THE ASTROPHYSICAL JOURNAL, 282:226–235, 1984 July 1

STABLE NONRADIAL PULSATIONS IN 53 PERSEI FROM 1977 TO 1983

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Received 1983 September 28; accepted 1984 January 13

ABSTRACT

New photometric and line profile data are combined with old in a reanalysis of the nonradial pulsation properties of the middle-B star 53 Persei, the prototype of its class.

Seventeen nights of *uvby* photometry in late 1981 have been combined with 1977 and 1978 photometry. An analysis of the data *in toto* and in subsets suggests the presence of stable frequencies of nearly equal amplitude at 0.464 and 0.595 cycles per day. This result is in general agreement with a 1979 study by Buta and Smith. Although these two frequencies dominate the light variability of 53 Per during 1977–1981, the overall fits are still fairly unsatisfactory and point to the presence of additional frequencies that cannot be recovered from these data alone.

We have achieved good fits of 23 new Si II λ4130 line profile observations of 53 Persei obtained during 1983 January and February with models using these two frequencies. It is also easy to phase-lock the photometric observations from late 1977 back to spectroscopic observations of 1977 August and to obtain good fits for these profiles as well. However, we are unable to fit earlier line profile observations with these frequencies, even by relaxing the phase-locking requirement. We conclude that 53 Persei changed its pulsational characteristics to excite the present pair of dominant frequencies sometime during 1977. The new photometric and line profile variations are consistent with the identifications of the frequencies as nonradial modes of high overtone and $l = 3$, $m = -3$ and -2.

The same small color variation noted by Buta and Smith continues to be present in the more recent data. This color term and the occasional presence of a "phantom" ultraweak line at λ4131.4 imply that temperature modulations associated with the oscillations probably do manifest themselves (a new claim), though not necessarily in accord with expectations of linear, adiabatic theory.

Subject headings: line profiles — stars: individual — stars: pulsation — stars: variable

I. INTRODUCTION

The star 53 Persei (B4 IV; Lesh 1968) is the prototype of a group of slowly rotating, early-B variables which show periodic line profile modulations in width, asymmetry, and intensity, and concomitant small variations in light and color. The star's spectroscopic and photometric behavior has been studied by Smith and McCall (1978), Buta and Smith (1979), and Smith and Buta (1979). It is generally accepted that nonradial pulsations (NRP) are responsible for its variability (Smith 1980; Percy 1980).

The 53 Persei stars show both similarities to and differences from other groups of nonradial pulsators (Smith 1982). Their large profile variations suggest the dominance, generally, of a single mode of a low l-harmonic. The low frequencies, as low as 0.5 cycles per day in 53 Persei itself, argue for k-overtones of up to 25 or 50. Low l- and high k-values are found in other NRP classes such as certain magnetic Ap stars and the ZZ Ceti (DA) stars (Kurtz 1982; Winget *et al.* 1982). In fact, for unknown reasons this seems to be the rule in most early-type, nonradially pulsating stars. Buta and Smith (1979) found two coexisting dominant modes in 53 Per itself that can be understood as rotational splitting of two m-states, a trait also apparently shared by numerous nonradially pulsating β Cephei and ZZ Ceti stars (Smith 1982; Robinson, Nather, and McGraw 1976), and by analogous magnetic splitting in certain Ap stars (Kurtz 1982).

One enigma surrounding the 53 Persei stars is the lack of coherence of the modes present in these stars. Several stars (53 Per, ι Her, 22 Ori, and υ Ori) seem to show different frequencies at different times, implying that pulsational energy is channeled into one or another dominant mode on a time scale of months (Smith 1982, and references therein). Often these frequencies are related to previous ones by a factor of 2. However, the prevalence of these mode changes, and to a certain extent even the correctness of this "mode-switching"

[1] Operated by the Association of Universities for Research in Astronomy, Inc., under contracts with the National Science Foundation.

interpretation, depend on a very large number of observations, both because of the large number of modes present and because the small frequencies involved require a large observing baseline. The interpretational problem is compounded further because secondary modes cannot as easily be detected by analysis of profile variations as they can by light variations (Smith and Stern 1979), and hence small-amplitude modes can be overlooked or lead to an alias result.

The photometric analysis of 53 Per by Buta and Smith (1979) made clear that this star itself had at least two quasi-stable modes, and that these modes persist for at least two observing seasons. Whenever simultaneous observations were possible, we found that the bright-star phase corresponds to the broad line profile phase. Several spectroscopic observations during the 1979 season (unpublished) suggested that the pair of frequencies near 0.5 cycles per day noted by Buta and Smith were still active a full year later. In 1981 J. L. A. organized a moderately successful photometric campaign that ran on 17 of 36 nights in December and January. The existence of this new data base prompted M. A. S. to observe 53 Persei spectroscopically the following season. The photometric results were Fourier analyzed by W. S. F. and found to be in basic agreement with the 1978 Buta and Smith photometry and with the early 1983 line profile observations.

II. OBSERVATIONS AND DATA REDUCTION

a) *Photometry*

The 1981–1982 photometric observations were done by J. L. A. and collaborators on the No. 4 0.4 m telescope of Kitt Peak National Observatory with a 1P21 photomultiplier in all four filters of the Strömgren *uvby* system. Ten second observations were made, with a "sky" observed each time, in a Comparison–53 Per–Comparison observing sequence.

The comparison chosen was HR 1261, an A0 IV star within 1° of 53 Per on the sky and having no known light variations above the millimagnitude level (Africano 1977; Buta and Smith 1979). Once each night a second standard, HR 1482, was observed to test the night-to-night consistency. From this check we estimate night-to-night errors in the mean light level of about ± 0.004 mag, a nonnegligible but unavoidable error source in our photometric analysis of this data block. Because of the long, anticipated period(s) in 53 Per, a secondary and unrelated program was run between blocks of data during each night. All the data were reduced with a standard KPNO data reduction routine using standard extinction coefficients derived for this filter set. Because we are not concerned with possible color variations in this particular study, we confine our attention to the y-magnitudes. The values are tabulated relative to HR 1261 as Δm_y in Table 1.

