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Philip H. Scherrer

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Review of Observations Relevant to Solar Oscillations

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1. Summary

This review will describe some recent solar oscillation observations and methods used. The problem of identification of modes of oscillation and interpretation (and thus motivation) will not be discussed here since those topics are discussed by Jorgen Christensen-Dalsgaard and Douglas Gough in these proceedings. This review is also restricted to observations made in integrated or almost integrated sunlight (i.e. sun-as-a-star observations).

The observations are easy to summarize: p-mode oscillations of low degree (l=0 to 5-10), and maybe g-modes, are found in velocity and brightness. The amplitudes are in the range of 10 cm/sec in velocity, 10^-6 in brightness, and 4x10^-7 in apparent diameter. The periods of the most certain observations are in the 5-minute range which includes periods from 3.5 to 7 minutes. While p-mode and g-mode oscillations are expected from 3 to more than 300 minutes, it is useful to divide the possible period range into the three intervals for which results have been reported. The three ranges are discussed below.

The first is the 5-minute range for which the most dramatic and certain results have been reported. The second is the 10-120 minute range for which solar "diameter" oscillations have been reported. The third is the 160-minute oscillation found in velocity and several other quantities.

Table 1 is a summary of the main results for each of these ranges. I make no claim that table 1 is complete. Where there is typically more than one author listed on papers produced by a given group or institution, the observer name listed is one that appears on all or most of the papers. In cases where the observations did not show clear evidences of oscillations, I have shown the implied upper limits in parentheses. In general the amplitudes reported are per mode rather than power per frequency interval.

2. 5-Minute Velocity Oscillations - Resonant Scattering Spectrometers

2.1. First Results

Acoustic mode oscillations were not observed on the sun until 1962 (Leighton et al) reported observations of 5-minute velocity oscillations. The nature of these observations was not understood and verified until the suggestion by Ulrich (1970) and verification by Deubner (1975) that they correspond to trapped acoustic or p-mode waves. These oscillations are characterized by low order (f through p11 or so) and high degree (l of a few hundred). These modes provide information about the outer few thousand kilometers of the sun. These high-l observations have been recently reviewed by Deubner (1981) Leibacher and Stein (1981) and by Rhodes et al (1981) and will not be further discussed here. In order to probe deeper into the sun the lowest order modes must be observed.

Observers		Parameter/Method	Amplitudes (upper limit) 5 minute	10-120 minute	160minute
Birmingham Isaac,...	V	Resonant scattering Na and K	10 cm/s 10^{-8} linewidth		
Nice Fossat,...	V	Resonant scattering Na			30 cm/s
Crimea Severny,...	ΔV	Modified magneotgraph Fe I 5124	✓		50 cm/s
Stanford Scherrer,...	ΔV	Modified magneotgraph Fe I 5124	<10 cm/s		20 cm/s
SCLERA Hill,...	R	FFTD limb position		0.4 milliarcsec 4×10^{-7} $R_\odot$	
SMM Hudson,...	L	ACRIM, total irradiance	2×10^{-6}		(5×10^{-6})
Deubner	I	Uranus and Neptune broadband photometry	5×10^{-5}	(6×10^{-5})	
Musman & Nye	ΔI	Large scale relative I		(0.3 K, 2×10^{-4} contrast)	
Livingston	T	C I 5380 relative to Cont.		(0.3 K, 3×10^{-4} L)	
Kouchmy	ΔI	IR center-limb variations			2×10^{-4}
Crimea	ΔI	Radio Temp.			2×10^{-4}
Crimea		Circ. Pol., radio			1.5×10^{-5}
Crimea	MF	Mean Magnetic Field			2 nT

Table 1. Summary of recent Sun-as-a-star oscillation observations.

Observations of the whole sun velocity oscillations in the 5-minute period range were first reported by Claverie et al (1979). A sample of this data is shown in figure 1. The data shown is a mean power spectrum from 6 sets of 2 contiguous days observations at Izana in the Canary Islands in 1978 (from Claverie et al, 1980). These observations have been interpreted as whole sun p-mode oscillations of degree l=0,1, and 2. The average 67.5 micro-Hz separation of the peaks corresponds to the average separation of modes with even and odd l.

The selection of l=0 to 2 is made by observing in integrated light. Integrated light observations yield the average velocity weighted by limb darkening and by the distortion of the line profile by solar rotation. For a given observing scheme, i.e. a given set of spectral windows on the line wings, the expected sensitivity to the various oscillation modes can be computed.

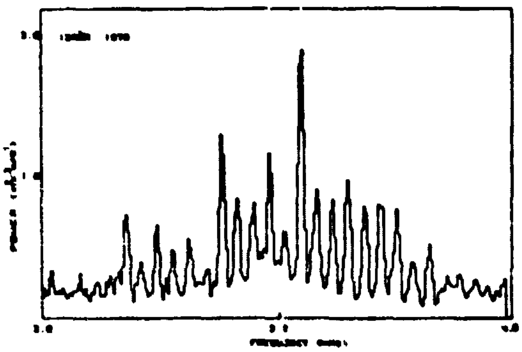

Figure 1. A typical mean power spectrum obtained by summing 6 power spectra of data strings of 2 contiguous days. From Claverie et al (1980).

