CHAPTER 9

TECHNIQUES FOR OBSERVING STELLAR OSCILLATIONS

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TECHNIQUES FOR OBSERVING STELLAR OSCILLATIONS

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ABSTRACT. Although stellar oscillations have been observed for more than two centuries, the demands of asteroseismology require new observations of substantially higher precision. Two major techniques are reviewed: Doppler spectroscopy and photometry. Fundamental limitations are described using the sun as a representative stellar target. The current state of the art is limited by lack of light in the case of Doppler methods and by atmospheric noise in the case of photometry. Prospects for improvements in both of these techniques are good and we may expect someday to be able to detect solar-like oscillations of stars as faint as 10th magnitude.

1. INTRODUCTION

1.1. The problem

Oscillations of stars have been observed since the discovery of the variability of δ Cephei and η Aquilae in 1784 by John Goodricke and Edward Pigott (Goodricke, 1786). Many techniques have been developed during the past two centuries to observe stellar oscillations. This paper is not intended to be a review of all of these techniques but rather a narrow look at techniques that appear to be valuable for asteroseismology. Since the power of asteroseismology increases with the number of different modes that can be measured, we focus on techniques that can reveal many oscillations. If a star is simultaneously oscillating in many different modes, it is generally the case that each oscillation mode is weak since various physical effects act to limit the net amplitude of all the oscillations. The detection of many weak oscillations in a large variety of stars is as challenging (and potentially valuable) a research area as any observational problem in contemporary astrophysics. The problem is to achieve considerably higher sensitivity and precision than has previously been available.

1.2. Overview of techniques

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There are two main classes of techniques that are used to detect weak stellar oscillations: Doppler spectroscopy and photometry. Each has its advantages and disadvantages. For example, Doppler methods work best with stars having many narrow spectrum lines while photometric methods should work with any star. On the other hand, photometric methods are sensitive to atmospheric noise while Doppler methods are nearly immune. There is no obvious best approach so both methods are in use.

1.3. Previous reviews

Several authors have addressed some or all of the subject of this review. Fossat (1984a,b) considered the problem of whether it is better to observe Doppler shifts or photometric fluctuations. Campbell and Walker (1985) reviewed Doppler methods. Young (1984) presented a history of precision in photometry and he (1974) beautifully discussed the limits of photoelectric photometric techniques. Borucki (1984) presented some of the limits of photometry for the detection of extrasolar planets, a problem with strong similarities to the detection of weak oscillations. Harvey (1985) briefly listed instrumental activities underway in both helio- and asteroseismology as of 1984. Dziembowski (1984) considered which modes of oscillation survive observational integration across a stellar disk with reasonable amplitude.

2. WHAT TO OBSERVE

It is conceivable that all stars could be observed to oscillate given sufficient sensitivity. This is a broad mandate and to limit the problem, we consider the sun as a typical lower main sequence star that shows oscillations of the sort that many stars may exhibit. Techniques that can be used to observe oscillations on stars like the sun will no doubt reveal oscillations in a wide range of stars across the H-R diagram.

The five-minute oscillations of the solar photosphere are the most readily observed solar oscillations and provide a good test of potential stellar oscillation techniques. Table I lists some of the observed characteristics of solar five-minute oscillations.

Degree (ℓ) is a measure of the scale of an oscillation and indicates the number of nodes around a stellar circumference. High degrees cannot be observed without resolving the disk because the positive and negative parts of such an oscillation pattern cancel each other. At low degree this cancellation is incomplete with the result that a significant fraction of the pattern can still be observed. Vertical Doppler oscillations are naturally weighted more toward the disk center than the scalar intensity fluctuations so that Doppler oscillations can be observed to degree 3 on the sun while intensity oscillations can be seen only to degree 2. This difference in degree sensitivity could be used in principle to help identify the degree of modes observed on a star other than the sun. This argues for making both types of observations. From a purely asteroseismology standpoint the Doppler observations are preferred because more modes are visible. Stars with strong limb darkening will exhibit a larger highest degree observable mode. This is desirable as long as the spectrum does not become so confused that identification of the various modes becomes unreliable.

