THE ASTROPHYSICAL JOURNAL, 368:599–609, 1991 February 20
© 1991. The American Astronomical Society. All rights reserved. Printed in U.S.A.

DETECTION OF POSSIBLE *p*-MODE OSCILLATIONS ON PROCYON

TIMOTHY M. BROWN
High Altitude Observatory/National Center for Atmospheric Research[1]
RONALD L. GILLILAND
Space Telescope Science Institute
ROBERT W. NOYES
Harvard-Smithsonian Center for Astrophysics
AND
LAWRENCE W. RAMSEY
Department of Astronomy, Pennsylvania State University
Received 1990 January 15; accepted 1990 August 13

ABSTRACT

In the course of a search for solar-like oscillations in bright late-type stars, we have observed Doppler variability in the F5 subgiant Procyon. The variations have frequencies within a 1.1 mHz range centered at 0.9 mHz, and a total rms amplitude within that range of 2.5 m s^{-1}. Observations of Arcturus and scattered sunlight made with the same equipment during the same time interval show no such variation, indicating that the variations seen on Procyon are of stellar origin. The Doppler signal seen is entirely consistent with solar-like *p*-modes on Procyon, with maximum mode amplitudes of about 50 cm s^{-1} and periods around 20 minutes. Several statistical tests support the identification of the signal with narrow-band oscillations, but none does so conclusively. Assuming that the signal does arise from *p*-modes, there is evidence that the frequency splitting ν_0 is 71 μHz. We emphasize, however, that the data do not permit a definitive estimate of this quantity, and other values of ν_0 fit the observations about equally well. In order to clarify the sources of ambiguity in this and similar observations, we describe in detail the data acquisition, reduction, and interpretation.

Subject headings: stars: individual (α Canis Minoris) — stars: pulsation

I. INTRODUCTION

Observations of solar *p*-mode oscillations have, in recent years, resulted in great progress in understanding the internal structure of the Sun. Successes in the solar case (see, e.g., recent reviews by Christensen-Dalsgaard 1988*a*; Christensen-Dalsgaard and Berthomieu 1990) have suggested that analogous progress might be made if one could obtain frequency and amplitude information about such oscillations on other Sun-like stars. Of course, the lack of spatial resolution in the stellar case implies that except in special circumstances only a few oscillation modes—those with angular degree l of 3 or less—can be observed on stars. For this reason, discussion of such oscillations has usually been in the context of the asymptotic frequency relation first developed by Tassoul (1980). This shows that, for modes with radial order n much greater than l, the mode frequencies are approximated by

$$\nu_{nl} = \tilde{\alpha} + \nu_0\left(n + \frac{l}{2}\right) + d_0\,\frac{l(l+1)}{6} + \cdots . \qquad (1)$$

Here ν_0, $\tilde{\alpha}$, and d_0 are parameters that depend on the stellar structure. For the solar case, ν_0 has a value of approximately 136 μHz, and for other stars it scales fairly accurately as $\rho^{-1/2}$, where ρ is the stellar mean density. The value of ν_0 therefore depends sensitively on the stellar radius. The parameter d_0 depends mainly on the radial gradient of the sound speed near the stellar center and is therefore sensitive to evolutionary changes in the chemical composition in the star's core. In the Sun, d_0 is about 10 μHz; it is expected to have a similar value for all main-sequence stars, and to decrease with increasing stellar age. The parameter $\tilde{\alpha}$ depends in detail on the structure near the stellar surface and has no simple representation. Several authors (Ulrich 1986, 1988; Christensen-Dalsgaard 1988*b*, summarized and extended by Gough 1987) have considered what might be inferred about a distant star if the oscillation parameters ν_0, d_0 were known. Gough (1987) concluded that knowledge of these parameters with the precision that might realistically be obtained could significantly constrain mass and age estimates for single stars, provided that independent information about the star's composition or surface gravity could be obtained. Observations of solar-like oscillations on other stars would therefore be of great interest, since they would provide a new source of detailed information about stars, and perforce a new test of the theory of stellar structure.

The chief difficulty in observing *p*-modes on stars other than the Sun is their very small amplitude. The largest solar *p*-modes have typical Doppler amplitudes of 15 cm s^{-1}, and although stars with lower surface gravity and higher temperature may have larger oscillation amplitudes (Christensen-Dalsgaard and Frandsen 1983), single-mode Doppler shifts are not anticipated to be much larger than 100 cm s^{-1} for any star of roughly solar type. The very small signal available encourages one to observe bright stars; the brightest star of near-solar type accessible from the northern hemisphere is Procyon (α CMi, F5 IV, $m_v = 0.4$), and we have therefore concentrated on this star in our observations and in the following discussion.

[1] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

The frequencies of observed solar p-modes lie between roughly 1.5 and 4.5 mHz, with a fairly pronounced maximum near 3 mHz. This frequency range is thought to be determined largely by the acoustic cutoff frequency ν_{ac} in the stellar atmosphere, which varies according to

$$\nu_{ac} \propto g T_{eff}^{-1/2}, \quad (2)$$

where g is the stellar surface gravity and T_{eff} is the effective temperature. In the solar photosphere ν_{ac} is roughly 5.5 mHz, about 1.8 times the frequency at which oscillation amplitudes are largest. Procyon is observed to have $T_{eff} = 6450$ K $\cong 1.1$ $(T_{eff})_\odot$, $r = 2.17$ $R_\odot$, with an astrometrically determined mass of 1.7 $M_\odot$ (Hanbury Brown *et al.* 1967; Strand 1951). Applying these values to equation (2) yields an acoustic cutoff frequency of 1.7 mHz, which, by scaling from the solar case, implies that the maximum oscillation amplitudes should be found near 1.0 mHz.

The frequency resolution (and hence the length of observing run required to resolve oscillation modes) depends on the frequency separation of the modes. From equation (1), one can see that modes occur in pairs with even or odd l, and that these pairs are separated from one another by roughly $0.5\nu_0$. Models of Procyon (Demarque and Guenther 1986) indicate that ν_0 for this star should lie between 50 and 60 μHz, implying a minimum observing interval of 11 hr in order to have one frequency resolution element for each pair of modes. The modes within each pair are separated by roughly d_0, which for Procyon is expected to be 3–5 μHz. Resolving this frequency splitting would take a run spanning at least 3 days.

Several workers have attempted to detect solar-like p-modes on other stars, but so far with no clear-cut success. Noyes *et al.* (1984) reported oscillations in the Ca II intensity observed from ϵ Eri, but the amplitude observed was roughly 100 times that expected from p-modes, and the signal appeared on only 2 out of the 4 nights on which observations were made. Gelly, Grec, and Fossat (1986, 1988), using data obtained with an atomic resonance cell, reported a Doppler signal from α Centauri A with rms amplitude 10 m s^{-1} integrated over the frequency range 2.0–4.5 mHz. But Brown and Gilliland (1990) found no evidence for oscillations on α Cen A at a level several times smaller than that reported by Gelly, Grec, and Fossat (1986, 1988). Gelly *et al.* also reported detection of p-modes on Procyon, chiefly in the frequency range 1.17–1.65 mHz, with peak amplitudes of about 70 cm s^{-1} per mode. We will discuss these observations in more detail in § V.

In view of this confused observational picture, we decided to search for p-mode oscillations on Procyon, using the highest Doppler precision we could obtain and interleaving observations of Procyon with similar ones of Arcturus (α Boo, K2 IIIp, $m_v = -0.1$) and of the day sky. Arcturus provided a very good Doppler standard for the range of frequencies of interest for Procyon, since the time required for sound to travel across an optical depth in Arcturus's atmosphere is more than an hour. For our purposes, the longer period (2 day) oscillations of Arcturus (e.g., Smith, McMillan, and Merline 1987; Irwin *et al.* 1989) were easily filtered out and ignored. Scattered sunlight served a similar calibration purpose during the daylight hours, although the diffuse nature of the light source does not permit one to see all of the causes of spurious signal that may afflict spectroscopic observations of stars. By comparing the observations of these three objects, we hoped to obtain an estimate of the magnitude and frequency dependence of instrumental noise sources, as well as of any possible stellar oscillation.