Standard frequency analysis of the photometric data was performed by W. S. F., using FORTRAN codes (fast Fourier transforms, linear and nonlinear least squares fits of frequencies to data) originally written for a CDC 6400 and adapted to run on a Vector Graphic microcomputer. The 13 nights of v measures by Buta and Smith (1979), the four nights of v measures by Smith and Buta (1979), and the 17 nights of y measures by J. L. A. and collaborators (Table 1) constitute three separate data blocks, which were treated both separately and jointly during the investigation. For convenience, two different data bases were used. The first simply combined the v and y magnitude differences without scaling corrections but with magnitude zero points $\Delta v_0 = -0.853$ and $\Delta y_0 = +0.545$, and required that separate whitening fits be performed on the v and y measures. The second data base used these same zero points and also scaled the v measures down to the y measures as $\Delta y = 0.825 \Delta v$, which is theoretically appropriate to 53 Per if all the light variations are caused only by variations in the effective temperature (Buta and Smith 1979). This is a larger reduction factor than the 0.90 which they adopted, and it may not be correct. It does, however, have the advantage of being approximately consistent with the observed amplitude ratios in v and y (see the first three fits in Table 2, which give average v/y ratios of 0.72 and 0.79), and it permits assembling all data in one block on the assumption that both amplitudes and frequencies have been constant over the time span of the photometric observations.

b) *Spectroscopy*

During early 1983 we observed the Si II $\lambda\lambda$4128, 4130 doublet in 53 Persei 23 times. This practice provides us with two line profiles for the price of one. The observations were made on the 2.1 m telescope and the 0.9 m cloudé feed telescope of Kitt Peak National Observatory during three observing runs. However, the time coverage during these runs was compromised by poor weather. The principal difference between the two telescopes was that the time needed to get good signal-to-noise ratios ($\sim$200 per pixel) was twice as long (40 minutes) on the coudé feed as it was on the 2.1 m. However, observational "phase smearing" in either case is inconsequential because the primary active frequencies turned out again to be small, near 0.5 cycles per day. We used the KPNO coudé grating "B" and Camera 6 to make the observations, giving a dispersion of 2.88 Å mm^{-1}. Our detector was the Universal Dewar No. 1, which contains an RCA, thinned, buried-channel CCD with 512, 30 μm × 30 μm pixels. Using this setup we found a pixel spacing of 86 mÅ and a resolution of 160 mÅ. While this resolution is inferior to the 100 mÅ resolution of the Texas data published in previous papers, it is quite adequate for modeling the extraordinary line profile variations of this particular star.

The line profile modeling procedure is identical to that followed in previous work. The ABUND program computes a grid of 20 intensity profiles from center-to-limb. A second program, NONRAD, computes a flux profile over a 60 element square model disk and incorporates the effects of velocity fields arising from rotation, radial-tangential macroturbulence, and in the present case, two NRP modes having a ratio of horizontal to vertical velocity amplitudes of $K = 0.15$. Because the primary two modes found from the photometric analyses are very close to those found by Buta and Smith, we chose as a starting point to model the line profile variations with the models determined by that work, namely, $l = 3$, $m = -2$ and -3, and at an inclination of 60°. These mode assignments are not altogether unique to the modeling. The success we encountered in fitting the observations to these line profile models is consistent with our earlier mode identifications but does not necessarily lend a great deal of new weight to them.

III. RESULTS

a) *Photometry*

In our period analysis we have found, as did Buta and Smith (1979), that it is possible to represent data blocks over a few days virtually to the level of observational accuracy by two frequencies near 0.5 cycles per day. However, Buta and Smith also found that they were unable to maintain that goodness

TABLE 1

PHOTOMETRIC OBSERVING LOG FOR 53 PERSEI (HJD 2,444,900+)