For the sun the amplitude of an individual oscillation mode is quite small

Table I. Some properties of unimaged solar p modes

Degree observable	
Doppler	0-3
Intensity	0-2
Peak signal amplitude	
Doppler	15 cm s^{-1}
Intensity $\delta I/I$	1.5×10^{-6}
Background noise (disk center)	
Doppler	$\propto$ 330 m s^{-1}
Intensity $\delta I/I$	$\propto$ 0.14
$(S/N)_D \div (S/N)_I$	~ 40
Frequency	
peak	3.1 mHz
range	2-5 mHz
spacing $\Delta n = 1$	136 μHz
spacing $\Delta \ell = 1$	68 μHz
spacing $\Delta \ell = 2$	9 μHz
line width	~1 μHz

measured either by Doppler spectroscopy or by photometry. This is the essential problem that confronts observational asteroseismology. Fortunately an oscillation mode is coherent (in the sun) for typically a thousand or more cycles so that long time series observations can be used to detect the feeble signals. We know that many stars show much stronger oscillations than the sun and we can expect that others will be weaker oscillators than the sun. In any event, a reasonable observational goal is to be able to detect coherent Doppler oscillations with amplitudes of the order of cm/s and photometric oscillations of order a tenth of a micromagnitude.

The sun exhibits non-oscillatory velocity and intensity fluctuations that produce a background "noise". The spectrum of this background noise depends on the average properties of the fluctuations and provides valuable information about these fluctuations. Nevertheless, this background limits the detection of oscillation modes. At the frequencies of solar p-modes, the background noise for both Doppler and photometric fluctuations is due almost entirely to granulation. Table I gives an estimate of the granular Doppler noise for spectrum lines formed about 200 km above the photosphere when observed at disk center with good spatial resolution, and an estimate of the intensity noise for the visible continuum at disk center with the same spatial resolution. With these estimates and the peak amplitudes observed, the signal-to-noise ratio of Doppler measurements compared to intensity measurements is 40 times more favorable for Doppler measurements. Other stars may be different and the situation may differ at other frequencies, but it is reasonable to expect that Doppler observations are likely to reveal weaker oscillations than intensity observations in a wide range of stars.

Aside from the issues of relative strengths and signal-to-noise there is little to guide the selection of one observational technique over the other. However, there are properties of both Doppler and intensity oscillations that are important in designing an observing strategy. In the sun p-mode oscillations are strongest at a frequency of about 3.1 mHz but extend over a range from below 2 mHz to about 5 mHz. This has the observational consequence that samples must be taken at a rate of at least 10 mHz (100 s period). The upper limit is controlled by the declining ability with increasing frequency of the atmosphere to reflect wave motions. In

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other stars the highest frequency for trapped waves can be higher than in the sun and a sampling frequency of 20 mHz or more might be needed.

How much temporal spectral resolution is required? In the sun, p modes of the same degree but different radial order number, n, differ in frequency by about 136 μHz. Modes of the same radial order but differing by one in degree are about 68 μHz apart. To resolve this amount of splitting requires observations covering at least 1/3 day. The corresponding splitting in more massive main sequence stars is smaller so that longer observational sequences are required - of order at least one day. Modes whose degrees differ by two and radial orders by one have frequencies that differ by about 9 μHz in the sun. Resolution of this separation is an important goal of asteroseismology and requires an observational span of at least 2.6 days. In more evolved stars the separation is smaller and a week of observational coverage might be required. The next stage in resolution is to resolve the intrinsic lifetime of modes as well as departures from the average frequency differences mentioned above. The width of the spectrum of individual solar p modes implies a lifetime of the order of a day or so at high frequency and a lifetime in excess of a month at low frequency. Each mode has a degeneracy that is removed by rotation and produces fine structure components in the spectrum separated by the rotation frequency. Thus, provided mode lifetimes are longer than the rotation period, there is a chance to resolve this structure and deduce information about interior rotation. One can conclude that a thorough reconnaissance of the oscillation spectrum of a star similar to the sun would require observations at a frequency of at least 20 mHz for a period of at least a month. A preliminary reconnaissance would require a span of about 3 days.

An argument has been made here that both Doppler and photometric techniques should be used for asteroseismology studies in order to help identify the degrees of the modes. However, if one technique appears more powerful it would be Doppler spectroscopy because of the larger number of modes potentially observable.