II. OBSERVATIONS AND DATA REDUCTIONS

During 1988 February and 1989 February we obtained high-precision, rapid-cadence (usually 1 minute integrations) observations of Procyon (α CMi), Arcturus (α Boo), and the Sun (daytime sky) using the Pennsylvania State University bench-mounted, fiber-fed echelle spectrograph (FOE) at the KPNO 2.1 m telescope. Procyon, our primary object, was observed at all possible times, with observations of Arcturus occurring only after Procyon had reached an hour angle in excess of 5 hr. Observations of the daytime sky 10° above the northern horizon were obtained over as long a time base each day as feasible. We obtained observations with the FOE from the coudé feed over 3 nights (1988) and 2 nights (1989) preceding the 2.1 m run; these were used to optimize the spectrograph setup and observing procedure, but did not contribute data of useful quality for full analysis. We describe below the results for the 4 nights (1988) and 6 nights (1989) of 2.1 m time. All 10 nights of allocated 2.1 m time were primarily clear, although observing conditions were moderate to poor on 4 nights and instrument stability problems (still not understood) compromised one night of data in 1988.

We report the measurements of spectral (Doppler) shifts with precision as good as 1 m s^{-1}, which is comparable to the photon noise limit for these observations. Since such precision requires careful attention to the spectrograph setup, observing procedure, and data reduction, we devote detailed discussion to all of these.

For the 1988 observing run, we set up the spectrograph to cover a total of about 150 Å of spectrum in 6 orders between 4870 and 5500 Å. The resulting resolution was about 60,000, with 1 CCD pixel spanning, in Doppler units, 1.81 km s^{-1}. Starlight reached the spectrograph through a single fiber of 200 μm diameter, which, in order to maintain resolution, was reimaged within the spectrograph at unit magnification onto a slit of roughly 80 μm width. Light from an Fe-Ar hollow cathode lamp was brought into the spectrograph with a second 200 μm fiber, which also was reimaged onto the slit. By moving the reference fiber at the source end, one could illuminate the reference fiber with an incandescent lamp in order to obtain flat-field exposures through the spectrograph. Because the shutter was located at the detector, the stellar and reference fiber exposures occurred at exactly the same time.

In 1989 the spectrograph setup was modified to cover a total of about 550 Å in 12 orders between 4440 and 5700 Å. In this setup, the Doppler width of a single CCD pixel was 3.52 km s^{-1}, and the resolution was roughly 35,000. The cross-disperser used was relatively inefficient in the blue part of the spectrum, so that the count rate at 4400 Å was only 12% of that at 5700 Å. The reference source and reference fiber feed arrangement were the same as in 1988, except that in 1989 we used a Th-Ar hollow cathode lamp instead of Fe-Ar. Halfway through the 1989 run our original Th-Ar lamp failed, but was kindly replaced with one from the FTS facility at the McMath telescope. No difference was noted between the performance of the original and replacement lamps.

In 1989 we also modified the steller fiber feed to incorporate a double-fiber scrambler (Ramsey *et al.* 1989). This device coupled the telescope to the spectrograph using two 200 μm fibers placed end to end. At the junction between the fibers, two short focal length (1 mm) lenses separated by 1 mm transformed the off-axis angle of rays emerging from the first fiber into off-axis distance on the face of the second fiber. After passing through the second fiber, the emerging light was well

© American Astronomical Society • Provided by the NASA Astrophysics Data System

TABLE 1

OBSERVATION LOG

Date (UT) (1)	Number of Spectra (2)	Length (s) (3)	Quality (4)	rms ($m\ s^{-1}$) (5)
		Procyon		
1988 Feb 9.....	274	60	Moderate	5.8
1988 Feb 10.....	272	60	Good	5.3
1988 Feb 11.....	287	60	Moderate	5.1
1988 Feb 12.....	195	60	Poor	7.3
1989 Feb 16.....	280	60	Good	3.7
1989 Feb 17.....	257	60	Good	3.7
1989 Feb 18.....	310	60	Good	3.5
1989 Feb 19.....	191	60	Poor	4.3
1989 Feb 20.....	244	60	Moderate	4.1
1989 Feb 21.....	265	60	Good	3.4
		Arcturus		
1988 Feb 11.....	80	60	Moderate	4.2
1988 Feb 12.....	60	60	Poor	8.4
1989 Feb 16.....	96	60	Good	1.1
1989 Feb 17.....	64	40	Good	1.5
1989 Feb 18.....	20	40	Good	1.5
1989 Feb 19.....	50	60/40	Moderate	1.6
1989 Feb 20.....	128	60	Moderate	1.8
1989 Feb 21.....	119	60	Good	1.3
		Sun		
1988 Feb 10.....	148	60	Poor	7.4
1989 Feb 16.....	278	60	Good	2.2
1989 Feb 17.....	198	60	Good	1.6
1989 Feb 18.....	231	60	Moderate	2.0
1989 Feb 19.....	287	60	Poor	2.7
1989 Feb 20.....	300	60	Good	1.8

scrambled in both space and angle. We found that the double scrambler eliminated temporal variations in grating illumination that were responsible for roughly 5 $m\ s^{-1}$ rms Doppler noise in our 1988 data. With the double scrambler in use, we were able for the first time to achieve shot-noise–limited Doppler precision. Since the 1989 data have smaller errors than those from 1988, we will base most of the following discussion on the 1989 observations.

For both observing runs we used TI 800 × 800 CCD detectors (TI2 in 1988 and TI3 in 1989). To reduce the readout time without sacrificing resolution, we used 1 × 2 pixel binning on readout. The detectors were oriented so that the echelle orders ran along CCD columns.

Table 1 summarizes the observations. Typically 10% more spectra than are shown in column (2) of the table were collected but were not analyzed because of poor signal levels. The Doppler rms shown in the last column applies to the time series after all of the reduction steps described below had been carried out.

a) Reduction Process

A typical spectrum for any of our primary objects has a signal-to-noise ratio per pixel (along the dispersion) of 300. Because the slit width (not pixel size) limited the spectral resolution, this corresponded to roughly 500 per resolution element. The detected photons spread in the cross-dispersion direction over about 5 pixels FWHM, with 99.5% of the full signal contained in the central 10 pixels of each spectral order. In the extraction of one-dimensional spectra, one may (1) perform an optimal extraction (Horne 1986), in which knowledge of the cross-dispersion point-spread function (PSF) is used to derive an unbiased estimate of intensity per wavelength bin, or (2) simply form the sum over a specified number of pixels in the cross-dispersion direction. In principle, the first is the best approach, using a PSF for the orders derived from continuum source flat fields. This allows an unbiased estimate of intensity, application of pixel-to-pixel flat-field corrections, and rejection of cosmic-ray events as multi-σ, local deviations from the PSF fit. But a cross-dispersion drift of the spectral orders of only 0.01 pixel between the continuum flat fields and stellar sources yields errors large compared with the inherent noise. The camera at the FOE showed cross-dispersion drifts of order 0.03 pixel hr^{-1}, making application of optimal extraction inadvisable. We have thus adopted the simpler approach of summing over 10 pixels per order in the cross-dispersion direction to extract one-dimensional spectra.

Removal of CCD–induced imperfections in the data requires the use of bias, dark, and flat-field corrections. Having adopted a simple summation to extract one-dimensional spectra, we could perform all of these linear operations after forming the one-dimensional spectra. Because of the excellent cosmetic quality of TI3 (and of most of TI2 used in 1988), and because of our high signal-to-noise ratio with short exposures, the bias and dark corrections proved to be of minor importance.

Over the six night 2.1 m run in 1989 the full range of cross-dispersion order positions varied by 2 (binned by 2) pixels. Drift within a night was as much as 0.5 pixel. Similar offsets existed for the 1988 data. The one-dimensional flat-fields, derived as simple sums across the orders and normalized to a mean of unity, are technically correct only if the PSF for the flat-field and stellar observations match precisely in both position and shape. We have chosen to adopt a mean flat-field derived from the average of 160 individual continuum source exposures taken over the full course of the run. The resulting mean flat field deviates from the weighting which would be appropriate for correcting any individual observation, simply as a function of cross-dispersion offset; we will return to a discussion of this point in the section on temporal filtering.