This has been done by several authors including Dziembowski (1977), Brookes et al (1978), Hill (1978), Christensen-Dalsgaard and Gough (1980), and Christensen-Dalsgaard and Gough (1982). The conclusion of these studies is that whole-disk integrated light observations are strongly weighted to l=0 to 2.

2.2. Methods

The observations of Brookes et al (1976), (referred to below as the Birmingham group) and of Grec et al (1980), (described below as the Nice group) were made with an optical resonance spectrometer. These spectrometers operate by measuring the intensity of Na or K resonant scattering. Figure 2 shows a typical arrangement. Sunlight enters the instrument through a narrow band interference filter and a linear polarizer. The polarized light then enters the Na (or K) vapor cell. The cell is located in a strong, uniform magnetic field oriented normal to the light path and normal to the linear polarizer.

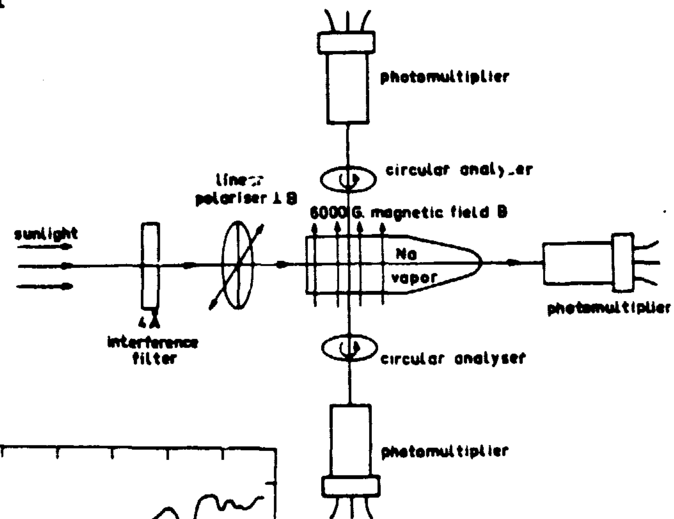

Figure 2. Schematic diagram of a resonance scattering spectrometer. (From Fossat and Roddier, 1971).

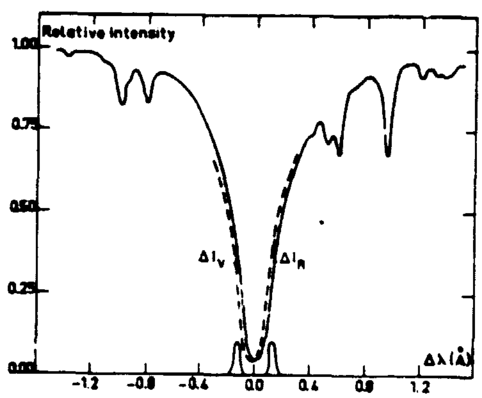

Figure 3. Principle of the resonant scattering devices. (From Grec et al, 1976).

The resonant scattering from the Zeeman split components of the Na (or K) line acts as spectral windows on the wings of the solar line (see figure 3). Light observed along the magnetic field will be the circularly polarized sigma components, one on each wing of the solar line. The relative intensity of the sigma components then is a measure of the solar line position.

These instruments have several advantages over traditional spectrographic techniques. They are small and inexpensive and thus easy to move to a remote location (such as the South Pole). Since the measurement is made by direct comparison to a physical standard, the usual sources of spectroscopic errors (mechanical flexure, spectrograph seeing, spectrograph dispersion, etc.) are absent. The instrument accuracy is limited by the magnetic field stability, vapor temperature and pressure stability, and detector stability. These factors are easy to control to the level needed to keep instrument variability well below the systematic errors that come from observing a rotating body through the atmosphere. These systematic errors will be described below. The instruments are described in detail by Grec et al (1976) and Brookes et al (1978).

2.3. South Pole

The most dramatic observations of whole sun oscillations are those made by Grec et al (1980 and 1982) at the South Pole in January 1980. The high frequency resolution made possible by the 6-day almost uninterrupted observation has allowed identification of a large number of solar modes. Figure 4 shows the resulting spectrum of 5-minute modes.

