *et al.* (1981)/present results)

n	$l = 0$	$l = 1$	$l = 2$
18		2.692/2.693	
19		2.829/2.828	
20		2.964/2.963	
21	3.033/3.033	3.099/3.099	3.160/3.160
22	3.168/3.169	3.234/3.234	
23	3.303/3.304	3.370/3.369	

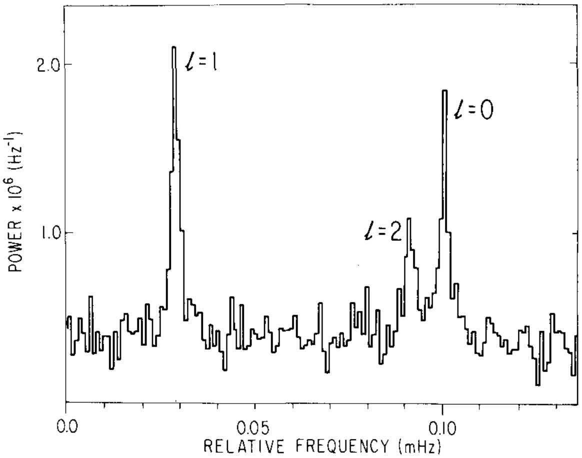

Fig. 2. Summed-frequency analysis of the type performed by Grec *et al.* (1980). The folding interval was 135.25 μHz, and the sum spans the frequency range 2.688 to 3.517 mHz. Note the relative strength of the lower-l modes in comparison with the velocity spectrum.

4. Analysis of *p*-Modes

In Table II we crudely estimate the average power, over the frequency band 2.688 to 3.517 mHz, of the modes $l = 0$, 1, and 2 (a sinusoidal wave train whose amplitude is C, in units of the average solar irradiance, has a total power of $C^2/2$). The amplitudes of the brightest individual modes are about four parts per million (half-amplitude) of the

TABLE II

Mean power in p-modes

l	Power
0	4.4×10^{-12}
1	5.8×10^{-12}
2	2.9×10^{-12}

total irradiance. The ratio of total-irradiance power to velocity power falls rapidly with l, so that at $l = 2$ the ratio is about half that at $l = 0$. We conclude from the rather narrow line widths that the oscillations are phase-coherent over a period of a week and possibly much longer; the $l = 0$ modes in particular appear to be completely unresolved at the resolution of Figure 1. We have not observed variations in the frequencies in different sub-intervals of our 137-day data set.

To test our understanding of the Sun's outer envelope we should compare the observed coupling between geometrical distortions and brightness oscillations with the coupling predicted by theory. Naturally, we cannot infer the vertical displacement of a patch of the solar surface until we know the precise relationship between actual modal amplitude and the observed velocity, which requires not only a theoretical understanding of the solar atmosphere but also an understanding of the instrumental response.

The observed l dependence probably arises in different spatial filtering resulting from the effects of limb darkening and velocity projection. Taking the interval 2.688 mHz–3.517 mHz in the published power spectrum of the Nice group (see Christiansen-Dalsgaard and Gough, 1982), we find that the r.m.s. velocity amplitude of the $l = 0$ mode is ~ 25 cm s^{-1}. Based on this value, we find that the corresponding irradiance amplitude agrees (within uncertainties) with the theoretical predictions of Gough (1980) and is therefore consistent with the notion that photospheric compression and heating are the main cause of brightness fluctuations.

5. Results for the 160-min Oscillation

To study the long-period spectral feature reported in the velocity signal (Severny *et al.*, 1976; Brookes *et al.*, 1976) we have computed the summed-epoch signal for a range of folding periods near 160 min. These composite time signals are used mainly for spectral analysis, but several were examined directly. This method of spectral analysis suffers from periodic data gap problems similar to those which occur when a power spectrum is calculated from the direct Fourier transform of the time series. A particularly annoying difficulty – the appearance of spurious, periodic, summed epoch signals – arises when large, low frequency trends in the data are seen through a slightly aperiodic data window. Because the period changes, the samples which are averaged to obtain a given phase bin of the summed epoch signal are unevenly distributed in time. Therefore, the estimate for a particular bin will be dominated by the values of the long-term trend near the temporal centroid of the distribution. However the distribution of samples is not the same for each bin. Therefore, the summed epoch signal will vary from bin to bin. This results in a non-Gaussian noise that is much larger than the true noise at periods near 160 min and leads to a poor spectral estimate. We emphasize that this leakage of low-frequency power into high frequencies does not occur in data with strictly periodic gaps. To circumvent this effect we have subtracted a running linear fit from the data (a high-pass filter with a cutoff frequency of ~ 1 cycle/day). A spectral estimate was obtained from the filtered data set at 100 equally spaced frequencies centered on 1/160 min (frequency spacing, $\Delta f = 0.0845$ μHz). The spectral power, P, is computed according to