With one-dimensional versions of mean bias, dark (scaled to stellar exposure times), and flat field in hand, we extracted and corrected one-dimensional spectra for all of the interleaved object and comparison lamp spectra in the usual way. For each night this reduction yields a time series of spectra, for each spectral order, that have been corrected for bias, dark, and gain variations. Seeing and extinction changes lead to both intensity and continuum shape variations. To minimize this effect, we flattened each individual stellar spectrum order by normalization to a Gaussian convolution of width 80 pixels. In the time series over the normalized one-dimensional spectra, we replaced large-amplitude (greater than 6 σ) discrepancies by the time-series mean, in order to eliminate effects of the strongest radiation events.

b) Analysis

Our aim was to derive the Doppler shift as a function of time from the stellar spectra. For each individual night and spectral order we formed cross-correlations between the individual observations and the mean of 10 spectra near the middle of the observation set. We derived the relative offsets in pixel units by finding the peak of the cross-correlation, using simple quadratic interpolation involving the values at 0 and ± 1 pixel offsets.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

As explained by Brown and Gilliland (1990), this technique for determining the spectrum shift is both simpler and less noisy than other methods we have tried.

Positional shifts of the stellar spectra arise from many factors, probably the least of which is the sought-for stellar oscillation. Here we will discuss only techniques for minimizing errors at frequencies higher than 0.0003 Hz. It is likely that several of our procedures would be altered if the highest priority were to maintain precision at lower frequencies. We discuss in turn several sources of apparent velocity change and the techniques used to remove these from the data set:

1. *Motion of telescope relative to the solar system barycenter* (typically 100 m s^{-1} h^{-1}).

2. *Drift of the instrument.*—This includes any offsets between the spectra and detector, such as Dewar slumping as liquid nitrogen boils off, spectrograph jitter due to mechanical vibrations, and spectrograph seeing effects. Both low- and high-frequency components exist. The simultaneous observation of the comparison lamp spectra allows for removal of these effects simply by forming the difference between the time series of shifts for the object and comparison spectra. This correction is of order 100 m s^{-1} over an hour for the low-frequency components, and up to 10 m s^{-1} frame to frame for high-frequency components.

3. *Residual errors due to flat-fielding imprecision, CCD nonlinearities, etc.*—To correct for these effects, we attempt to remove small errors that can be correlated with external parameters of the observations, even if the chain of causality is not known explicitly. For example, the variations in mean stellar intensity resulting from pulsations are expected to be very small, while those from atmospheric and instrumental sources may be large. Any substantial correlation of apparent velocity and observed intensity must therefore be dominated by factors not intrinsic to the star. One may correct the velocity time series by subtracting from it a multiple of the intensity time series, where the multiplying factor is chosen so that the cross-correlation between the velocity variation and the intensity is zero. More generally, we retain during the extraction of one-dimensional spectra a time series of external parameters characterizing each exposure. The external parameters, in rough order of decreasing importance, are the mean intensity, the mean width of a Gaussian function best fitting the order widths, the mean cross-dispersion position of orders on the CCD, and a measure of order tilts relative to the CCD. We correct the apparent pixel shift time series by subtraction of a simultaneous linear least-squares fit against all of the external parameters. In order to decorrelate optimally at the desired high frequencies, and to avoid spurious correlations resulting from processes with long time scales, we high-pass–filter all time series before performing the deprojection. This high-pass filtering was performed by convolving the various time series with a Gaussian with FWHM = 900 s, and subtracting this smoothed time series from the original. The transfer function of the effective filter has a power response of 0.5 at 0.35 mHz and 0.9 at 0.63 mHz. The decorrelation step generally removes only small errors of order 1–10 m s^{-1}, but can result in a much cleaner velocity time series.

After application of all of the above steps to the pixel shift time series derived from individual orders, a weighted sum is taken to yield a final relative velocity time series. Weights for individual orders are chosen empirically to minimize scatter in the combined result. The resulting individual order weights reflect simple signal-to-noise and line density considerations, as would be expected.

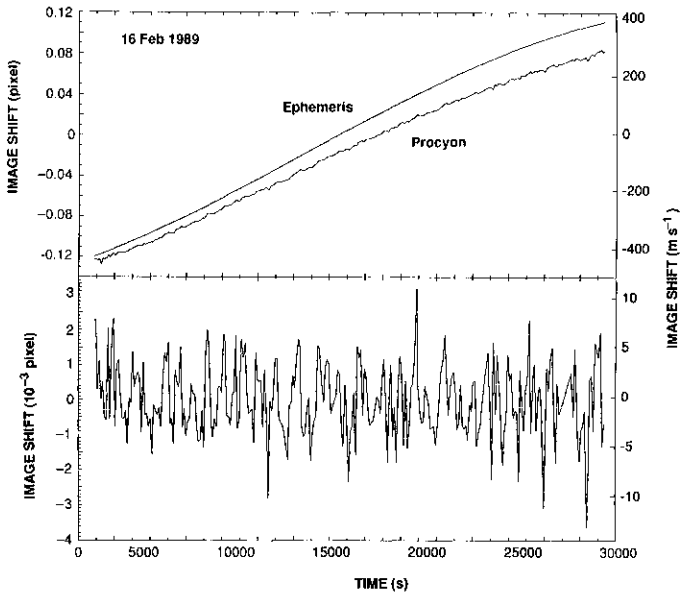

FIG. 1.—Time series of Procyon's measured Doppler shift for the night of 1989 February 16. *Top:* Raw Doppler shift in pixel units, after subtraction of the instrumental shift as measured by the reference spectrum. *Bottom:* The same time series after correction for Earth's motion, high-pass filtering, and deprojection against external variables.

Figure 1 shows the apparent velocity change, after removal of instrumental drift by differencing the stellar pixel shift time series against that for the comparison lamp. Plotted with a small (arbitrary) offset is the expected variation due to motion of the telescope relative to Procyon (primarily Earth rotation) for the night of 1989 February 16. (The low frequency drift of our velocities relative to the ephemeris values has not been accounted for but may be a residual of small temperature drifts in the spectrograph. This term is not a problem for detection of stellar oscillations, as it is easily filtered out.) The lower panel of Figure 1 shows the final pixel shift time series after high-pass filtering and decorrelation against external parameters; the rms of the final time series is 0.00105 pixels, or 3.7 m s^{-1}. The ultimate measure of our precision is the rms of a stellar time series following all of the reduction steps. For Arcturus, with its high signal-to-noise ratio and very strong, sharp spectral lines, we have attained a best rms variation over a 2.5 hr time series of 1.1 m s^{-1}. This rms corresponds quite closely to the limit imposed by our shot-noise, spectral resolution, and wavelength coverage. We note that 1.1 m s^{-1} corresponds to (1) a relative shift of spectra by 3×10^{-4} pixels, (2) a physical displacement at the CCD of less than 50 Å, and (3) a 1.8×10^{-5} Å change in the center wavelength of a typical spectrum line.

III. RESULTS AND INTERPRETATION

In this section, we discuss many ways of looking at the Doppler observations, in an attempt to answer three questions: Is there a demonstrable stellar Doppler signal from Procyon? If so, does it result from narrow-band oscillations, or might it arise from some broad-band process such as convection? If an oscillating signal is observed, what are the amplitudes, frequency splittings, and lifetimes characterizing its spectrum?

As will become apparent, the answer to the first question is almost certainly yes. But the other two questions cannot yet be answered so decisively. The data are consistent with *p*-modes

© American Astronomical Society • Provided by the NASA Astrophysics Data System

on Procyon, and in many ways point in that direction, but they do not suffice to reveal the oscillations unambiguously. One also finds that, with noisy and gapped data, it is much easier to form an impression of oscillatory behavior than to prove its existence. This point relates both to our own observations and to those of other workers (e.g., Gelly, Grec, and Fossat 1986, 1988). For these reasons, we discuss various aspects of the data in considerable detail in the remainder of this section.

a) General Characteristics of the Time Series and Power Spectra

Using the average observed spectra and a model of the measurement noise, we compared the rms of the filtered, deprojected time series of Procyon, Arcturus, and the Sun with the values expected from detector and photon shot noise combined. This comparison showed that the variances for the Arcturus and solar time series were within 10%–20% of that calculated from shot noise, but that for Procyon was larger than expected by a factor of 3.4.