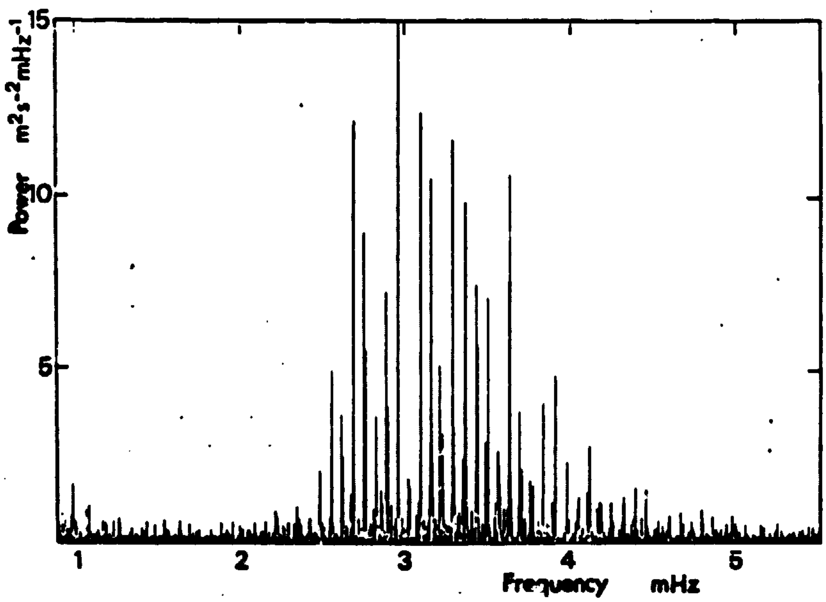

Figure 4. Power spectrum of the South Pole data. The sample analysed has a duration of about 6 days. The frequency resolution is 1.97 micro-Hz. (From Grec et al, 1982).

Figure 5 shows an Echelle diagram of this spectrum. When the data is presented in this form, the mode structure is self-evident. The procedures used to identify the l-values and to understand the frequency separation and change in separation with order are reviewed by Christensen-Dalsgaard and by Gough in the two following papers.

Once the identification of the modes seems certain, the next interesting questions concern the lifetimes of individual modes and any rotational splitting of the 2l+1 degeneracy. The frequency resolution of this spectrum (about 2 micro-Hz) is enough to allow a clean separation of the modes that can be seen with a full disk integration, but is not small enough to see any rotational splitting that might be reasonably expected. Superposed frequency analyses of the modes of each degree show the width of the peaks is broader than the resolution in the spectrum. This can come from an average lifetime of less than 6 days, rotational splitting, or a combination of both. It is also shown that the peaks at higher frequencies are broader than those at lower frequencies. Plots of the amplitudes of individual modes (obtained from spectra of 12-hour segments) show power modulation with a time scale of 1-2 days.

The conclusion of Grec et al is that the modes may be amplitude modulated with a shorter lifetime with increasing frequency. The amount of phase modulation is uncertain. There is a suggestion from the longer duration observations made by the Birmingham group that the phase may be maintained for at least a month. In this case, the amplitude modulation seen by the Nice group may be due to beating between the rotationally split modes.

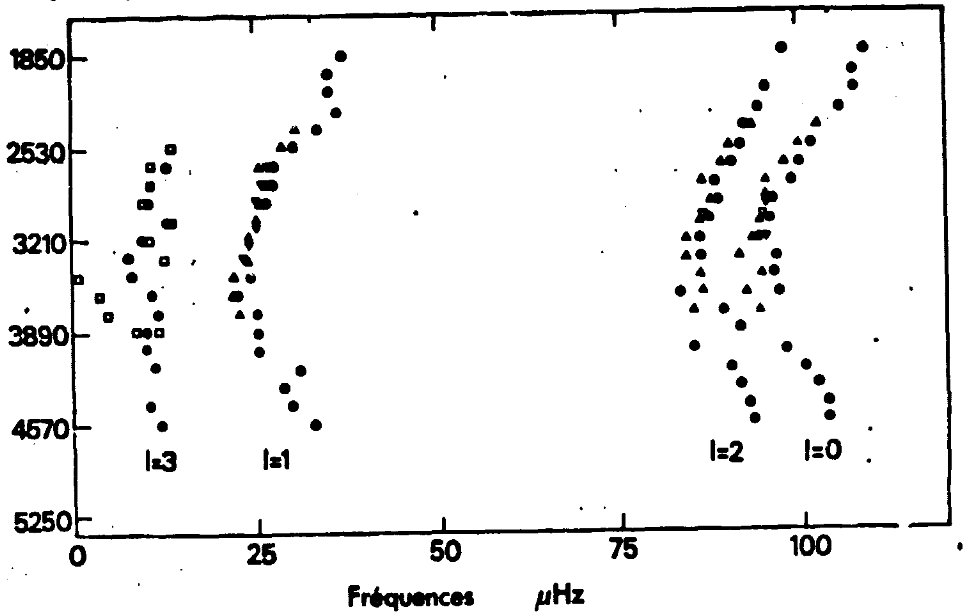

Figure 5. Echelle, or frequency-frequency diagram of the South Pole data. South Pole data in dots, Birmingham data triangles, Stanford data boxes, and ACRIM data inverted triangles. (From Grec et al, 1982).

I have attempted to summarize the lifetime question in figure 6. This figure is a schematic drawing of the oscillation lifetimes reported by a number of authors. The Nice results are shown cross-hatched from 2 to 5 mHz. There is a general trend in figure 6 for longer lifetimes for lower frequencies. The trend may be due to the lifetime of the observations as much as to the lifetime of the oscillations.