H.J.D.	Δm_y*	H.J.D.	Δm_y	H.J.D.	Δm_y	H.J.D.	Δm_y	H.J.D.	Δm_y
43.717	.561	46.595	.533	52.929	.560	57.853	.548	61.676	.542
43.724	.554	46.603	.540	52.953	.560	58.708	.525	61.681	.539
43.737	.558	46.609	.544	52.959	.555	58.715	.528	61.686	.542
43.743	.561	46.617	.540	52.965	.552	58.721	.525	61.691	.541
43.750	.562	46.623	.540	52.971	.560	58.763	.529	61.696	.543
43.783	.568	46.637	.547	52.977	.554	58.769	.531	61.702	.540
43.789	.564	46.645	.550	52.983	.553	58.775	.531	61.707	.537
43.795	.565	46.652	.543	53.030	.556	58.781	.533	61.713	.535
43.803	.562	46.658	.543	53.036	.555	58.788	.538	61.718	.535
43.809	.561	46.665	.550	54.644	.551	58.795	.535	61.723	.538
43.815	.561	46.671	.542	54.650	.550	58.825	.535	61.728	.540
43.845	.564	46.702	.543	54.693	.555	58.831	.538	61.734	.535
43.851	.562	46.708	.540	54.703	.548	58.837	.537	61.746	.539
44.744	.527	46.714	.544	54.711	.542	58.843	.537	61.751	.536
44.751	.531	46.720	.546	54.727	.545	58.852	.543	61.755	.535
44.756	.533	46.726	.546	54.734	.546	58.976	.549	61.761	.540
44.762	.531	46.734	.550	54.737	.547	58.998	.548	61.766	.536
44.769	.530	46.741	.544	54.772	.545	59.005	.548	61.907	.535
44.775	.530	46.743	.538	54.779	.550	59.012	.545	61.915	.534
44.836	.537	46.808	.547	54.789	.543	59.657	.552	61.921	.536
44.844	.527	46.814	.549	54.795	.541	59.663	.547	61.926	.538
44.853	.526	46.820	.549	54.802	.545	59.670	.558	61.932	.537
44.861	.521	46.828	.551	54.883	.545	59.684	.556	61.938	.532
44.869	.529	46.833	.550	54.890	.542	59.690	.552	62.005	.536
44.878	.526	46.840	.556	54.897	.542	59.697	.557	62.009	.545
44.917	.524	46.882	.552	54.904	.542	59.703	.555	62.015	.529
44.926	.524	46.889	.550	54.911	.544	59.709	.553	62.021	.536
44.935	.531	46.895	.550	54.919	.543	59.716	.552	62.028	.532
44.942	.529	46.901	.549	54.955	.540	59.722	.556	62.034	.539
44.950	.526	46.903	.551	54.962	.540	59.727	.559	62.694	.545
44.958	.525	46.914	.553	54.970	.532	59.734	.554	62.700	.554
45.011	.521	46.952	.554	54.977	.533	59.746	.554	62.710	.543
45.020	.516	46.958	.552	54.986	.542	59.752	.551	62.715	.551
45.028	.518	46.965	.553	54.993	.540	59.759	.551	62.721	.552
45.598	.545	46.972	.557	56.659	.514	59.765	.544	62.726	.552
45.605	.538	46.979	.555	56.665	.515	59.771	.546	62.732	.551
45.612	.536	46.986	.557	56.709	.520	59.778	.550	62.737	.550
45.619	.533	46.992	.557	56.716	.518	59.784	.547	62.747	.549
45.625	.541	46.999	.550	56.722	.529	59.812	.551	62.754	.553
45.631	.538	47.625	.543	56.728	.522	59.817	.550	62.761	.553
45.694	.552	47.632	.549	56.735	.521	59.822	.541	62.766	.557
45.701	.548	47.638	.535	56.741	.526	59.827	.541	62.772	.552
45.709	.546	47.645	.536	56.747	.520	59.833	.548	62.777	.553
45.716	.546	47.651	.536	56.791	.527	59.887	.542	74.849	.529
45.721	.549	47.658	.537	56.799	.524	59.896	.546	74.857	.528
45.723	.551	47.664	.538	56.806	.526	59.902	.540	74.864	.518
45.751	.560	47.865	.538	56.812	.525	59.909	.542	74.873	.519
45.758	.555	47.872	.537	56.818	.527	59.916	.534	74.880	.518
45.764	.555	47.878	.541	56.849	.526	59.922	.543	74.887	.521
45.770	.554	48.598	.564	56.856	.529	59.928	.538	74.962	.517
45.776	.555	48.603	.557	56.976	.542	60.850	.543	74.970	.529
45.810	.554	48.609	.551	56.983	.537	60.858	.551	74.976	.526
45.815	.552	48.616	.550	56.991	.538	60.862	.554	74.982	.522
45.822	.555	48.622	.552	56.998	.537	60.866	.555	74.987	.528
45.828	.556	48.635	.549	57.004	.537	60.870	.553	74.993	.525
45.833	.558	48.642	.563	57.012	.545	60.948	.552	75.018	.526
45.839	.558	48.643	.566	57.665	.556	60.954	.549	75.022	.520
45.883	.565	48.656	.559	57.671	.558	60.959	.552	75.027	.537
45.888	.563	48.662	.558	57.678	.557	60.964	.544	75.031	.526
45.894	.561	48.669	.565	57.686	.559	60.970	.552	75.035	.525
45.899	.558	48.675	.564	57.708	.562	60.975	.555	79.890	.527
45.904	.556	48.709	.567	57.715	.558	60.980	.556	79.900	.531
45.910	.566	48.714	.566	57.721	.555	60.985	.558	79.908	.531
45.939	.557	48.721	.567	57.728	.551	60.991	.559	79.916	.534
45.946	.563	48.727	.572	57.735	.542	60.995	.554	79.924	.531
45.951	.563	48.732	.575	57.742	.562	61.001	.559	79.946	.532
45.957	.554	48.738	.571	57.748	.552	61.006	.558	79.954	.529
45.962	.555	52.897	.557	57.754	.551	61.011	.555	79.960	.537
45.969	.555	52.904	.555	57.828	.548	61.016	.560	79.968	.540
46.003	.564	52.910	.555	57.835	.534	61.023	.558	79.976	.532
46.012	.557	52.916	.555	57.841	.532	61.027	.554	79.984	.535
46.588	.540	52.922	.557	57.847	.540	61.671	.543		

* $\Delta m_y = m_y(53\ \mathrm{Per}) - m_y(\mathrm{HR}\ 1261)$.

of fit to the next or preceding month, so they suggested that additional frequencies must be present. In the following, we will demonstrate that indeed 53 Persei has exhibited a more stable behavior over the last few years than anticipated. Nonetheless, we have been unable to determine a good frequency fit to the entire data block.

To obtain a definitive representation of the variations it is necessary to phase-lock all the photometric data, but this introduces both annual and triennial sidelobes in the Fourier transforms, corresponding to uncertainties in the cycle counts linking the three separate data blocks. Further, the frequencies involved are so low that their lower diurnal sidelobes appear in the frequency spectra as reflected *negative* frequencies. Finally, because of gaps in the coverage, complicated lobe interactions from the real frequencies produce a ghost at 0.658 cycles per day in the unwhitened transforms of both the v and the y measures. This was originally believed to be one of the two dominant modes but, on fitting with three-frequency sets, proved to be caused by lobes on 0.467 and 0.595 cycles per day.