Figure 2 shows average power spectra for the three astronomical sources. These spectra are all displayed with the same scale in power density ($cm^2\ s^{-2}\ \mu Hz^{-1}$), and at a frequency resolution of 20 μHz, corresponding to the frequency resolution attainable in about 14 hr. The spectra are unweighted averages of the spectra obtained on N_{spec} nights (or days), where N_{spec} is indicated separately for each panel in the figure caption. The solar p-modes do not appear in the center panel of Figure 2 because their amplitudes are smaller (by a factor of about 2) than that of the background noise. The Arcturus spectrum has lower frequency resolution than the others because the observing time per night was always much shorter than for the Sun or Procyon. The excess variance in the Procyon time series may thus be identified with the broad hump in the spectrum between 0.3 and 1.4 mHz. The mean power level within this feature is 2.7 times that at higher frequencies; comparison of this ratio with the probability distributions for power spectra derived by Groth (1975) show that the low-frequency feature is unambiguously significant.

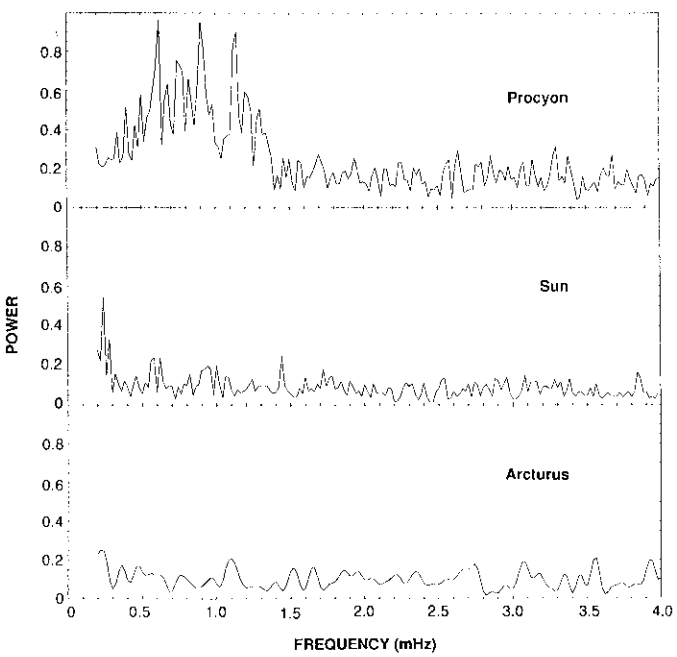

FIG. 2.—Average power spectra of the Doppler shift for Procyon, Arcturus, and the Sun. These spectra are displayed with a frequency resolution of 20 μHz, corresponding to a time series length of 13.9 hr. The averages for Procyon and the Sun are unweighted averages over the observations from all $N_{spec} = 6$ nights and 5 days (respectively) in 1989. The Arcturus average spectrum is the average over $N_{spec} = 6$ nights in 1989, weighted by the number of observations in each night. Here and in Figs. 3–7 the power spectra are scaled in such a way that a pure sinusoidal signal with amplitude 1 m s^{-1} yields a peak with approximately unit height.

Two arguments suggest that this hump is of stellar, rather than instrumental, origin. Most convincing, in our view, is that no such feature exists in the spectra of the Sun or of Arcturus. The solar observations have roughly the same window function as those of Procyon and, moreover, have a similar level of shot noise. Also, they are more strongly affected by changes in the strength and position of atmospheric absorption lines. On the other hand, the day sky is a diffuse source, and as such does not allow testing the instrumental sensitivity to stellar motion, seeing, and defocus. The Arcturus time series, however, are fully susceptible to these problems, while the high Doppler precision available with Arcturus should have made any purely instrumental effects easy to see. Although the Arcturus time series were always shorter than those of Procyon and the Sun, most allowed frequency resolution of 0.15 mHz or better, easily able to resolve a feature extending to 1.4 mHz. The absence of any low-frequency excess power in the spectra of Arcturus, even on these nights, speaks against any instrumental source for the excess Procyon power.

The second argument for the stellar origin of the excess power (and for the interpretation as p-mode oscillations) is that the shape of the power spectrum agrees with that expected from p-modes but does not resemble familiar sorts of instrumental noise. Instrumental noise (as well as convection and some other stellar processes) are usually characterized by power-law spectra. The Procyon excess power, in contrast, rises sharply out of the shot-noise background at about 1.4 mHz, rises to a maximum near 0.9 mHz, and then decreases to lower frequencies, reaching a minimum near 0.3 mHz. The high-pass filtering operation does limit the power in the Procyon spectrum at the very lowest frequencies, but only about one-third of the decrease between 0.9 and 0.3 mHz can be attributed to this filtering. Of course, considerations of this sort can never be conclusive, since an unknown noise source may in principle produce a power spectrum with any shape whatever.

Another way of looking at the data is to assemble for each object one time string covering the entire 6 day observing period. Figure 3 shows power spectra computed in this way for Procyon, Arcturus, and the Sun. The spectra in this figure have the same general shape as in Figure 2, but show the smaller scale features and larger point-to-point variability characteristic of high-resolution, unaveraged power spectra. If a single narrow-band oscillation were present in these data, one would expect it to appear as a narrow peak, surrounded by sidelobes separated from the central lobe by multiples of $(1\ day)^{-1}$, or 11.6 μHz. Many of the larger peaks in the Procyon spectrum do indeed have this appearance, but so do some of the peaks in the spectra of Arcturus and the Sun, which presumably result from noise alone.

b) Peak Height Distribution

Accepting that the excess power in the Procyon spectrum is of stellar origin, we now wish to search for statistical characteristics that may distinguish stellar p-modes from broad-band sources of power. One such characteristic is the probability

© American Astronomical Society • Provided by the NASA Astrophysics Data System

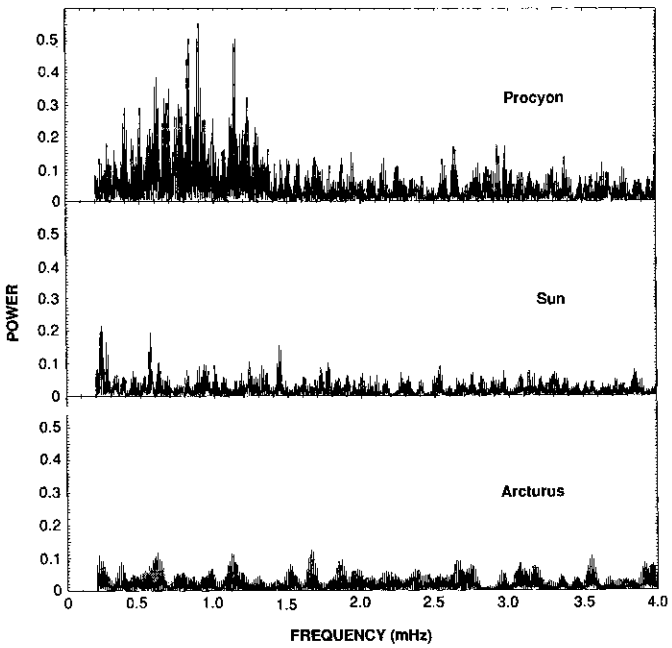

FIG. 3.—Power spectra of the Doppler shift for Procyon, Arcturus, and the Sun, computed from all of the 1989 observations, reduced as continuous time strings. The spectra are plotted with resolution of 1.0 μHz, although the intrinsic resolution available in the data is approximately 1.9 μHz.

distribution of power values in the observed spectrum. The power at one frequency resulting from one realization of a white-noise source should be distributed according to a χ^2 distribution with 2 degrees of freedom. In a spectrum dominated by narrow resonances, however, one expects that even narrow frequency ranges will contain significant variations in the mean power level. In this case the distribution of power values becomes skewed, with an excess of samples that are either very low or very high relative to the mean. The presence of such a probability distribution may thus be interpreted as evidence for a power source that is not broad-band, and may represent oscillations.