3. DOPPLER TECHNIQUES

3.1. Observational limits

The problem is to measure the oscillatory Doppler shift of one or more spectrum lines with precision at the cm s^{-1} level. Several investigators (Hall and Hinkle, 1981; Brault, 1985; Bobroff, 1986) have shown that the shift of a spectrum line can be measured with an rms velocity error, σ_v, that can be expressed approximately by

$$\sigma_v = (W_{inst} W_{line})^{1/2} \, [(S/N)_I]^{-1} \tag{1}$$

where W_{inst} is the full width at half maximum of the instrumental spectral resolution function, W_{line} is the full width at half maximum of the spectrum line (both in velocity units) and $(S/N)_I$ is the signal-to-noise ratio of a measurement of the intensity at the half maximum depth point of the spectral line profile. If one assumes that $(S/N)_I$ is due solely to photon noise having a constant value at all temporal frequencies and one considers a perfect telescope of aperture d (m) operating at 5500 Å then the photon noise power density, P (m^2 s^{-2} Hz^{-1}), is

$$P = W_{line}/(150 \, n \, d^2 \, 10^{-0.4V}) \tag{2}$$

where n is the number of spectrum lines observed simultaneously and V is the

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apparent visual magnitude of the star. Figure 1 shows the solution of equation (2) for d = 1 m and W_{line} = 8000 m s^{-1} (a typical solar value) and various values of n.

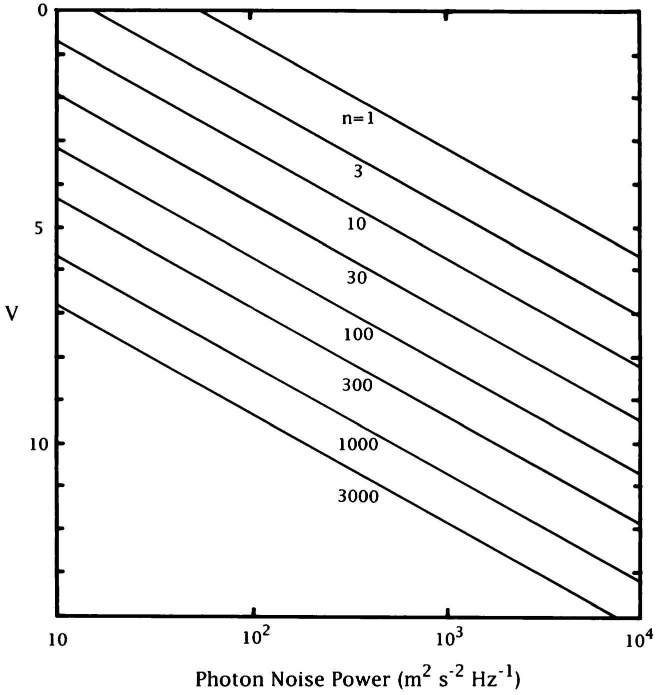

Figure 1. Visual magnitude *vs.* noise power density for a Doppler shift measurement due to photon noise as a function of the number, n, of spectrum lines observed simultaneously with a 100% efficient 1-m telescope. The spectrum lines are assumed to have a full width at half maximum of 8 km/s and the wavelength is 5500Å.

The solar p modes have power densities up to 10^4 and the background is about 10 in the units of figure 1. Thus, solar-like oscillations can be observed only on bright stars if just one or a few spectrum lines are used. On the other hand, we can expect to observe solar-like oscillations on stars fainter than V=10 if large numbers of spectrum lines can be observed simultaneously and efficiently.

3.2. Instrumental limits

There are many problems that tend to prevent the limits of figure 1 from being reached. A fully efficient telescope and spectrometer were assumed while in practice it is hard to achieve even 10% efficiency. It is also unreasonable to expect to be able to observe thousands of stellar spectrum lines without any blending with each other or with telluric lines. The evil effects of the latter have been described in detail by Campbell and Walker (1985). Major sources of noise in addition to photon noise are instabilities of guiding and spectrometer dispersion. Most spectrometers have gradients of dispersion across their entrance apertures. If a star image moves across the entrance, the spectrometer may register a false Doppler shift of the spectrum. A partial solution to this problem is to use a fast autoguider to keep the image centered (but differential atmospheric refraction ultimately defeats this strategy) and to scramble the image with, e.g. fiber optics. Even if there is no guiding noise, most spectrometers drift to some extent and it is necessary to provide a stable reference to allow the drift to be measured and compensated. Many ingenious reference schemes have been devised: the most popular are passing the starlight through an atomic or molecular vapor that adds its own stable absorption lines to the stellar spectrum and transmitting or reflecting the starlight from a stable Fabry-Perot etalon which also imposes a stable set of spectral reference features. These are described below.