Our nonlinear least squares fitting routine as used for Table 2 provides a seven-parameter adjustment by successive approximations to initial values of mean light level, frequencies, amplitudes, and phases. For each of the five solution sets displayed in Table 2 it converged very nicely to the stable values displayed. In Table 2 are listed the dates for the first and last measures, the number of nights and number of measures in the data block fitted, the mean differential magnitude, mean error σ of a single measure (in units of the mean light level) as determined by residuals to the adopted fit, and the best values for the frequencies, amplitudes, and phases. The numbers in parentheses are the mean errors of the displayed quantities in units of the last significant figure shown. To the formal uncertainties in the frequencies for the last three fits must be added the annual lobe uncertainties, and for the last two fits the triennial lobe uncertainties must also be added (i.e., $\pm 0.00273m \pm 0.00091n$ cycles per day, where m, n are small integers or zero). If we note that for multiperiodic variables the formal errors on frequency determinations are almost always much smaller than the real uncertainties, it will be seen from Table 2 that a constant frequency pair near 0.467 and 0.595 cycles per day has been present during the total span of the photometric data. The most probable pair, based only on the photometry, is given by the fourth fit in Table 2. However, according to Table 3, both modes were at spectroscopic phase 0.5 (Osaki convention) on JD 2,443,387.38, which corresponds to our photometric phase 0.0. The phases for the last fit in Table 2, performed with this time zero point, show that indeed the photometric and spectroscopic variations agree in both frequency and phase, provided that we adopt for both frequencies values of the first annual sidelobes that are lower than those used in the fourth fit.

To illustrate both the approximate agreement between observations and adopted solutions, and the systematic nature of the residual fitting errors between them, in Figure 1 we present a comparison between the v-magnitude photometry by Buta and Smith (1979) and the first solution in Table 2. The circles here are the slightly smoothed data base obtained by luminosity averages of all measures falling within successive 0.01 day time steps. The single seven-parameter fit forced through the 13 nights' data is much poorer than those three fits obtained by Buta and Smith (1979) with a total of 21 adjustable parameters. We believe the obvious systematic fitting errors are probably caused by further periodicities which we have not been able to unambiguously resolve with the presently available data base. If sufficient new photometry is ever obtained, it may turn out that both our adopted frequencies are actually doublets or triplets. Also, it is possible that the amplitudes of 53 Per may have decreased by a small amount between 1978 and 1981. We have treated the data in most of our analysis as if the amplitudes were constant, an assumption which appears to be consistent with the available photometry and with the spectroscopic results.

b) *Line Profile Fitting*

The new photometry shows clearly that the same two frequencies and color terms are present in the new data as in the data reported by Buta and Smith. Therefore, we set out to model the line profile variations with the same modes as determined in that study, namely $l = 3, m = -3$ for 0.595 cycles

TABLE 2

NONLINEAR LEAST SQUARES FITS TO THE PHOTOMETRIC DATA

Data Block	JD Low JD High	No. Nights No. Obs.	Δv_0, Δy_0 (σ)	Frequency (cycles per day)	Amplitude	Phase
Buta's v magnitudes	2,443,467 2,443,531	13 509	$-0.8530(3)$ ± 0.0051	0.4661(2) 0.5953(2)	0.0235(6) 0.0195(4)	0.920(5) 0.027(5)
All y magnitudes	2,444,943 2,444,979	17 359	$+0.5438(5)$ ± 0.0067	0.4673(6) 0.5921(6)	0.0145(8) 0.0164(7)	0.095(10) 0.139(9)
All v magnitudes	2,443,467 2,443,878	17 597	$-0.8519(3)$ ± 0.0068	0.46668(3) 0.59362(3)	0.0218(6) 0.0174(5)	0.904(5) 0.055(5)
All mags. (v to y)	2,443,467 2,444,979	34 956	$+0.5452(2)$[a] ± 0.0065	0.466935(5) 0.593544(5)	0.0156(4) 0.0148(4)	0.908(5) 0.052(5)
All mags. (v to y)	2,443,467 2,444,979	34 956	$+0.5449(2)$[a] $+0.0067$	0.464225(4) 0.590847(5)	0.0170(4) 0.0150(4)	0.986(5) 0.028(5)

NOTE.—$\Delta m = \Delta m_0 - 2.5 \log [1 + A_1 \sin 2\pi(f_1 \Delta t + \phi_1) + A_2 \sin 2\pi(f_2 \Delta t + \phi_2)]$. $\Delta t = t -$ HJD 2,443,467.0, except $\Delta t = t -$ HJD 2,444,943.0 on the second fit and $\Delta t = t -$ HJD 2,443,387.38 on the least fit.

[a] Δv converted to Δy, using $\Delta v_0 = -0.853$, $\Delta y_0 = +0.545$, $\Delta y = 0.825 \Delta v$.

TABLE 3

PROFILE-FITTING PARAMETERS FOR 53 PERSEI

Jan-Feb 1983 Data		(f_{33} = 0.595 day^{-1}; f_{32} = 0.468 day^{-1}) (A_{32} = 12 km s^{-1}; A_{32} = 12 km s^{-1})			
KPNO OBSN	HJD (2445300+)	E.W. λ4130	M_{RT} (km s^{-1})	ϕ_{33}	ϕ_{32}
1	49.680	81	12	0.23	0.60
2	49.838	81	10	0.32	0.67
3	50.601	77	11	0.78	1.03
4	50.731	75	11	0.86	1.09
5	50.820	72	12	0.91	1.13
6	52.627	81	10	1.99	1.98
7	52.739	77	8	2.05	2.03
8	52.777	72	8	2.08	2.05
9	63.604	85	8	8.52	7.12
10	63.674	85	8	8.55	7.15
11	63.823	87	8	8.65	7.22
12	89.656	80	10	24.02	19.32
13	89.684	78	10	24.04	19.33
14	91.592	80	8	25.19	20.23
15	91.621	80	8	25.20	20.24
16	91.653	80	8	25.22	20.26
17	91.687	83	8	25.24	20.27
18	91.739	80	8	25.27	20.30
19	92.610	75	12	25.79	20.71
20	92.652	75	12	25.82	20.72
21	92.682	75	12	25.84	20.74
22	92.717	73	12	25.86	20.75
23	92.759	76	12	25.88	20.77