To apply these ideas to the observations of Procyon, we compared χ^2 distributions with cumulative distributions of power for the 6 night spectrum (Fig. 3), as well as for most of the spectra spanning shorter time intervals that we describe below. For these comparisons, we used the Kolmogorov-Smirnov test (Press *et al.* 1986), in the same manner as described by Brown and Gilliland (1990). In about three-quarters of the cases the distributions were skewed in the expected sense, but the confidence level associated with this skewness was always low. In no case did we find a probability of chance occurrence smaller than 0.06, while typical values were about 0.4. We do not believe that these confidence levels are high enough to permit any conclusion about the nature of the spectrum. This negative result may not be surprising, however, since the theory of convective excitation of *p*-modes (Goldreich and Keeley 1977*a*, *b*; Goldreich and Kumar 1988) predicts that mode power should have a probability distribution identical to the χ^2 distribution assumed for broad-band noise.

c) Search for Repeatability in the Spectra

If the excess power in the Procyon spectrum results from *p*-modes, and if the mode frequencies are well enough defined to be useful for defining stellar properties, one would expect to see similar oscillation frequencies on successive nights. This similarity would be expected to persist for a time comparable to the lifetime of the modes, which in the solar case is typically 3–6 days. We have tried and described here several methods to determine whether peaks in the Procyon spectrum are more repeatable than chance would allow. All of these consist of comparing power spectra covering two or more different time intervals, sometimes (in the case of intervals spanning several days, so that there are gaps in the data) using the CLEAN algorithm (Roberts, Lehar, and Dreher 1987) to minimize the influence of sidelobes in the power spectra.

The simplest test of repeatability is to intercompare the six nightly power spectra of Procyon, which are displayed in Figure 4. It is evident that the excess of power between 0.3 and 1.4 mHz is present on all of the single-night spectra. Also, some peaks appear to recur on successive nights, but most do not. This lack of recurrence is not very surprising, however, since the typical frequency spacing between modes on Procyon is expected to be less than 40 μHz ($\nu_0/2$; cf. § I). Ignoring possible multiplicity due to different *m*-values, one thus expects roughly two modes (with *n* varying by 1 and *l* varying by 2) within each resolution element. Beating effects between modes with similar frequencies are thus likely to cause large night-to-night power variations within single resolution elements. In addition, the current data have relatively high noise (S/N $\lesssim$ 2 in the amplitude, even near the peak of the power excess at 0.9 mHz), so that interference between a stellar signal and the noise background is also likely to lead to large power fluctuations.

In order to minimize these effects, we have compared power spectra computed from the first and the last 3 nights of Procyon data (February 16–18 and 19–21). These time series are completely independent, each with frequency resolution near 5 μHz, and separated in mean epoch by about 72 hr. They

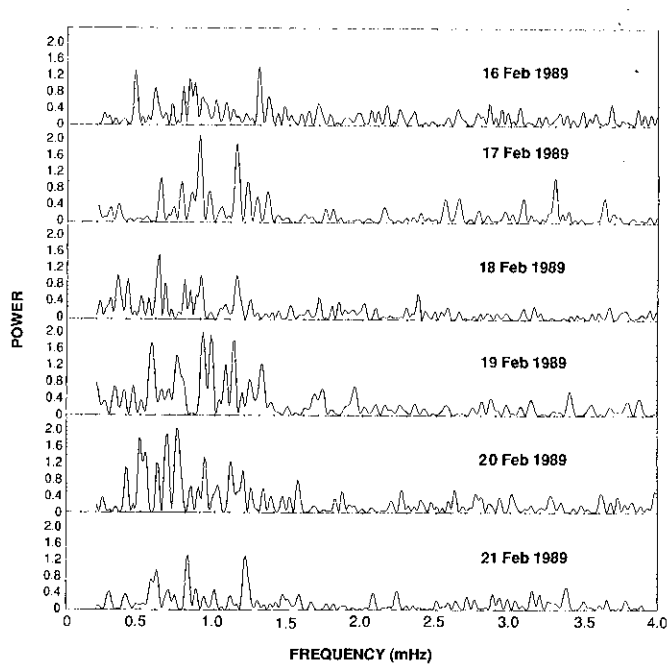

FIG. 4.—Power spectra of the Doppler shift for Procyon, computed separately for each of the 6 nights for which data are available in 1989. The unweighted average of these spectra is shown in the top panel of Fig. 2. These spectra are shown at a frequency resolution of 10 μHz.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

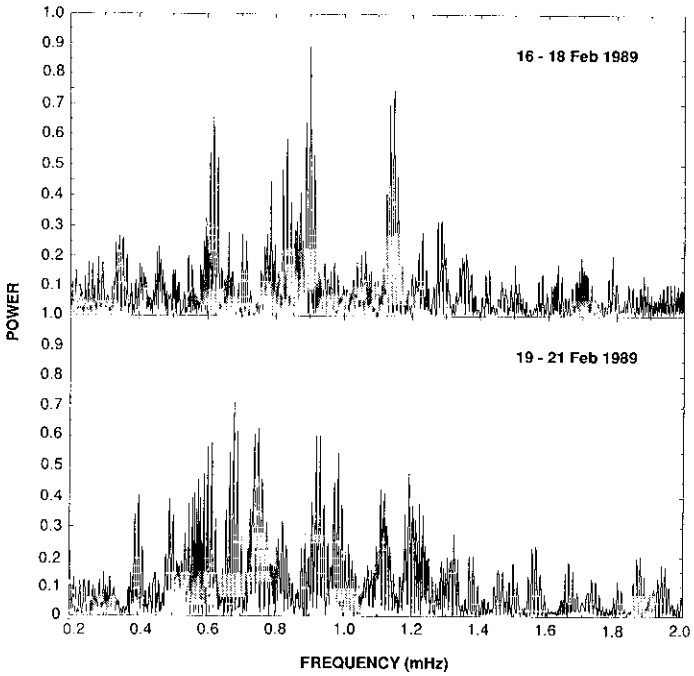

FIG. 5.—Power spectra of the Doppler shift for Procyon, reduced as two independent segments of 3 contiguous nights. These spectra are shown at a frequency resolution of 1.5 μHz.

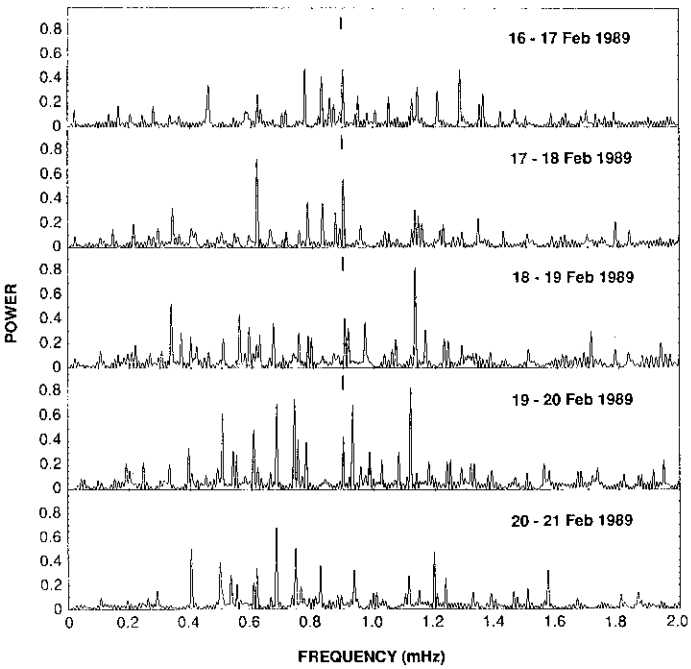

FIG. 6.—CLEANed power spectra of the Doppler shift of Procyon. Each of these spectra was computed from the two contiguous nights of data indicated on the corresponding panel, and are shown at a frequency resolution of 1 μHz. Because of the data segments common to adjacent panels, only three of the five spectra are completely independent. The 902 μHz feature is indicated by short vertical lines in the top four spectra (where it is present).

are shown in Figure 5. The two spectra evidently have the same large-scale distribution of power, but in detail they bear little resemblance to each other. From this comparison we conclude that p-modes on Procyon, if present, have *apparent* lifetimes shorter than about 3 days. This does not necessarily imply that such modes must have damping times as short as 3 days, since the effects discussed above (or even interference between rotationally split modes with the same l but different m) might be responsible for changing the observed mode amplitudes on time scales of days. It is clear, however, that one must search for repeatability in the power spectrum on shorter time scales.