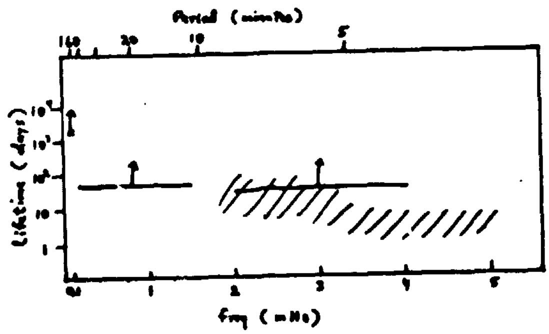

Figure 6. Schematic diagram showing reported lifetimes of velocity observations.

2.4. Rotation?

The Birmingham group has made an effort to extend the frequency resolution by combining data from many nearly consecutive days into one analysis. The obvious advantage with this procedure is a very high resolution spectrum. The disadvantage comes from combining data from different instrument and sky conditions, and from the horrible ghost structure in the spectrum introduced by data gaps. The benefit of increased resolution makes the painstaking data analysis worthwhile.

Figure 7 (Claverie et al, 1981) shows a superposed spectrum made by aligning all the l=1 peaks from a spectrum of 28-days of observations. This triplet has been interpreted as the 2l+1 rotationally split components. The resulting solar core rotation would be 2-9 times faster than the surface. This easy interpretation is actually complicated by the appearance of all 3 components (and 5 in the case of l=2). The "selection rules" that can be derived for the symmetry of the full disk observations show that only l+1 peaks are expected. (These points are discussed by Hill (1978) and by Gough in these proceedings). There does not yet appear to be a completely satisfying resolution to this difficulty. The agreement between Birmingham, Nice, and Stanford frequencies, and the agreement of observed and model frequency spacings seems to rule out an error in mode identification.

Note that the width of the peaks in figure 7 is consistent with a high

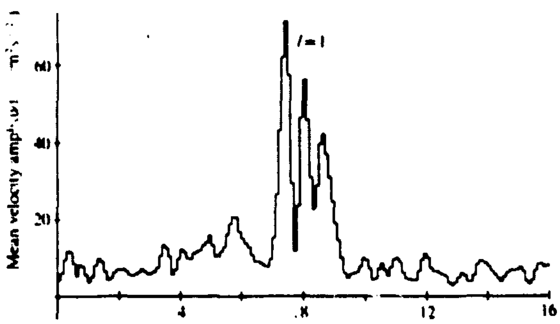

Figure 7. Superposed spectrum of the l=1 peaks from a spectrum of 28-days of data. (From Claverie et al, 1981).

Q mode, i.e. lifetime greater than the observation. This is shown as an arrow at 3 mHz on figure 6.

3. 5-Minute Velocity Oscillations - Modified Magnetograph Spectrometers

3.1. Method

The resonant scattering observations described above were made in completely integrated light, thus observing the whole solar disk. An alternate method for observing whole sun oscillations was developed in 1974 by Severny et al (1976). This method is based on a simple modification to the solar magnetograph as configured to measure the integrated light solar magnetic field. The result is an instrument to measure differential velocities. The procedures used in the Crimea and at Stanford since 1976 (Scherrer et al, 1979) are similar. The Stanford instrument will be described here.

In the integrated light mode, there is an image of the sun placed well above the spectrograph entrance aperture. Light from all parts of this image enters the spectrograph with no weighting. The solar magnetograph measures the wavelength difference between left and right circularly polarized components of a solar Fraunhofer line. In this mode, the magnetograph measures the mean magnetic field. If left and right circular polarizers are inserted into the beam at the "integrated light image" ahead of the polarization analyzer, the magnetograph signal will be the average velocity difference between the oppositely polarized beams. The polarizer configuration used at Stanford is shown in figure 8. With this arrangement, when observing in a magnetically insensitive line ($g=0$, FeI 5124 Å), the instrument measures the average velocity difference between the center of the disk and the annulus around the center. Since this is a differential measurement, the normal spectrograph errors are absent. Earth's rotation is also essentially absent from the signal.

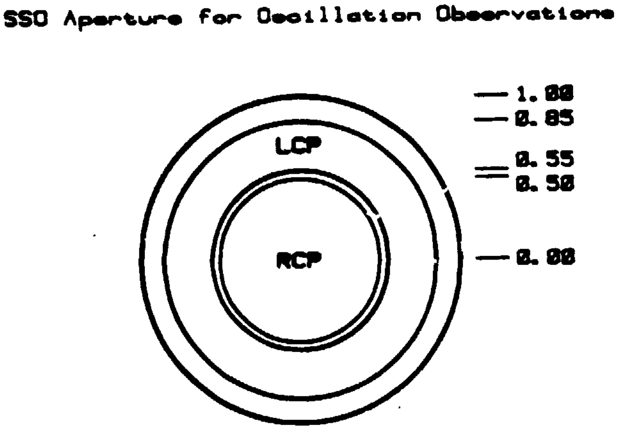

Figure 8. Polarizer configuration for Stanford modified magnetograph spectrometer.