3.3. Current Doppler techniques

A convenient way of listing current efforts to observe small Doppler shift oscillations is by the number of spectral lines used. Table II is such a list restricted to techniques that are likely to provide high precision.

Table II. Precise Doppler techniques

Lines	Spectrometer	Reference	$\lambda/\Delta\lambda$	Noise $(m/s)^2\ Hz^{-1}$	Literature
1	Fabry-Perot	none	110000	10000	Traub *et al.* (1978)
1	Fabry-Perot	capacitance	~12000	54000	Pietraszewski *et al.* (1986)
1	Fabry-Perot	capacitance	50000	(>10)	Butcher & Hicks (1986)
1	Michelson	atomic emission line	~10000	3000000	Pietraszewski *et al.* (1986)
1	K vapor filter	none	?	180000	Isaac & Jones (1986)
2	Na vapor filter	none	50000	10000	Fossat *et al.* (1982)
2	Na vapor filter	none	?	?	Rhodes *et al.* (1986)
~10	coudé	atm O_2	63000	13000	Smith (1983)
~10	coudé	HF abs cell	61000	27000	Campbell (1983)
~100	FTS	N_2O abs cell	85000	1000000	Hall & Hinkle (1981)
~300	echelle	Fabry-Perot	90000	300000	McMillan *et al.* (1985)
~1000	coudé	Fabry-Perot	50000	(~100)	Cochran & Young (1985)
>1000	echelle	Fabry-Perot + stable laser	?	?	Connes (1985b)

Table II indicates that, with two exceptions, high spectral resolution is employed in order to resolve the stellar spectral line profiles. The question of how much resolution is enough has been addressed in detail by Merline (1985) and Connes (1985b). Sensitivity is lost with too little and efficiency is lost with too much. The optimum falls around a few resolution elements across a line profile. The table lists an estimated sensitivity in terms of spectral noise power density using the assumption of a white noise spectrum. Various authors indicate noise performance in many different ways and the listing in the table should be regarded as a rough estimate only. We recall that detection of the strongest solar oscillation modes requires a noise level less than 10000 $m^2\ s^{-2}\ Hz^{-1}$.

In the pioneering attempt to detect solar-like stellar oscillations by Traub *et al.* (1978) they used a triple Fabry-Perot etalon with its transmission maximum set to the wing of a suitable spectral line. A second signal was measured in the nearby continuum and the ratio of the Fabry-Perot signal to the continuum signal was presumed to indicate Doppler shifts of the spectrum line. No positive detections were achieved except during some test observations of sunlight.

Pietraszewski, Reay and Ring (1986), (see also Reay *et al.*, 1983 and Ring *et al.*, 1986) use a single, capacitively stabilized Fabry-Perot etalon whose passband is rapidly chopped between the red and blue wings of a suitable spectrum line. This instrument works well for the relatively strong oscillations of δ Scuti stars but is presently too noisy for detection of solar-like oscillations. Future improvements include a quieter capacitance stabilization servo and the use of up to 100 spectral lines simultaneously.

Butcher and Hicks (1986) describe plans for a similar Fabry-Perot system that will employ the quieter capacitance stabilization servo. The estimated noise performance of this servo is listed in table II and indicates that other sources of noise such as photon shot noise will likely dominate the performance of the system.

A Michelson interferometer has been used to scan a channel spectrum across a selected stellar spectrum line alternating with a laboratory reference line to determine a relative Doppler offset between the lines (Forrest, 1983; Pietraszewski, Ring and Forrest, 1986; Reay *et al.*, 1986; Ring *et al.*, 1986). So far there has been only marginal evidence for solar-like oscillations because of the high noise level. Future plans include improving the noise performance of the capacitive servo that varies the path difference in one arm of the interferometer and possible use of several spectral lines simultaneously.

The only apparently successful detection of solar-like oscillations on other stars with Doppler techniques is reported by Fossat and his collaborators (Fossat, Grec and Gelly, 1984; Fossat *et al.*, 1984; Fossat, Gelly and Grec, 1986; Gelly, Grec and Fossat, 1986). The instrument is based on the transmission of starlight through a magnetized sodium vapor in such a way that only light from the wings of the stellar sodium D lines is detected. Such a spectrometer is in principle very stable. The signal is divided by a signal derived from the nearby continuum to cancel noise due to the earth's atmosphere. The original instrument is described by Fossat, Decanini and Grec (1982) but has been replaced by an improved one described by Schmider, Fossat and Grec (1986). Unfortunately, only bright stars with significant D lines and apparent radial velocities that put the wings of the D lines at the transmission wavelength of the spectrometer can be observed.