August 1977 Data		(f_{33} = 0.595 day^{-1}; f_{32} = 0.467 day^{-1}) (A_{33} = 12 km s^{-1}; A_{32} = 12 km s^{-1})			
McD OBSN	HJD (2443380+)	λ4128E.W.	M_{RT} (km s^{-1})	ϕ_{33}	ϕ_{32}
550	3.993	80	12	0.48	0.92
564	4.900	71	10	1.02	1.34
568	4.987	67	10	1.07	1.38
594	5.895	79	12	1.61	1.81
600	5.994	81	12	1.67	1.85
629	6.911	76	10	2.22	2.28
656	7.852	83	12	2.78	2.72
683	8.865	78	10	3.39	3.19

per day and $l = 3$, $m = -2$ for 0.467 cycles per day. The character of the line profile data suggests almost immediately that two nearly equal amplitude modes are present. The 1983 February data (KPNO observations 14–23) show extreme variations in line width, whereas the January observations (especially observations 1 and 2, 9–11) show less pronounced variations. We proceeded by fixing the zero points of the phases of the two modes such that they passed through $\Phi = 0.25$ (narrow-line phase, Osaki convention) on the night of HJD 2,445,391. We then took the photometric frequencies, computed phases for each mode for the appropriate times, and computed line profiles for these phases. In making these computations we chose the same rotational velocity ($V_r \sin i = 17$ km s^{-1}), inclination ($i = 60°$), and ratio of nonradial horizontal to vertical velocities ($K = 0.15$) as in earlier work. The NRP velocity amplitudes for the two modes, A_{33} and A_{32}, were derived by trial-and-error; we settled on values of 12 km s^{-1} for each. As a matter of interest, note that this combination of A and $V_r \sin i$ is optimal for producing the largest profile variations and the narrowest profiles at $\Phi = 0.25$ possible for a slowly rotating, NRP star. Thus the choice of this particular star as the prototype of its class appears in retrospect to be less than historically accidental.

The fitting of the line profiles became simple and straightforward once the phases were chosen, indicating that 53 Per maintained its two dominant oscillations coherently between 1982 and 1983. These results are shown in Figures 2 and 3 and are summarized in Table 3. As in earlier work, we were obliged to vary the macroturbulence by up to ± 2 km s^{-1}, largely to suppress the double-lobed structure in the broad-line phase of the models. We also noticed a tendency for the equivalent widths of the lines to vary slightly, but this appears to be a low-level effect which cannot be easily correlated with the complex combination of phase changes. We will return to these two points in § IV. On the whole, the profile fits of λ1430 shown in Figures 2 and 3 are as good as any shown in this series of papers on 53 Persei stars. There appear to be other small effects occasionally present in the profiles that cannot be simulated with our models, most notably an extended red shoulder on the profile, during observations 6–8. However,

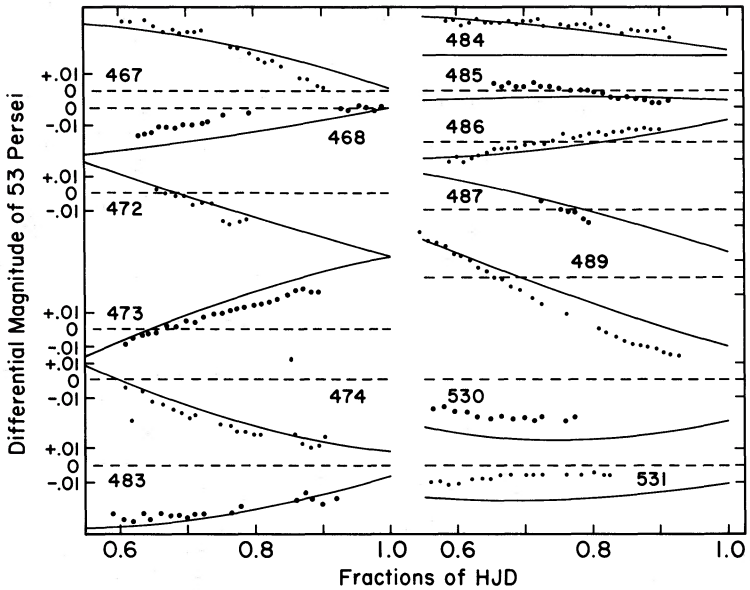

FIG. 1.—Observed (*solid circles*) and computed (*smooth curves*) v-magnitude variations in 53 Per. The observed points are slightly smoothed from the original data set. The computed variations are as given by the first solution in Table 2. The horizontal lines indicate the mean light level, and the scales of abscissae indicate the decimal fractions of HJD 2,443,000+ the number shown on each plot.