The main source of error in this observation has the same source as in the resonant scattering spectrometers. That is, differential transmission through the atmosphere across the solar disk makes the instrument sensitive to solar rotation. The motion at the east and west limbs from rotation is about 2000 m/s. This means that even a small intensity imbalance between east and west will result in a net velocity signal large compared to the expected oscillation velocity. Even in a perfectly clean sky, the variation of airmass with zenith angle will result in a drift through the day of some tens of m/s. This whole sky transparency structure effectively limits the range of oscillation periods that can be examined to periods less than 4 or 5 hours (on the best days). Small scale transparency patches introduce noise throughout the spectrum. Grec et al (1979) examined this question and found that the typical atmospheric transparency coherence size is about 1 degree with amplitudes of 0.7 to 2 percent on clear days. The experience at Stanford has shown that meaningful data can only be obtained on very clear days.

3.2. Results

The first observations with the modified magnetograph method were of long period oscillations to be described below. Dittmer et al (1978) examined the integrated power around 5-minutes in search of variations in power with solar rotation (not found), but did not resolve individual p-modes. Christensen-Dalsgaard and Gough (1982) have examined the sensitivity of the Stanford aperture to different modes. They found that only l=3-7 modes should be found with appreciable amplitudes. With such a range of modes, the average separation between peaks would be 46 micro-Hz as compared to 68 micro-Hz for the integrated light observations. Therefore, for individual observations as short as those by Dittmer et al (1978), discrete modes should not be expected.

Longer observations (> 8 hours) were made by Severny et al (1981) and Scherrer et al (1982). In the case of the latter observations made during a month of exceptionally clear sky conditions in 1981, p-mode oscillations have been identified with l=3,4 and 5. Figure 9 shows the average of the 15 separate spectra obtained. Line segments are shown at the locations of the l=3 modes identified in the Nice South Pole observations. An Echelle plot of the spectra is shown in figure 10. Here, all Stanford peaks are

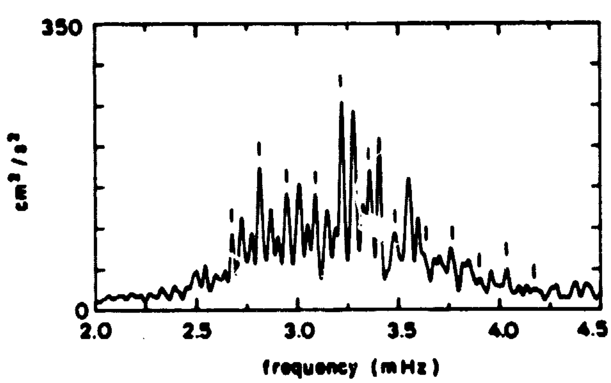

Figure 9. Average of 15 spectra from observations with an average duration of 9.6 hours. The vertical lines are the l=3 frequencies from Grec et al, 1982. (From Scherrer et al, 1982).

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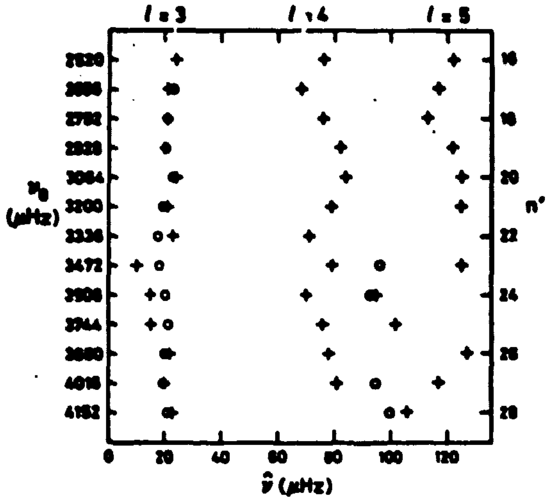

Figure 10. Echelle diagram of Stanford peaks (X). Also shown are the octupole and some of the dipole modes from the South Pole data (o). (From Scherrer et al, 1982).

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represented by dots and the Nice data by squares. There is a suggestion of l=2 modes and of higher l-value modes causing some interference with modes l=3 to 5.

The analysis of this data as a combined data set to allow an analysis of the lifetime or rotation questions has not yet been completed. Spectra have been computed using all the data spanning 28 days and do show well defined p-mode peaks suggesting that the Stanford lifetime results will be closer to the Birmingham than the Nice conclusions. The spectrum is confused by the ghosts from missing days and nights.

4. Five Minute Oscillations - Luminosity

4.1. First Results

A number of investigations of global scale temperature, total irradiance, and relative brightness variations have been made. Most of the earlier (prior to 1981) papers reported only upper bounds to oscillation amplitudes. These are represented by Livingston et al (1977), Musman and Nye (1977), and Deubner (1977) in Table 1. In each of these sets of observations the upper bounds of any possible oscillation amplitudes was found to be on the order of 1 part in 10000. At this level there is no conflict with the amplitudes that might be expected based on the reported velocity observations.

4.2. ACRIM Results

More recent observations of Deubner (1981) and Woodard and Hudson (1982) have shown clear evidence of oscillations in solar irradiance. Deubner, using broadband photometry of Uranus and Neptune, found statistical evidence for discrete p-modes with l=0 and 1 at periods close to those observed with the resonant scattering spectrometers.