Rhodes, Cacciani and Tomczyk (1985) have proposed a sodium vapor instrument. A similar approach, except using one of the potassium resonance lines, has been used by Isaac and Jones (1986) to observe Procyon. A positive detection was not achieved, probably because only one spectrum line could be used and the telescope was smaller than available to Fossat's group.

Coudé spectrographs have been employed by Smith (1983), Campbell (1983) and Cochran and Young (1985) together with linear diode array detectors to measure Doppler shifts using many lines simultaneously. As mentioned earlier, there is a need to supply a stable reference when using a classical spectrograph. Smith used telluric oxygen lines but winds caused noise of a few meters per second. Campbell and his colleagues have used an absorption cell filled with HF vapor and observed at the wavelength of the 3-0 vibration-rotation band (Campbell and Walker, 1979). By chance this falls in a spectral region with few stellar spectrum lines and so the potential gain of using many spectrum lines is limited. Cochran and his colleagues reflect starlight from a stable Fabry-Perot etalon to produce a regular pattern of artificial absorption lines superposed on the stellar spectrum (Cochran *et al.*, 1982; Cochran, 1984; Cochran and Young, 1985). Their system allows many spectrum lines to be observed at once so the expected noise level should allow easy detection of solar-like oscillations.

Hall and Hinkle (1981) use a Fourier transform spectrometer with a 4m telescope and an absorption cell containing N_2O to observe about 100 lines in the infrared spectra of bright stars. Unfortunately, the method has insufficient time resolution to observe solar-like oscillations and the noise level is high because only a single detector is used.

In the quest for simultaneous observation of many spectrum lines, attention has naturally turned to echelle spectrographs equipped with two-dimensional array detectors. A group at the University of Arizona (Frecker *et al.*, 1984; McMillan *et al.* 1985, 1986) transmit starlight through a tilt-tunable Fabry-Perot interferometer to provide a stable reference. This system has the advantage of not requiring high performance from the echelle spectrograph but is limited to sampling the stellar spectrum only at the transmission peaks of the Fabry-Perot etalon. Smith *et al.* (1986) report detecting low frequency Doppler shift variations in the spectrum of Arcturus using this instrument. Connes (1985a,b; 1986) has proposed using an echelle spectrograph, a ccd detector in its focal plane, a Fabry-Perot reference spectrum and a stable laser to control the stability of the Fabry-Perot. The entire wavelength system of the instrument is traceable to the stabilized laser with the result that a very low noise level should result.

4. PHOTOMETRIC TECHNIQUES

4.1. Observational limits

For rapidly rotating stars or stars with few spectrum lines, Doppler spectroscopic techniques are not necessarily the best method. The obvious alternative is precise photometry. As indicated in table I, the amplitude of the strongest solar oscillation modes is only a few parts per million. With a line width of roughly 1μHz, the signal power density of solar oscillations is of the order of 10^{-6} in units of $(\delta I/I)^2$ Hz^{-1}. The problem is to measure photometric fluctuations of this and smaller size. Considering only photon shot noise, the noise power density is simply the reciprocal of the number of photons detected per second and a reasonable goal is to obtain a flux of 3×10^6 s^{-1}. It is easy to show that to obtain this photon flux the relation between telescope diameter, d(m), bandwidth, W(Å) and stellar V magnitude is

$$V = 1.0 + 2.5 \log W + 5 \log d \ . \qquad (3)$$

Figure 2 shows this relation for a range of spectral bandwidths centered at 5500 Å. A perfect telescope and instrument without an atmosphere are assumed and real devices will not perform nearly as well. The conclusion that one can draw from figure 2 is that it should be possible to observe solar-like oscillations of stars as faint as about V=10.

4.2. Instrumental limits

As in the case of Doppler techniques there are many problems that prevent the limits of figure 2 from being reached. By far the worst of these is noise produced by the earth's atmosphere. Scintillation has a flat noise spectrum at low frequencies and falls off at high frequencies at a rate that depends on the form of the telescope aperture (cf. Young, 1974). The frequency of the turnover depends on the aperture of the telescope and the wind speed but is too high to be of interest here. The noise level of the flat part of the spectrum depends on a number of factors but aperture size and zenith distance are most significant. As shown in figure 3, even a large aperture telescope observing at the zenith is not sufficient to reduce scintillation significantly below the level required to detect solar-like oscillations.