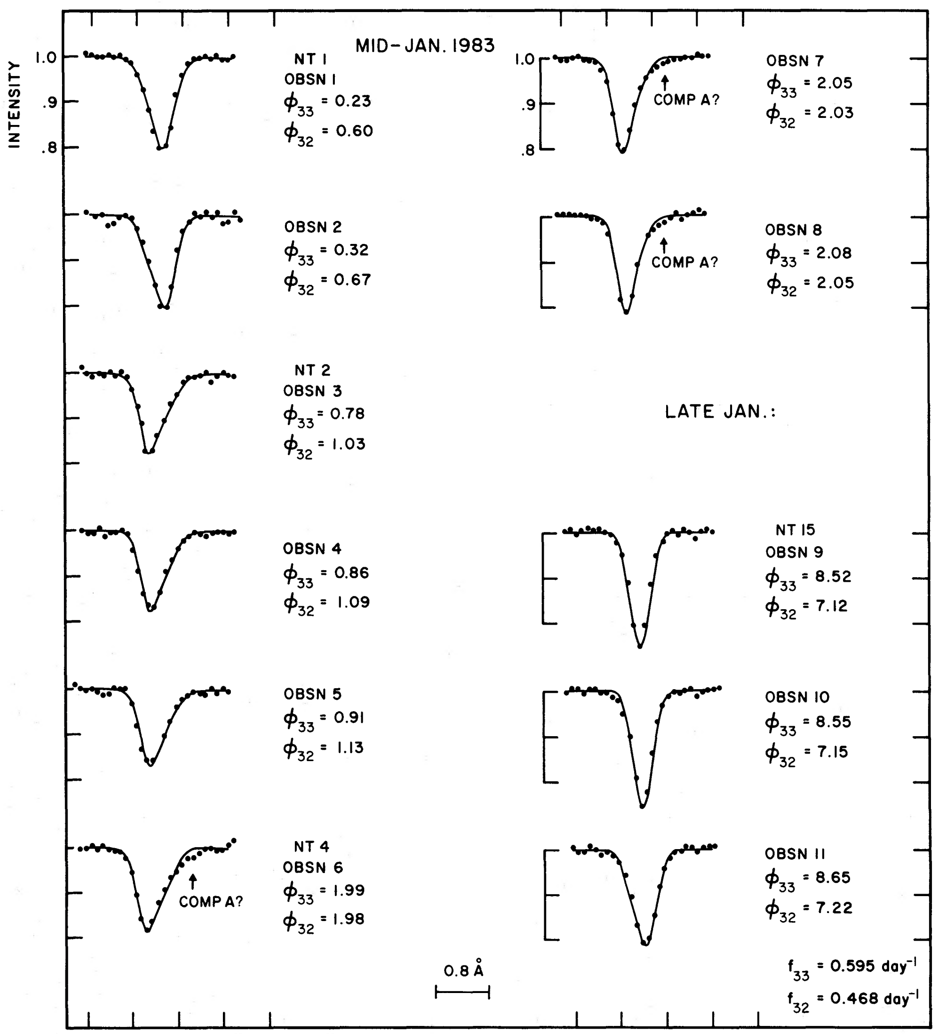

FIG. 2.—Line profile fits (*solid lines*) to a two-mode nonradial pulsation model of the Si II λ4130 line profile observed during 1983 January in 53 Persei. Models were computed with $V_r \sin i = 17$ km s^{-1}, pulsation amplitudes of 12 km s^{-1}, a radial-tangential macroturbulence, and an assumed mode identification of $l = 3$, $m = -3$ and -2. (The assumed frequencies in these computations may be incorrect in the third decimal place because they were taken before the photometric analysis was completed.) The "phantom line component A" is indicated by a vertical arrow.

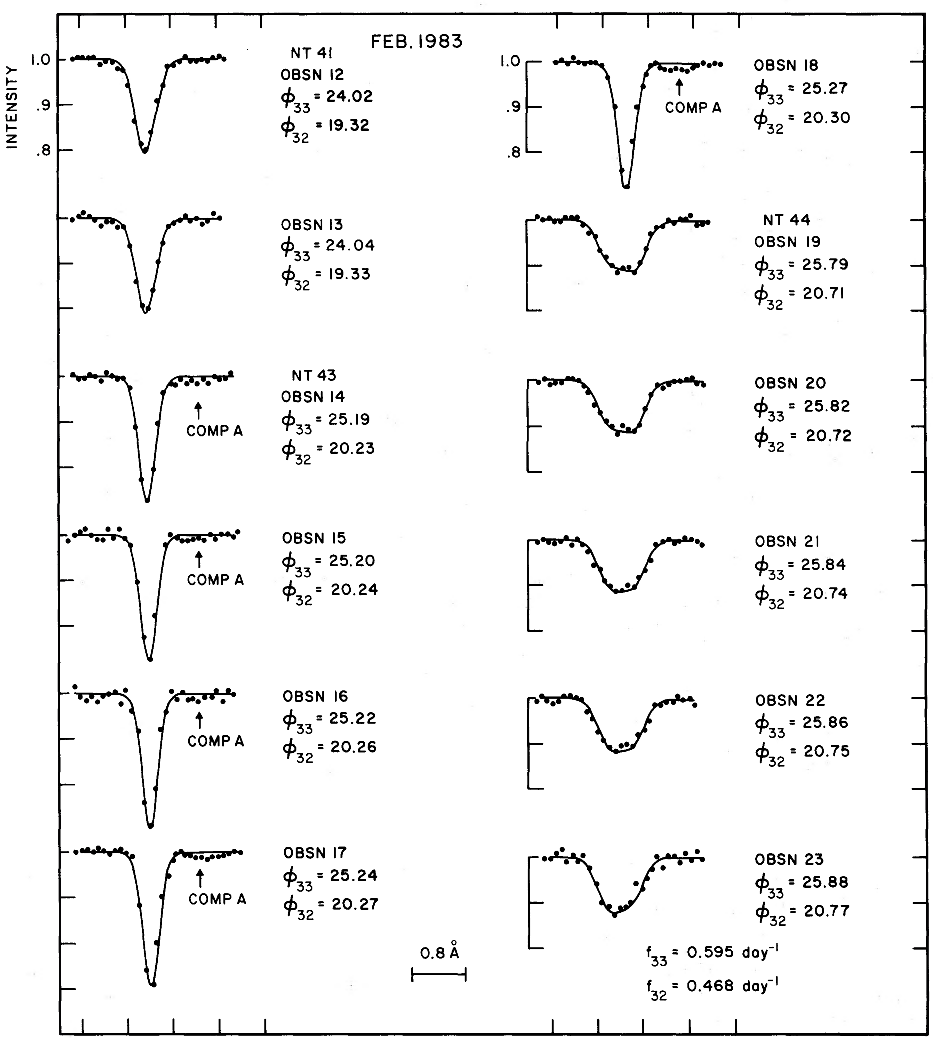

FIG. 3.—Additional λ4130 line profile fits for the 1983 February data for 53 Per

these discrepancies do not show up in the λ4128 profile and appear to be caused by the presence of a separate "phantom absorption feature" discussed below.

Our success in matching line profiles of 1983 with the earlier photometric data led us to inquire whether Smith and McCall (1978) may have derived spurious periods for earlier sets of data based on inadequate data sampling. We reexamined the profile data in that work and satisfied ourselves that, with one exception, the pair of periods near 2 days could not possibly give rise to earlier profile variations observed in 1976–1977. The conspicuous exception to this statement are the data of 1977 August, which are shown in Figure 4. We were able to fit this old data set to the same two periods as the new Kitt Peak Observations.