To do this, we computed power spectra from each of the five possible segments containing two contiguous nights. These have significantly better frequency resolution (roughly 9 μHz) than the single-night spectra, but they should suffer from large sidelobes surrounding true spectrum peaks, because of the data gap between the 2 nights in each segment. To reduce the effects of these sidelobes, we used power spectra computed using the CLEAN algorithm (Roberts, Lehar, and Dreher 1987). Simulations indicate that with our window function and noise level, the CLEANing process isolates one lobe of the spectral response function, but not always the central one. Thus, frequencies inferred from CLEANed spectra may be in error by $\pm(1\ \mathrm{day})^{-1}$. Figure 6 shows the power spectra computed in this way.

Assessing repeatability in the spectra of Figure 6 is a delicate matter because of the relatively complicated process used to obtain the spectra, and because successive spectra have one night in common and are thus not independent. In order to make objective inferences, we compared the observed spectra with synthetic ones, computed from a model that includes no narrow-band oscillations but that otherwise reproduces the broad features of the average Procyon power spectrum in Figure 2. Our strategy was then to derive statistics relating to the tendency of spectrum peaks to repeat at the same frequency (or perhaps the same frequency ± 11.6 μHz), and to compute these statistics for the observed spectra and for a number of realizations of model spectra. Finally, comparing the observed statistics with the distributions derived from the model realizations gave an estimate of the significance of any tendency toward repeatability. The model we used produced synthetic time series with data points falling at exactly the same times as our real observations. The expectation value of the power spectrum of these synthetic time series contained two components: one independent of frequency and one consisting of a broad parabolic hump, centered at 0.85 mHz and going to zero at 0.3 and 1.4 mHz. We chose the magnitudes of these two components to reproduce the rms of the Procyon time series and the shape of its smoothed spectrum, but for each particular realization of the time series the Fourier amplitudes and phases at each frequency were chosen randomly.

To obtain a statistical measure of the repeatability of the peak distribution in the spectra (both observed and synthetic), we first identified the N_{peak} highest peaks in each 2 night spectrum, where N_{peak} could be chosen freely. Small values of N_{peak} assure one that only the biggest (and presumably most significant) peaks are being used in the analysis, but the small number of peaks being considered undermines the significance of the results. Large values of N_{peak} give one a bigger statistical population, but risk contaminating good data with noise peaks. We found that the strongest conclusions could usually be drawn with $N_{\mathrm{peak}} \cong 6$. Unless otherwise stated, this value will be assumed in the following discussion. No attempt was made to exclude close pairs of peaks arising from single power spectra. As it turned out, no such pairs were close enough to

© American Astronomical Society • Provided by the NASA Astrophysics Data System

interfere with the statistical estimates made below. Once the list of peak frequencies was compiled, we sorted it into order of increasing frequency. Power spectrum peaks that recur on different nights appear on such a list as clumps of closely spaced or identical frequencies. We thus required a quantitative measure of clumpiness, in order to compare the observed distribution of peak frequencies with the synthetic ones. We used several such measures:

1. The "potential energy" of the peak distribution, defined as

$$\Phi = \sum_{i=1}^{N_{\rm peak}} \sum_{j \neq i} \frac{1}{|\nu_i - \nu_j|}, \quad (3)$$

where ν_i is the frequency of peak i in the list.

2. The mean distance to the nearest neighbor in the frequency list, averaged over all of the peak frequencies on the sorted list:

$$\overline{\nu_{\rm ND}} = \frac{1}{N_{\rm peak}} \sum_{i=1}^{N_{\rm peak}} \min\left(|\nu_i - \nu_{i-1}|, |\nu_i - \nu_{i+1}|\right). \quad (4)$$

3. The frequency difference ν_{30} such that 30% of all peak frequencies on the sorted list have a nearest neighbor at least as close as ν_{30}. We computed similar quantities for other percentiles, getting similar results except for percentiles near 0% or 100%.

4. A Kolmogorov-Smirnov statistic D (see Press *et al.* 1986), relating to the cumulative distribution of nearest-neighbor distances for the peak list under consideration to that for a large sample of similar synthetic lists.

When computed for the list of frequencies observed on Procyon, all of the measures just described proved to be mildly anomalous, in the sense that they showed greater clumpiness than was normal for the synthetic data. The strength of this anomaly was not very large, however; according to any of the measures, roughly 10%–20% of the synthetic spectra were equally clumpy, or more so.

The most outstanding example of repeatability that appeared in all of the peak frequency analysis is the peak at 902 μHz, which appears with significant power in four of the five 2 night spectra in Figure 6, and with the same frequency to within ± 2 μHz. We saw no similar coincidence in any of the simulated sets of spectra (totaling about 20). Simple considerations suggest that the probability of chance occurrence in this case is less than 1%, though of course rare events may appear in any sample. We were, however, able to make one further test of the reality of the 902 μHz peak. Since this peak is very near the maximum of the excess power envelope in the Procyon data, it might be visible even in observations with higher noise than those from 1989. We thus found it worthwhile to examine our Procyon observations from 1988 to see whether the peak was present in them. Figure 7 shows the CLEANed power spectrum for 1988 February 9–11 (the 3 best nights). The 902 μHz feature appears on this spectrum also, suggesting that it may indeed be a genuine oscillation frequency of Procyon. The repeated presence of this feature is the best single piece of evidence for the presence of p-modes on Procyon.

d) Search for Patterns in the Frequency Spectrum

Another strategy for isolating p-modes in the observed power spectra is to search for a signature of the regular mode spacing ν_0 from the asymptotic frequency expression in equation (1). If such a search is successful, it has the advantage of providing an immediate estimate of ν_0 itself, which is perhaps the single most important and easily interpreted parameter of the oscillation spectrum.

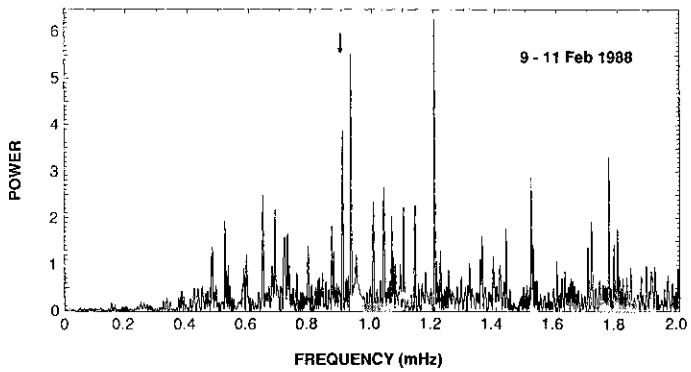

FIG. 7.—CLEANed power spectrum of the Doppler shift of Procyon, computed with 1 μHz resolution from the 3 best nights of observations in 1988. The 902 μHz feature is indicated with a vertical arrow.

One time-honored method of estimating ν_0 is to examine the power spectrum of the power spectrum. If spectrum peaks occur on a regular grid according to equation (1), then there is a component of the spectrum that is periodic with period $\nu_0/2$. The spectrum of the spectrum should show peaks at frequencies (measured in timelike units of cycles per μHz) that are multiples of $(\nu_0/2)^{-1}$. Unfortunately, as explained above, the 7 hr length of each night's data set implies that the data contain very little information about power spectrum features with $\nu_0/2$ in the expected range. Simulations with realistic amounts of noise added to plausible synthetic oscillation signals confirm that this form of analysis is unlikely to be helpful in the current case. We examined the spectrum of the spectrum for our 1989 Procyon data, on the chance that ν_0 might be larger than predicted, but saw nothing that appeared significant.

Another method to search for periodicities in the locations of spectrum peaks is to construct a sequence of echelle diagrams. Conceptually, this involves displaying the one-dimensional power spectrum as a two-dimensional raster image. If the raster line length is exactly ν_0, then modes with the same value of l appear in approximately the same position on each raster line, with the even- and odd-l modes separated by roughly one-half line length. If the line length is $\nu_0/2$, then all modes should fall at the same place in the line, to within an accuracy of roughly d_0.