An even worse source of atmospheric noise is that due to transparency

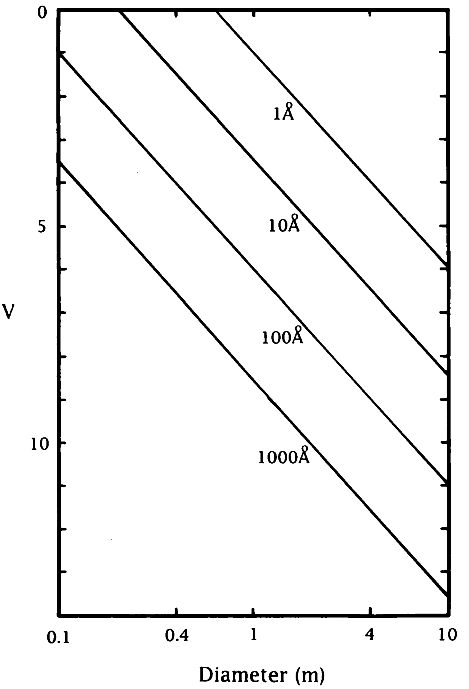

Figure 2. Visual magnitude of stars as functions of telescope aperture and spectral bandwidth necessary to obtain 3 x 10^6 photons per second at 5500 Å.

fluctuations (also called extinction variations). This noise is caused by local changes in the pressure, humidity and turbidity of the atmosphere blowing across the path between the observer and a star (cf. Heintze, 1984; Winkler, 1984). At frequencies of the order of 1 mHz the spectrum of many meteorological variables varies as the -5/3 power of frequency so we would not be surprised to see a similar variation in photometric observations. It is interesting that observations show a -2 power dependence on frequency rather than the expected -5/3. In any event the level of this noise is highly variable from site to site and with time at a given site. The best sites at the best times all show about the same level. A representative plot from an excellent photometric site is included in figure 3.

Figure 3 includes measurements of the solar irradiance spectrum with the ACRIM instrument and a simple model that attributes the variations to solar active regions and granulation. One might conclude from figure 3 that it is hopeless to try to observe solar-like oscillations from inside the earth's atmosphere. What figure 3 really indicates is that one has to be clever in attempting such observations. For example, if independent information on the variations of transparency was available then corrections could be made to reduce the effective noise level. A common strategy is to simultaneously observe one or more reference stars near the target star. Such a scheme might be successful in reducing transparency fluctuation noise to insignificance but would not attack the problem of scintillation. This is because scintillation is uncorrelated over even small angular distances. It follows that a successful attack on the problem requires use of the target star itself as a reference.

Consider light of two different colors from the star and suppose that the

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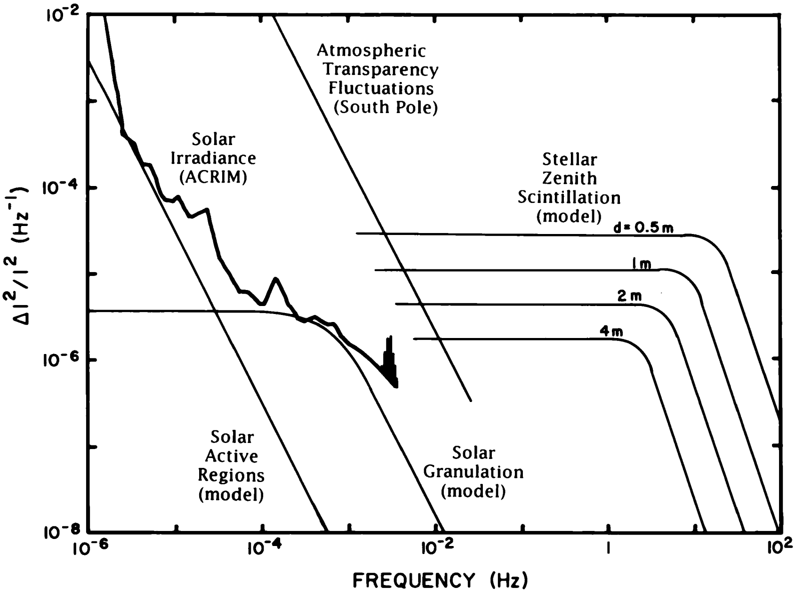