At the present time, it appears that the period Smith and McCall chose for that data set, 14 hr, is a $\frac{1}{3}$ alias of the correct value of the *mean* of the pair of 2 day modes. However, even so, we are unable to fit the 1977 March or earlier data of Smith and McCall with these two periods, and we see no reason to call into question the 14 hr period determination made by Smith and McCall for 1977 March. In particular, in the earlier data we are able to see perceptible changes in profile observations taken a few hours apart, and this is not the case in the recent data. Based upon a reexamination of the pre–1977 August data, we are unable to say whether several *other* coexisting modes were active in this star, or whether other single modes were excited at different times. There seems to be no substitute for "spot-checking" this star every couple of years in the future to determine how stable the mode structure will be.

It remains to be added that whereas the phase match with the 0.596 cycles per day frequency is good between the 1977 November photometry and the August spectroscopy, there is a mismatch of 0.24 cycles for the second mode with the frequency 0.467 cycles per day. This discrepancy can be reduced to a negligible 0.02 cycles if one assumes that we miscounted the number of cycles per year by 1 in our overall solution. Therefore, the correct value for this frequency is probably at the next annual sidelobe value, 0.46417 cycles per day.

c) A Phantom Line Component

Smith (1981) has called attention to a cluster of six ultraweak lines which sometimes appear near the Si II doublet in the spectrum of the very sharp-lined 53 Persei star ι Herculis. He gave possible identifications for four of the lines. Each identification was with an ion which is quite sensitive to

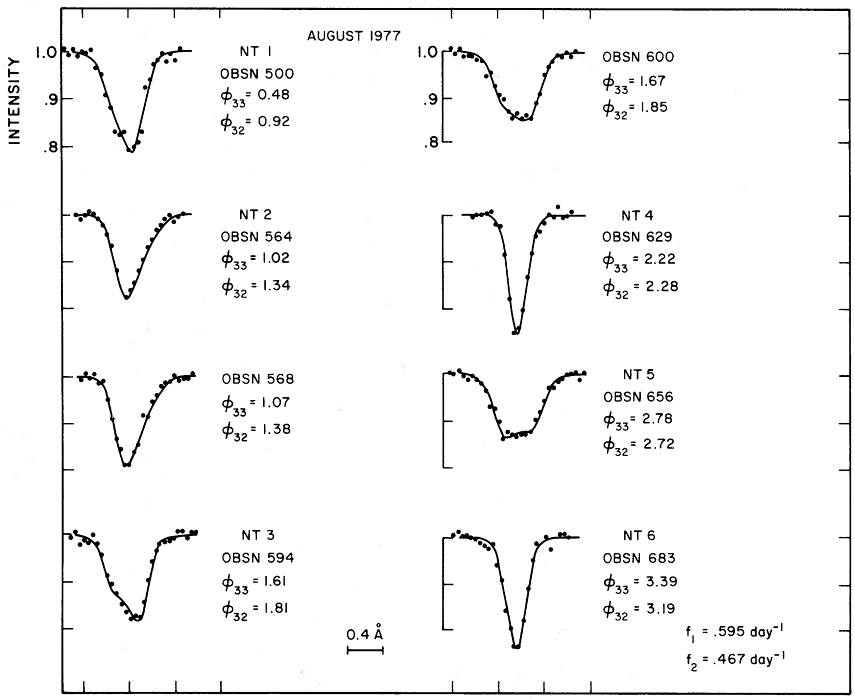

FIG. 4.—Line profile fits to the 1977 August data of Smith and McCall based on the two frequencies determined from an analysis of the 1977–1981 photometry.

temperature in early-B stars. One of these lines, labeled component A in the earlier paper, appears to be present in several of our 1983 spectra of 53 Persei and is indicated by an arrow in Figures 2 and 3 at λ4131.45. A reexamination of some of our earlier 53 Per data indicates its occasional presence. However, the "higher" rotational velocity of 53 Per already causes the line to appear too diffuse to have been reported prior to the study of these lines in the ι Her paper. None of the other "phantom" lines is present. In any case, component A happens to be one of the two lines that remain unidentified. Smith did note that the component was present during the broad-line phase (temperature maximum) in a large number of spectra of ι Her. However, he was unable to establish any correlation or to shed any further light on the appearance of this feature other than to point out its occasional presence. However, based on all the work on these lines, we believe that component A varies in strength just below and above our detection threshold, and that these variations reflect the special sensitivity of the feature to temperature fluctuations caused by the observed oscillations.

IV. DISCUSSION

The major purpose of this paper is to show that the pair of 2 day modes found by Buta and Smith (1979) seems to have continued to be dominant in this star over at least an interval of $5\frac{1}{2}$ yr. These oscillations appear to arise from a high overtone ($25 \leq k \leq 50$). Our photometric coverage is much too inadequate to resolve the star's total modal structure. Frequencies other than this pair also appear to be present, but confirmation will require a more concerted effort. Certainly, a long-term, well-paced photometric campaign will provide the greatest insight into these low-amplitude modes. Of particular interest would be a search for "satellite" frequencies near the two dominant ones. Such frequencies would reflect the star's ability to pulsate in overtones adjacent to the primary one and, in a sense, define the star's "resonance" bandwidth in frequency. For β Cephei stars this bandwidth appears to be about $\pm 3\%$, which is just about the predicted frequency spacing for neighboring overtones in 53 Persei.

Happily, new evidence from another source may already be available. Burki (1983) reports that HR 3562, a member of the photometric group of "slow variables," shares many of the traits we find in 53 Per. This slowly rotating B3 IV star shows multiple low frequencies (three of them near 0.5 cycles per day) which appear to vary in amplitude over several months. Its light curve also shows a coincidence of color minimum and temperature maximum, so this characteristic can now be considered a "given" for long-period, NRP B stars.

There is an indication that in 1977 53 Persei underwent an episodic change in its pulsational character. A coordinated spectroscopic, photometric campaign every two years or so would resolve these ambiguities.