$$P = (A^2 + B^2)/2\Delta f,$$

where A and B are the fundamental Fourier coefficients in the expansion of the summed epoch signal:

$$\delta F/F = A\cos\Phi + B\sin\Phi \quad (+\text{ higher harmonics}),$$

where $\delta F/F$ = flux variation/mean solar flux, and Φ = phase.

A plot of the resulting power spectrum appears in Figure 3. Within errors the data are consistent with no oscillation of 160 min period. Hence, we compute the maximum amplitude, $C = (A^2 + B^2)^{1/2}$, that a phase-stable oscillation could have. We assume that the Fourier components (A, B) are uncorrelated Gaussian variables with zero mean and determine their variance from the 100 sample frequencies. We find $C < 4.5 \times 10^{-6}$, with greater than 99.9% confidence.

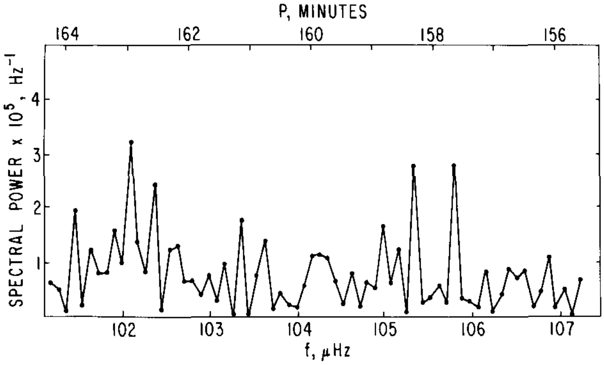

Fig. 3. Power spectrum in the 160-min band. The results set a strong upper limit of 5 parts per million (99.9% confidence) on the amplitude of a sinusoidal variation in solar irradiance at 160 min period.

To compare the ACRIM data with the velocity data for the 160 min oscillation, we select, as the proper measure of physical displacement, $\delta R/R$, the amplitude of the radial displacement in units of the solar radius. (Photospheric heating will probably be an unimportant source of brightness variation, since atmospheric compression seems to be negligible at this low frequency (Whitaker, 1963).) Defining a radiative efficiency, W, according to $\delta F/F = W\delta R/R$, and taking $\delta R \sim 5 \times 10^6$ cm (from the data of Scherrer *et al.*, 1979), we rule out oscillatory modes (or atmospheric models) for which $W < 7$. To put this result into perspective, a purely radial oscillation, in which the photosphere oscillates isothermally, would have $W = 2$ (since $F \sim R^2T^4$). Thus, we see no conflict between the velocity observations and our apparent null detection. However it seems difficult to reconcile this result with the intensity observations reported by Kotov *et al.* (1978).

6. Conclusions

The total-irradiance observations from the Solar Maximum Mission show that the low-degree *p*-modes affect the bolometric flux from the Sun. We have confirmed the frequencies reported by Claverie *et al.* (1981), suggesting that there are no slow drifts of the modal frequencies. We have demonstrated that the oscillatory modes persist for periods of a week or longer. The amplitudes – a few parts per million – are small, but appear to be consistent with the theory of the oscillatory response of the solar atmosphere (Gough, 1980). We do not find any evidence for the 160-min mode, but this is probably not in conflict with the results of the velocity spectroscopy.

The results reported here are preliminary. In the future we will extend the data base to take full advantage of the high resolution afforded by the long time series, and will also study the intermediate spectral range observed by Hill *et al.* (1976). We would also like to establish the relative phase between the velocity and the irradiance oscillations. The detection of solar flux variations, caused by non-radial oscillations, encourages us to believe that precise photometric observations of other stars can similarly help us to understand their interior structures.

Acknowledgements

We would like to thank Dick Willson for obtaining the beautiful ACRIM data, for designing the instrument in such a way that this unanticipated analysis could be carried out, and for assistance and discussions. We have also benefited greatly from discussions of time-series analysis techniques with Bill Coles, Rod Frehlich, and Charley Lindsey. The National Aeronautics and Space Administration supported this research under grant NSG–5322.

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