Figure 3. Noise power density spectrum of photometric measurements. Measurements of the sun are shown from the ACRIM instrument (Woodard, 1984) along with a crude model attributing the solar spectrum to active regions and granulation. Atmospheric transparency noise measurements were made at the South Pole by Duvall, Harvey and Pomerantz. Scintillation noise is shown for telescopes of different diameters observing at the zenith, a wind velocity of 30 m/s and a ground altitude of 2 km.

stellar oscillations are 50% correlated at these wavelengths. Further suppose that scintillation and transparency fluctuations are 99% correlated at the two different wavelengths. The results of these assumptions are shown in figure 4 where we see that although more light is required to detect the oscillation signal, taking the ratio of the observations at two wavelengths succeeds in driving the noise level below that required to detect solar-like oscillations. This basic scheme has led to two different observing strategies. First, a relatively broadband approach in which spectral resolution of the order of 40 is used to isolate two spectral regions. These regions are selected to respond as differently as possible to the stellar oscillations and as nearly the same as possible to atmospheric noise. Unfortunately, scintillation noise is not perfectly correlated at all wavelengths. The result is a restriction on the width of the filters that can be used and therefore on the brightness of stars that can be observed with a given sized telescope. Furthermore, to judge by the sun, the difference in the strength of photometric fluctuations at different wavelengths observed with low spectral resolution is small. A better plan appears to be to use enough spectral resolution to resolve individual spectrum lines (in stars with suitable lines) and to take advantage of the fact that intensity oscillations are stronger in the cores of lines than in the nearby continuum (Andersen 1984, 1986; Frandsen 1984, 1986a). This strategy allows the use of very wide spectral ranges but requires sophisticated spectrophotometric instrumentation.

By observing from space, the severe noise problems that make

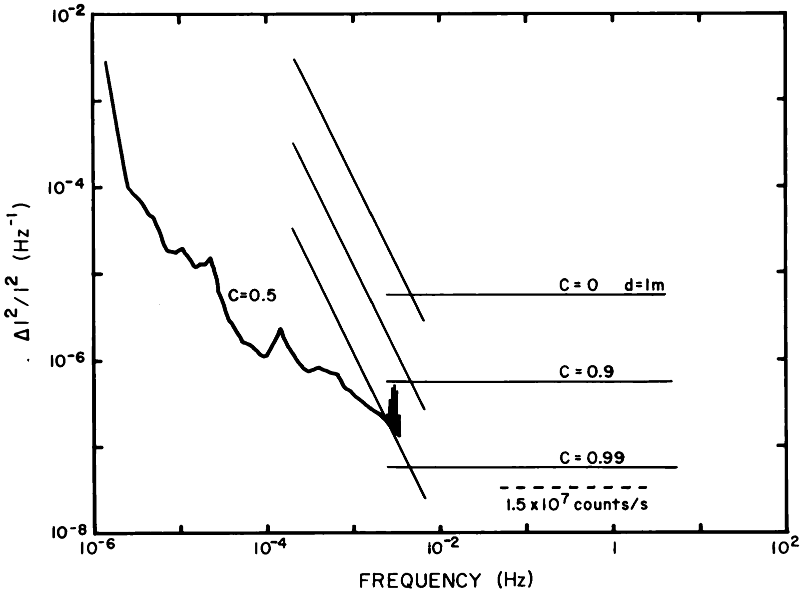

Figure 4. Same as figure 3 but the signal is assumed to be the ratio of measurements at two different wavelengths that are correlated with coefficients *c* and an aperture of 1 m is assumed. The dashed line is the photon noise associated with a count rate as indicated.

micromagnitude oscillation observations difficult from the ground are largely eliminated. As a result, a number of proposals have been made to use photometric methods for asteroseismology from space (see Noyes, these proceedings).

4.3. Current photometric techniques

It is convenient to list present attempts to achieve high precision photometry in terms of the number of spatial and spectral channels. This is done in table III. In this table, standard photoelectric photometry with photomultiplier tube detectors (pmt) is represented by the work of Kurtz (1984) and Deubner and Isserstedt (1983) (see also Schmidt-Kahler, 1984; Balona and Marang, 1986; Belmonte *et al.*, 1986; Kreidl, 1986). The noise levels achieved are sufficient for work on many oscillating stars but fail by at least two orders of magnitude to reach the level of solar-like oscillations. Narrowband photometry is represented by the work of Duvall and Harvey (1983, unpublished) who used a filter to isolate the CaII K-line in Procyon in an unsuccessful attempt to detect enhanced solar-like oscillations. Evidently the atmospheric noise was still larger than the stellar oscillation signal.