The new data for 53 Per continue to support the picture arrived at by Buta and Smith (1979) and Smith and Buta (1979) that two rotationally split modes *dominate* the oscillations of 53 Persei. The pulsational energy of these modes appears to be approximately equipartitioned, according to the derived pulsational velocity amplitudes for each mode and according to its apparent intermediate aspect ($45° \leq i \leq 60°$) to the observer. It should be noted that because of the star's rotation, the true periods of 53 Persei will be somewhat longer than their *apparent* values, a point overlooked by Buta and Smith.

There is also evidence—the presence of a small color term in the photometric variations, as well as the occasional presence of "phantom line component A"—of temperature variations associated with these oscillations. The intuitive and straightforward interpretation that the faint-star phase corresponds to temperature minimum could reconcile both the sense of the color and the phantom line observations. The problem, as pointed out by Buta and Smith, and as confirmed in the "slow variable" HR 3562 (Burki 1983), is that for low frequencies atmospheric pressure fluctuations are supposed to be dominated by the horizontal nonradial wave motions. These motions run 180° out of phase with the vertical motions in the wave that normally dominate and that normally heat the star's atmosphere at the bright-star phase—as apparently also observed in 53 Per and HR 3562! Then either this theoretical expectation is invalid for some reason or the color variations arise from an alternate source, e.g., as a second-order effect of the geometrical distortion of the stellar disk. As discussed by Smith and McCall (1978), the same horizontal motions should dominate the line profile distortions for low-frequency oscillations, but they are observed not to. Horizontal wave motions come into our profile modeling explicitly as the K-parameter (ratio of horizontal to vertical velocities), and they manifest themselves as triangular profiles with very extended wings and as double-lobed profiles at $\Phi \approx 0.75$. They also tend to reduce the size of the profile variations. Nothing of this sort has ever been indicated in our line profile data. In short, *every physical phenomenon in which the effects of horizontal wave motions lend themselves to an observable test fails that test.* We believe that this situation is serious enough to question whether horizontal motions ever dominate at all. In the following, we surmise that the failure could arise from the large pulsation velocities in this star (nearly the sound speed for each mode), which may well invalidate the linear fluid theory on which such predictions are based.

The NRP velocity amplitudes of certain 53 Persei and β Cephei stars are large enough that nonlinearities can be expected to be important. There is already some evidence that certain spectroscopic properties can be attributed to local nonlinear motions. The equivalent width variations of these stars during the pulsation cycle are probably one example. Especially revealing evidence comes from a related class of rapidly rotating early-B stars such as ζ Oph. These stars appear to oscillate nonradially in high l-indices and with velocity amplitudes near the sound speed (Vogt and Penrod 1983). The oscillations manifest themselves as narrow "emission" and "absorption" components that travel across the line profile from blue to red. One of the surprising aspects of the behavior of these features is that as they travel across the line profile, they become more diffuse; that is, there is no mirror symmetry in their detailed appearance across line center. The most promising interpretation of this behavior is that the traveling waves causing these spectral bumps are highly nonsinusoidal, so that they produce different spectral appearances when the observer views the wave from the front and the back. Also, in modeling the traveling waves, G. D. Penrod and M. A. Smith (unpublished) each find that it is necessary to invoke a large microturbulence in the localized intensity line profile. This is probably an indication that some of the wave's energy is converted to "turbulence" and heat on a local level. (Even in smaller amplitude pulsators, changes in microturbulence are apparently responsible for modulating the line strength during the pulsation cycle [Smith 1978].) In this connection, we notice the tendency of component A to appear in Figures 2 and 3 when both oscillations of 53 Per are *in phase* near $\Phi = 0.25$, when one usually sees an unusually low turbulence and temperature. To summarize, we wonder whether, in large-amplitude pulsators, turbulence from wave dissipation can override the horizontal motions which are predicted but not observed in the line profiles and color variations of 53 Per. Such localized effects should come as no great surprise since it is generally expected that the radially pulsating β Cephei stars exhibit nonlinearities as "bouncing shells" in their spectra. With a maximum total velocity amplitude near 24 km s^{-1} when the oscillations are in phase, 53 Persei can be expected to show an occasional analogous behavior over localized areas of its disk.

V. SUMMARY

The conclusions herein may be summarized as follows:

1. The photometric behavior of 53 Persei is such that several modes are required to explain it.

2. There are two dominant coherent frequencies near 0.54 cycles per day, first found by Buta and Smith (1979), that dominate the photometric behavior of the star from late 1977 to the present (early 1983) and are probably coherent for this duration. We continue to identify these frequencies with a high k-mode and $m = -l$ and $-l + 1$, where $l \geq 3$. The intrinsic periods in the star are at least 4 days long.

3. The 1983 line profile variations appear to be well described by these two large-amplitude modes and can be phase-locked to the photometry over the same $5\frac{1}{2}$ yr interval, such that bright-star phase corresponds to broad-line phase.

4. There is a strong indication from the Smith and McCall (1978) line profile observations that frequencies *higher* than the two just cited dominated the star's variability from late 1975 to early 1977.

5. We find essentially the same color term in the light variations as did Buta and Smith. The small color-to-light amplitude ratio observed is unique to nonradial oscillations.

6. Several of these characteristics, e.g., the existence of multiple periods near 2 days with slowly varying amplitudes, and the occurrence of color minimum with light maximum, are strongly reminiscent of the photometric group of "slow variable" β Cephei stars (Burki 1983). This group and the 53 Per stars appear photometrically indistinguishable.

7. An ultraweak phantom line component at λ4131.4 previously observed in ι Her is sometimes found in 53 Per, particularly when the phases of the two dominant oscillations are in the range 0.0–0.3. We believe temperature variations are responsible for the variation of this line's strength. Temperature modulations (rather than geometric variations) may also be the cause of the color term noted in No. 5.

In this last context there are grounds to believe that nonlinearities arising from dissipation of waves propagating near the atmospheric sound speed cause a breakdown in detailed predictions of the theory of traveling waves. We differ from our earlier opinion (Smith and Buta 1979) in believing that temperature variations *do* produce the small color variation in the light curve of 53 Per. This opinion is based on the behavior of the phantom line component and the failure to find signatures of substantial horizontal wave motions in the Si II line profiles.

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