Woodard and Hudson used data from the Active Cavity Radiometer Irradiance Monitor (ACRIM) onboard the SMM spacecraft. The ACRIM data has a greater accuracy than is possible from the ground and shows a clear set of p-mode peaks. Figure 11 is a portion of the power spectrum of 137 days of data. The frequencies observed by the Birmingham group are shown for comparison. The amplitudes of the brightest individual modes are about four parts per million with more power in the l=2 modes than in the l=0 modes.

The amplitudes are consistent with the observed velocity amplitudes with the assumption that photospheric compression and heating are the main cause of the brightness fluctuations. The width of the peaks suggests that the oscillations are phase coherent for at least a week and possibly longer. The analysis has not yet been done with enough spectral resolution to examine the question of rotation.

5. Diameter Observations

At about the same time that the Crimean, Birmingham, and Nice groups were beginning to observe whole sun velocities, the group at SCLERA (Hill

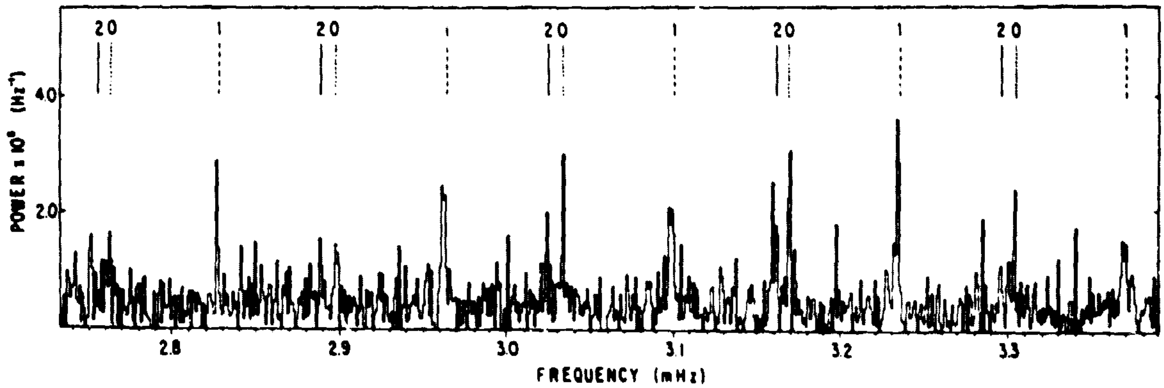

Figure 11. Power spectrum from ACRIM total irradiance data. The frequencies measured by the Birmingham group are shown for comparison. (From Woodard and Hudson, 1982).

et al, 1976) began a series of "diameter" measurements. Unlike the velocity observations, the diameter observations were begun to measure the solar oblateness rather than oscillations. The signal that is noise to the oblateness observations has turned out to be variations in the limb darkening profile that mimics diameter oscillations. Due to the limited area on the limb of the observations, these measurements are most sensitive to modes of low to intermediate degree. The period range reported has been limited to the 10 to 120 minute interval.

The observations are made by recording the position of the solar limb. The limb is repeatedly scanned with a small aperture. The limb position is then defined as the location at which a convolution of the scan intensity and a predefined weighted window passes through zero. With properly chosen weights, the method is very insensitive to effects of atmospheric seeing (Brown et al, 1978).

These observations have been the subject of a number of criticisms. The objections have centered on the possible influence of differential refraction, the lack of a measurable velocity signal in the same frequency range, and the lack of observed limb oscillations in the 5-minute range. As a result of these criticisms, Hill et al (1982) have made a careful study of criteria that can be used to distinguish solar oscillations from terrestrial noise. Their conclusion is that the "diameter" oscillations (particularly the 1979 data) are almost certainly of solar origin.

The most recent observations reported (Bos & Hill, 1982) have removed the objections concerning atmospheric affects. This was accomplished by scanning simultaneously with two scan lengths at six separate limb positions. Since the effect is limited to the extreme limb, the larger scan is insensitive to the limb darkening variations and can be used as a reference. Thus, six independent measurements are made. These have been examined in various combinations to study the amount of differential refraction and the symmetries of the oscillations. They concluded:

[1] The oscillatory phenomena are spatially global;

[2] The frequencies are stable to better than one part in 1000 over an interval of 41 days; and

[3] The horizontal spatial characteristics have symmetry properties that identify an axis in the Sun coinciding with the rotation axis.

The initial interpretation of the limb oscillations as a change in radius were in conflict with the velocity measurements (Dittmer et al,

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1978). Hill et al (1979) have since shown that the signal comes from a change in the limb profile rather than a radius change. The lack of velocity data in the 10-120 minute range is also partly due to lack of thorough analysis. It is clear from the spectra presented that any amplitudes are very small (<2cm/s). This is at the level of detectability from the ground and may not be in conflict with the diameter results.

The lack of reported power in the 5-minute range would seem to suggest the observation is not sensitive to p-modes. Perhaps this topic has not yet received enough attention.