Considering instruments with two spectral channels, Noyes *et al.* (1984) made an apparently successful observation of oscillations in ϵ Eridani using the K-line and a nearby continuum reference channel. The high noise level was a result of the narrow passband used to isolate the K-line. An improved instrument with variable spectral resolution and tuning has been tested by Nisenson *et al.* (1986). Duvall and Harvey (1985, unpublished) made a number of observations with a two channel instrument but did not succeed in positively detecting solar-like oscillations

Table III. Precise Photometric techniques

Spatial channels	λ channels	λ/Δλ	Noise $(\Delta I/I)^2\ Hz^{-1}$	Detector	Literature
1	1	~4	3×10^{-4}	pmt	Kurtz (1984)
1	1	400	2×10^{-4}	pmt	Duvall & Harvey (1983)
1	2	10	3×10^{-4}	pmt	Deubner & Isserstedt (1983)
1	2	40	1×10^{-6}	pmt	Duvall & Harvey (1985)
1	2	4000	6×10^{-3}	pmt	Noyes *et al.* (1984)
1	2	400-4000	?	pmt	Nisenson *et al.* (1986)
1	2	50000	?	Si diode	Butcher & Hicks (1986)
1	many	~30000	?	ccd	Brown *et al.* (1986)
3	1	~30	?	Si diode	Borucki (1984)
many	1	~4	5×10^{-4}	ccd	Walker (1984)
many	1	~4	2×10^{-3}	ccd	Howell & Jacoby (1986)
many	1		?	ccd	McGraw *et al.* (1986)

despite a low noise in the ratio signal. Butcher and Hicks (1986) have proposed to use their Fabry-Perot spectrometer to isolate two spectral regions in which photometric fluctuations would be observed. The narrow spectral bandpass suggests that only the brightest stars would be suitable targets.

Brown *et al.* (1986) and Frandsen (1986b) have independently started projects to measure solar-like oscillations using coudè spectrometers and charge coupled device (ccd) detectors. The idea is to compare the presumably stronger oscillations in the cores of spectrum lines with the nearby continuum. Atmospheric noise will be suppressed provided that the detectors are extremely linear in intensity response. Any non-linearity will prevent a complete correction of common fluctuations.

Borucki (1984) has proposed to use three detectors (but one spectral channel) to monitor the brightnesses of a target star, a reference star and the sky. As mentioned above, this approach will not lead to a correction of scintillation noise but rather will enhance it. A number of other instruments are being used for photometry of many stars at once but these all suffer from the scintillation noise problem.

5. OTHER TECHNIQUES

A modest amount of one-dimensional imaging of the surface of rapidly rotating stars is possible by studying the details of their Doppler broadened spectrum line profiles. This technique of Doppler imaging has been used by Vogt and Penrod (1983) and others to study large amplitude Doppler oscillations of O and B type stars. The method seems to be the only way of observing stellar oscillations of degrees higher than 3 or 4 in the foreseeable future. Unfortunately, slowly rotating stars cannot be observed with this method.

One might imagine trying to detect stellar oscillations by means other than photometry and Doppler spectroscopy. The feeble effects that are expected make the prospects of such observations rather unpromising. However, one is often surprised in observational astronomy and exotic ideas should not be dismissed casually. It is not unreasonable to expect broadband polarization to exhibit changes due to stellar oscillations although the amplitude might be very weak. Schafgans and Tinbergen (1979) made an exploratory observation that produced negative results. Higher sensitivity or different stars might produce positive results.

6. CONCLUSION

Fundamental limitations suggest that solar-like oscillations should be observable on stars brighter than magnitude 10 using both photometric and Doppler spectroscopy. Present instrumental practice is approximately 10 magnitudes away from this limit so the future prospects for observational asteroseismology are very encouraging. It seems clear that Doppler spectroscopy using as many spectrum lines as possible simultaneously, and with careful attention to a stable reference and telluric blends, is an attractive technique for the near future. While photometry is best pursued from space, the possibility of comparing fluctuations within spectrum line cores with the nearby continuum may soon prove to be a useful ground-based technique.

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