As a start in this direction, we modeled each of the nightly power spectra shown in Figure 3 as the sum of a number of Gaussian peaks, located at frequencies $\nu_{j,k}$ such that

$$\nu_{j,k} = \nu_{\rm min} + \frac{k}{10}\frac{\nu_0}{2} + j\frac{\nu_0}{2}, \quad 1 \leq j \leq N_j. \quad (5)$$

For the purposes of this fitting process, $\nu_{\rm min}$ was held constant at 0.4 mHz. The parameter space determined by ν_0 and k was swept out as follows. In each power spectrum, within the frequency range from 0.4 to 1.4 mHz, we fitted by multiple linear regression the amplitudes of N_j distinct Gaussians, each with width chosen to match the resolution of the power spectrum, and with frequencies given by $\nu_{j,k}$. For $\nu_0/2 = 40$ μHz this requires 25 separate Gaussians to span the 1 mHz domain. At each choice of $\nu_0/2$ we varied the parameter k from 0 to 9, thus shifting all of the Gaussians together in steps of 0.1 times the separation between them. The best choice for k and $\nu_0/2$ is that

© American Astronomical Society • Provided by the NASA Astrophysics Data System

which minimizes the mean-square difference between the model and observed power. We would expect spectra with significant power from p-modes to show (1) a favored value of $\nu_0/2$ independent of the night, and (2) at the favored $\nu_0/2$ the absolute position k of the representative features should be the same for each independent power spectrum. By these criteria, and within the range 33.6 μHz $\leq \nu_0/2 \leq$ 44 μHz, the preferred value for $\nu_0/2$ is 35.5 μHz. Unfortunately, tests of this procedure with random data have shown that some 20% of the time similarly significant minima appear. Therefore, as with the other statistical tests in this paper, we find suggestive but inconclusive evidence that the excess power detected near 0.9 mHz in Procyon is indeed due to p-modes.

Echelle diagrams constructed with a folding frequency of 35.5 μHz show some evidence for a more or less vertical feature, curved in the sense that $d^2\nu/dn^2 < 0$, and flanked by two similar features separated from the first by 11.6 μHz. It is tempting to identify the peaks making up these features with the p-modes on Procyon, along with their (1 day)$^{-1}$ sidelobes. In this case the curvature would represent departures from the purely asymptotic behavior described in equation (1). Such departures are observed in the solar p-mode spectrum, although the corresponding curvature on a solar echelle diagram is smaller in magnitude and of the opposite sign. A distinction between solar p-modes and those that may exist on Procyon between 0.3 and 1.4 mHz is that the former have higher values of the radial order n than do the latter, by a factor of about 2. Since the asymptotic frequency relations depend on n being much larger than l, it may not be surprising if departures from strict asymptotic behavior are larger on Procyon than on the Sun. Also, there is evidence from both theory (e.g., the low-n p-mode frequencies computed by Iben and Mahaffey 1976) and observation (Henning and Scherrer 1986) that for solar p-modes at low frequency (and hence low n), $d^2\nu/dn^2 < 0$.

Although the foregoing discussion provides some evidence that the excess power near 0.9 mHz is due to p-modes with $\nu_0 = 71$ μHz, other ways of looking at the power spectra render this evidence less convincing. Performing the Gaussian peak fitting procedure on the CLEANed 2 night spectra does yield a good fit with $\nu_0/2 = 35.5$ μHz, but other folding frequencies (27, 31, and 41 μHz) give fits that are equally good or better. Also, fits to CLEANed synthetic noise spectra fairly often give fits that are as good as those using the real data.

A similar analysis of the CLEANed Procyon spectra starts from a list of peak frequencies like that used in the repeatability analysis (§ IIIc). Allowing for departures from the asymptotic behavior of equation (1), one may parameterize the expected mode frequencies as

$$\nu_{nl} = \tilde{\alpha} + \nu_0(n + l/2) + \epsilon(n - n_0)^2 + \cdots , \qquad (6)$$

where $\tilde{\alpha}$, ν_0, and ϵ are free parameters that may be chosen by least-squares fitting, and n_0 is a somewhat arbitrary value of n, usually chosen to lie in the center of the range of n-values for which frequencies are to be fitted. For given values of $\tilde{\alpha}$, ν_0, and ϵ, one may locate the mode whose computed frequency lies closest to each of the frequencies in the list of observed peaks. A cost function equal to the sum of the squares of the differences between the observed peak frequencies and the corresponding model frequencies then provides an index of how well the model fits the data. We actually employed an elaboration of this scheme, in which frequency differences near 11.6 μHz in absolute value contributed less to the cost function than the straightforward least-squares formulation would imply. This procedure made some allowance for the possibility of (1 day)$^{-1}$ sidelobes being mistaken for true peaks in the CLEANed spectra. To determine the best values of $\tilde{\alpha}$, ν_0, and ϵ, we performed an exhaustive search (on a grid of 0.2 μHz in ν_0 and 1 μHz in $\tilde{\alpha}$) for the minimum value of the cost function, using several values of ϵ.

The principal result of this procedure, when applied to lists of peak frequencies from 3 night and 6 night Procyon spectra, was that many values of the parameters fitted the data about equally well. We obtained the best fits for $\nu_0 = 55$ μHz, and roughly 20 other combinations of ν_0, $\tilde{\alpha}$, and ϵ gave better fits than any with ν_0 equal to 71 μHz. This result suggests either that the 71 μHz value for ν_0 is not as special as analysis of the raw spectra made it appear, or that the CLEANing process introduces significant distortions into the data. In the absence of specific reasons to exclude the CLEAN analysis, we feel that a firm conclusion that $\nu_0 = 71$ μHz would be premature.

IV. DISCUSSION

To summarize the results of the previous section, we believe that one can draw two conclusions from our observations of Procyon, with more confidence in the first than in the second:

1. There is detectable Doppler signal in the Procyon data. It arises from Procyon itself, not from the instrument, atmosphere, or photon statistics. All of the power in this signal is contained between frequencies of 0.3 and 1.4 mHz. The total rms velocity integrated over this frequency range (after subtracting known photon noise) is 2.5 m s^{-1}; no single frequency component has amplitude greater than 1.3 m s^{-1}, however.

2. It is very probable (but not certain) that the Doppler signal from Procyon results from p-mode oscillations. Such oscillations provide the best explanation for the observed properties of the data; the repeated feature at 902 μHz is very suggestive, but it has not been possible to identify some features that one would expect an oscillation signal to have.

Detection of an oscillating Doppler signal of Procyon with properties similar to these has been reported by Gelly, Grec, and Fossat (1986, 1988). It is possible that our two sets of observations are representations of the same thing, but for several reasons we doubt it. Gelly, Grec, and Fossat (1986) found apparent oscillation power in the frequency range between 0.6 and 1.7 mHz. This is in fair agreement with our observed range, but their strongest evidence for oscillations was found between 1.17 and 1.65 mHz, and the largest amplitudes were found at about 1.6 mHz. These frequencies are near or above the highest frequency at which we see any detectable stellar power. Second, the value of ν_0 derived by Gelly *et al.* is significantly larger than our most probable value, and this larger value of ν_0 would have been easier to see in our data than the value we actually found. To the extent that either of these determinations can be believed, they are evidently not measuring the same quantities. Finally, our simulations have made us extremely cautious about interpreting spectra (and particularly spectra of spectra) with marginal signal levels. The results by Gelly *et al.* rely largely on such an analysis, using data with a noise level that is probably a little larger than for the set described here. Attempts to combine our results with those by Gelly *et al.* in order to extract more information are therefore not likely to be very fruitful.

For the remainder of this discussion we will suppose that the observed Doppler signal does represent oscillations on

© American Astronomical Society • Provided by the NASA Astrophysics Data System

Procyon, and compare the inferred properties of the oscillations with those predicted by theory.

From the estimated acoustic cutoff frequency in Procyon's photosphere, and assuming the same scaling as in the Sun, one predicts that the high-frequency limit of oscillation power should be approximately 1.4 mHz, almost exactly equal to the observed value. The same argument leads to a low-frequency limit (for power roughly 0.3 times the peak power) of approximately 0.6 mHz, which is considerably larger than the 0.3 mHz actually observed. Put differently, the solar p-modes have most of their power within a single octave in frequency, while the Procyon signal spans more than two octaves. According to one current theory (Goldreich and Kumar 1990), this low-frequency cutoff may carry information about the structure of a pulsating star's convection zone.