Only a small part of the spectrum from the 1979 data has been published. This is shown in figure 12. According to the analysis of Bos and Hill (1982), most of the structure in figure 12 is solar power.

Hill (1982) has recently reported rotational splitting in the spectra from the 1979 observations. This splitting suggests a core rotation significantly faster than the surface, as does the velocity data. Hopefully, the normal processes of open exchange of information will lead to comparisons of these different types of data.

6. 160 Minute Oscillations

6.1. First Observations

The first results of solar observations reported by the Crimean group (Severny et al, 1976) was of 160-minute velocity oscillations. The 160-minute oscillations have been confirmed by the Birmingham group (Brookes et al, 1976) and the Stanford group (Scherrer et al, 1979). Additional confirmation was made by Scherrer et al (1980) and details of the observations and analysis and problems were discussed by Kotov et al (1978). The observations are made with the same equipment (and usually is the same data) as for the 5-minute velocity observations.

The results can be summarized as a whole sun velocity oscillation with amplitude of 20-50 cm/s and a period of 160.0095 +/- 0.001 minutes. The phase is coherent for at least 6 years. The signal has been seen with both modified magnetograph spectrometers and with resonant scattering spectrometers. The result has been met with a great deal of skepticism.

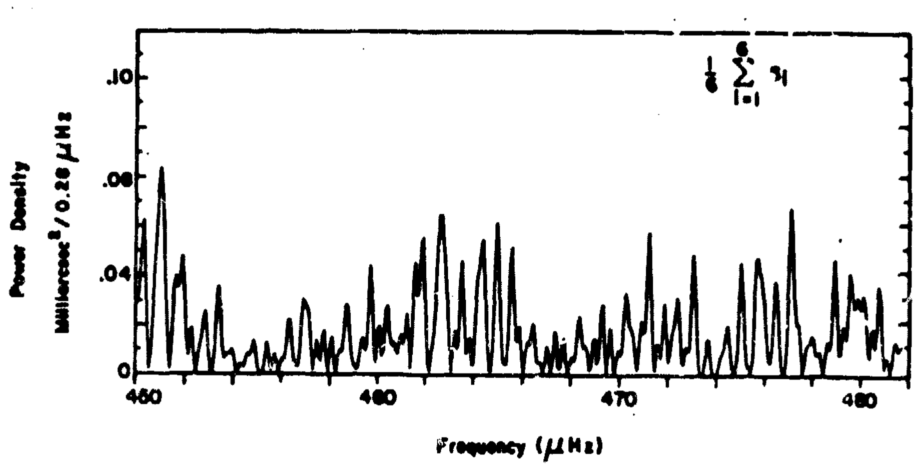

Figure 12. A portion of the power spectrum from the Santa Catalina Laboratory for Experimental Astrophysics. (SCLERA). (From Bos and Hill, 1982).

There are two basic reasons for doubting the solar origin of the 160-minute oscillation. These are the nearness of 160.0095 minutes to 160.0000 minutes which happens to be 1/9 day, and the apparent lack of other significant peaks in the same region of the spectrum.

In spite of many tests by the groups making the observations, the single best support for solar origin comes from the existence of the signal with the same phase at two separate observatories. The systematic errors due to sky transparency described above introduces significant power at low frequencies into the data. The analysis procedures used to date have not been able to remove this power except by fitting a polynomial to each observation. Since the sky-transparency drift is not exactly fit by a low order polynomial some power will be shifted into the region of interest by the parabola subtraction. Thus, any independent observatory would not be able to separate the nearly 1/9 day signal (and its +/- 1/day ghosts) from the sky transparency artifact. However, since the signal is seen with the same phase at both the Crimean and Stanford observatories, a strong case can be made for solar origin. It is also of note that the period is only very near 1/9 day and not exactly 1/9 day, but the raw data without removing parabolas also has peaks not exactly 1/9 day.

It should be noted that only a single observable g-mode (solar oscillations with periods much longer than 60 minutes can not be p-modes). Gough has suggested that one or a few g-modes might be excited preferentially by a resonance with p-modes. In any case the fundamental rule that "anything that does happen, can happen" must be remembered.

6.2. Recent Results

Scherrer et al (1982) have combined all the available data into one analysis with the spectrum in figure 13 resulting. This spectrum was calculated with a resolution of 2 nano-Hz. The peak near 160 minutes is actually three peaks, including the 1/year ghosts at +/- 33 nano-Hz. It is clear from this spectrum that there is something special about the 160 minute oscillation.

6.3. Other Parameters

In addition to velocity observations, the 160 minute period range has been studied in brightness, radio temperature, radio polarization, IR center-limb variations, total irradiance, and mean magnetic field (summarized by Kotov et al, 1982).

The ACRIM data does not show any significant power near 160 minutes with an upper limit of 5 parts per million. This seems in conflict with the report by Kouchmy et al (1980) of IR variations with amplitude of 400 parts per million. Until these other parameters are observed at other observatories, preferably with different longitudes, their solar origin is likely to be viewed with some skepticism.

7. Conclusion

The field of solar oscillations is clearly exciting. While ground based velocity measurements appear to be limited to about 1 cm/s, there is still much to be learned about the solar interior from these observations. The recent observations of many days obtained by the Birmingham group during the summer of 1981 has not yet been fully analyzed. They have attempted to kill the "ghosts" of the nights by running two observatories with a large longitude separation. Perhaps this data will answer the lifetime and rotation questions.

The six years of data collected by the Crimean and Stanford groups is just now being examined for lower amplitude g-modes. The Stanford data with a 15-second time resolution is also being re-examined for 5-minute oscillations by combining data into longer data streams. The ghost problem may prevent success.

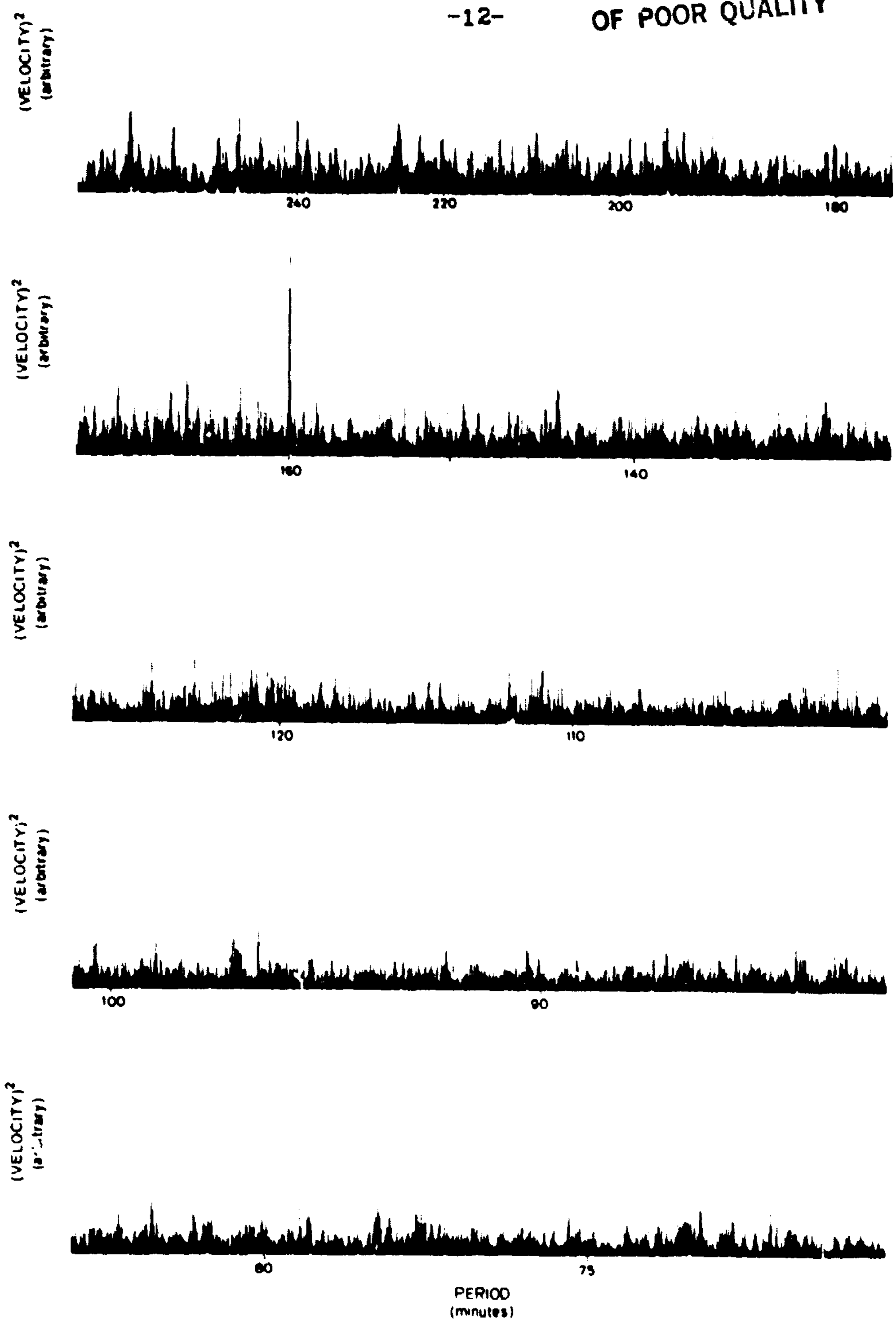

Figure 13. C ·bined Stanford and Crimean power spectrum. The spectrum includes periods from 1.2 hours to 4.6 hours, computed in steps of 2 nano-Hz. The peak near 160 minutes is seen to be unique in this range. (From Scherrer et al, 1982).

There are plans by the Nice group to return to the South Pole in December 1982 with a more stable instrument with better data acquisition equipment. If the weather cooperates, the South Pole still can provide the best ground based data since there is no component of Earth's rotation and only one instrument is needed.

In the longer term, the possible flight of the Disco spacecraft by the European Space Agency near the end of the decade may be the best hope of making the mm/s observations that can really pin down the solar models.

8. Acknowledgements

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