Amplitudes for oscillation modes on Procyon may be estimated in two different ways. Assuming that all of the modes in the observed frequency range (including modes with various values of m) are equally excited, one may estimate the power per mode P_{nlm} near the envelope peak at 0.9 mHz as

$$P_{nlm} \cong 1.5 \frac{\text{rms}^2}{N_{\text{mode}}}, \quad (7)$$

where rms^2 is the total observed excess power, and the factor of 1.5 arises from the parabolic shape of the excess power hump. Taking account of the visibility factors for the various modes, the effective number of visible modes N_{mode} is about 50. This leads to an estimate of about 35 cm s^{-1} for typical mode amplitudes near the peak of the power envelope. Alternatively, one may simply examine the observed power spectra, noting that the highest peaks correspond to amplitudes of approximately 120 cm s^{-1}. These peaks typically consist of sums of 4–7 modes with nearly identical frequency. Again allowing for visibility effects, and for the probable distribution of power in the 10 or so such groups near the peak of the power envelope, one arrives at an estimate of about 50 cm s^{-1} per mode. These estimates of mode amplitudes are 3–5 times as large as those observed near 3 mHz on the Sun, but they appear to agree well with those calculated by Christensen-Dalsgaard and Frandsen (1983) for a subgiant with Procyon's effective temperature.

The most probable (but still highly uncertain) value for ν_0 derived from the Procyon observations is 71 μHz. This value is consistent with the idea that Procyon is somewhat evolved, with a substantially lower mean density than the Sun, but it is noticeably outside the range (50–60 μHz) calculated by Demarque and Guenther (1986). In this context it is worth noting that the astrometrically derived mass of Procyon A (1.77 $M_\odot$; Strand 1951) is in significant disagreement with the mass (roughly 1.5 $M_\odot$) required to reproduce Procyon's observed luminosity and temperature (Demarque and Guenther 1986; Steffen 1985). Perhaps if ν_0 could be reliably determined for Procyon, the source of this disagreement would become clearer.

Our observations suggest that the apparent lifetimes of p-modes on Procyon are approximately 2 days. This is somewhat shorter than the corresponding solar value. Assuming a rotational period of about 40 days ($v \sin i = 2.8$ km s^{-1}; de Jager and Neven 1982, Gray 1981), rotational splitting may contribute to the apparent lifetime but is unlikely to dominate it. Another possible explanation is that d_0 may be small for Procyon, leading to groups of modes in the spectrum that are separated by only a few microhertz. If Procyon is indeed more centrally condensed than the Sun, such an effect is to be expected. Finally, the mode lifetimes may be intrinsically short, for reasons that would presumably have to do with the strength of the coupling between the modes and the convective driving.

Although tantalizing, the results we have presented here fall short of what is needed to place firm constraints on models of Procyon or of the oscillation process. There are several ways in which one might do better. A lower level of noise in the raw Doppler signal would of course be helpful. This could be attained by improving the spectrograph throughput, resolution, or wavelength coverage. Improvements of a factor of 2 or so in rms noise should be fairly readily achievable in this way, and much greater improvements are possible in principle (Connes 1985). Longer observing sequences may be even more important, since they would allow one to build up better statistics by observing more independent realizations of the oscillation spectrum. Doubling the number of confidently identified frequencies would probably allow one to determine ν_0 with confidence (or to determine that the excess power does not come from p-modes, if no ν_0 can be found). The most powerful extension of these observations, however, would be to observe simultaneously from two or more different sites, well separated in longitude. By increasing the daily coverage of Procyon from 8 hr to 16 hr or more, one would drastically reduce the confusing influence of sidelobes in the power spectra and of short effective mode lifetimes. We hope that such a cooperative program can be initiated in the near future.

We thank Sam Barden, Daryl Willmarth, and the staff at the KPNO 2.1 m telescope for their assistance in obtaining the data described here. Support from NSF grant AST 8618167 (to L. W. R.) for the installation of the FOE and construction of the fiber scrambler is gratefully acknowledged. We are grateful to the staff of the McMath telescope for allowing us to use their Th-Ar hollow cathode lamp when ours failed.

REFERENCES

Brown, T. M., and Gilliland, R. L. *Ap. J.*, **350**, 839.
Christensen-Dalsgaard, J. 1988*a*, in *Advances in Helio- and Asteroseismology*, ed. J. Christensen-Dalsgaard and S. Frandsen (Dordrecht: Reidel), p. 3.
———. 1988*b*, *Advances in Helio- and Asteroseismology*, ed. J. Christensen-Dalsgaard and S. Frandsen (Dordrecht: Reidel), p. 295.
Christensen-Dalsgaard, J., and Berthomieu, G. 1990, in *Solar Interior and Atmosphere*, ed. A. N. Cox, W. C. Livingston, and M. Matthews (Space Science Series; Tucson: University of Arizona Press), in press.
Christensen-Dalsgaard, J., and Frandsen, S. 1983, *Solar Phys.*, **82**, 469.
Connes, P. 1985, *Ap. Space Sci.*, **110**, 211.
de Jager, C., and Neven, L. 1982, *Ap. Space Sci.*, **84**, 297.
Demarque, P., and Guenther, D. B. 1986, in *Cool Stars, Stellar Systems, and the Sun*, ed. M. Zeilik and D. M. Gibson (Berlin: Springer), p. 187.
Gelly, B., Grec, G., and Fossat, E. 1986, *Astr. Ap.*, **164**, 383.
Gelly, B., Grec, G., and Fossat, E. 1988, in *Advances in Helio- and Asteroseismology*, ed. J. Christensen-Dalsgaard and S. Frandsen (Dordrecht: Reidel), p. 249.
Goldreich, P., and Keeley, D. A. 1977*a*, *Ap. J.*, **211**, 934.
———. 1977*b*, *Ap. J.*, **212**, 243.
Goldreich, P., and Kumar, P. 1988, *Ap. J.*, **326**, 462.
———. 1990, *Ap. J.*, **363**, 694.
Gough, D. O. 1987, *Nature*, **326**, 257.
Gray, D. F. 1981, *Ap. J.*, **251**, 152.
Groth, E. J. 1975, *Ap. J. Suppl.*, **29**, 286.
Hanbury Brown, R., Davis, J., Allen, L. R., and Rome, J. M. 1967, *M.N.R.A.S.*, **137**, 393.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

Henning, H. M., and Scherrer, P. H. 1986, in *Seismology of the Sun and the Distant Stars*, ed. D. O. Gough (Dordrecht: Reidel), p. 55.
Horne, K. 1986, *Pub. A.S.P.*, **98**, 609.
Iben, I., Jr., and Mahaffey, J. 1976, *Ap. J. (Letters)*, **209**, L39.
Irwin, A. W., Campbell, B., Moreby, C. L., Walker, G. A. H., and Yang, S. 1989, *Pub. A.S.P.*, **101**, 147.
Noyes, R. W., Baliunas, S. L., Belserene, E., Duncan, D. K., Horne, J., and Widrow, L. 1984, *Ap. J. (Letters)*, **285**, L23.
Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T. 1986, *Numerical Recipes: the Art of Scientific Computing* (Cambridge: Cambridge University Press).
Ramsey, L. W., Brown, T. M., Gilliland, R. L., and Noyes, R. W. 1989, in *Frontiers in Stellar Evolution*, ed. D. Lambert (*Pub. A.S.P.* Proc. Ser.; San Francisco: ASP), in press.
Roberts, D. H., Lehar, J., and Dreher, J. W. 1987, *A.J.*, **93**, 968.
Smith, P. H., McMillan, R. S., and Merline, W. J. 1987, *Ap. J. (Letters)*, **317**, L79.
Steffen, M. 1985, *Astr. Ap., Suppl.*, **59**, 403.
Strand, K. Aa. 1951, *Ap. J.*, **113**, 1.
Tassoul, M. 1980, *Ap. J. Suppl.*, **43**, 469.
Ulrich, R. K. 1986, *Ap. J. (Letters)*, **306**, L37.
———. 1988, in *Advances in Helio- and Asteroseismology*, ed. J. Christensen-Dalsgaard and S. Frandsen (Dordrecht: Reidel), p. 299.

TIMOTHY M. BROWN: High Altitude Observatory, P.O. Box 3000, Boulder, CO 80307

RONALD L. GILLILAND: Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218

ROBERT W. NOYES: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

LAWRENCE W. RAMSEY: Department of Astronomy, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802

© American Astronomical Society • Provided by the NASA Astrophysics Data System