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THE NONRADIAL MODE IDENTIFICATION OF 53 PERSEI DURING LATE 1977 AND 1978

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ABSTRACT

Various theoretical constraints are imposed on simultaneous light, color, and line profile observations to identify the surface indices of two nonradial modes present in the line profile variable B star 53 Persei during late 1977 and 1978. Excellent quantitative agreement between linear nonradial theory and the observations is reached for the modes $l = 3$, $m = -2$ and -3, but for no other modes. This unambiguous mode identification is made possible because of the fortunate circumstance that the light variations in this long-period pulsator are evidently due to geometric and not temperature effects.
Subject headings: stars: pulsation — stars: variables

I. INTRODUCTION

In this *Letter* we intend to show that light and color curves, when combined with high-resolution spectroscopy, can lead to the identification of the l, m surface indices of the nonradially pulsating star 53 Persei. To do this it is first necessary to summarize portions of recent work by Buta and Smith (1979, hereafter BS) concerning the peculiar spectroscopic and photometric behavior of this sharp-lined, middle B-type star.

Periodic line profile variations in this star have been attributed to traveling wave nonradial oscillations (Smith and McCall 1978). Strömgren v filter observations of 53 Per during 13 nights in 1977 November through 1978 January, suggested the presence of beating due to a pair of nearly equal-amplitude modes closely spaced in frequency ($P_1 = 1.74$ days, and $P_2 = 2.04$ days). Their mean period, 1.88 days, agreed with the period obtained from line profile variations in November. The phasing between the spectroscopic and photometric results is consistent with the light variations being caused by geometric distortions of the star from its spherical shape. From an analysis of the photometric data, BS concluded that the two inferred modes are rotationally split m-modes satisfying the condition $\Delta m = 1$. All constraints at that time led to the designation $l = 2$ or 3, $m = -l, -l + 1$, for the two modes. In this *Letter* these constraints are refined on the basis of new 1978 data. The analysis to follow will apply only to the modes associated with the ~1.9 day period, and not to periods dominant before (Smith and McCall 1978) or since (Smith, Buta, and Africano, in preparation) the interval between 1977 November and 1979 early January.

II. 1978 DATA AND THEIR IMPLICATIONS

The 1978 data consist of four nights of photometry during 1977 November to 1978–1979 January in both the Strömgren v and y filters as well as three nights of photographic spectroscopy following a photometric night in November. The photometry was obtained by both authors on the 30 inch (76 cm) or 36 inch (91 cm) telescopes of McDonald Observatory (see BS for observing and reduction details). The 3.0 Å mm^{-1} spectroscopic plates were obtained at the coudé focus of the Struve 82 inch (2.1 m) reflector.

Spectroscopic line profiles of the Si II λλ4128–4130 region are presented in Figure 1 along with a traveling wave fit. This fit was achieved by using a velocity field due to an $l = 3$, $m = -3$ mode viewed at an inclination of $i = 60°$. These parameters follow from the solution derived later. Additional parameters required to achieve profile fits were standard values of the rotational velocity ($V \sin i = 17$ km s^{-1}) and radial-tangential macroturbulence ($M = 10$ km s^{-1}) (Smith and McCall 1978). The required pulsational velocity amplitude, 12 km s^{-1}, to make the fit is typical for this star. The period following from these seven profiles, 1.7 days, is sufficiently close to both 1.74 and 1.88 days that one cannot be sure whether one or two modes are active during this time.

Figure 2 shows the photometry for November 17, the night immediately preceding the spectroscopic run. The rms errors between the two standards, HR 1261 and HR 1482 (both near A0), during this particularly good night were 0.0017 mag. The zero point in the light curve (*upper panel*) is that adopted by BS. No period can be estimated from this night alone, though it is consistent with a 1.7 or 1.88 day period. If one adopts $P = 1.7$ days one finds a phase $\phi = 0.02$ at the time of the zero-crossing in the light curve of Figure 2. This corresponds to $\phi = 0.77$ (i.e., broad-lined phase, $\phi \approx 0.75$) at maximum light, or the same spectroscopic-photometric relationship found by BS from the 1977 data. This confirmation fixes rather firmly the phasing correspondence.

The lower panel of Figure 2 illustrates the $(v - y)$ color behavior of 53 Per. The low ratio in the color-to-light amplitude, $\Delta(v - y)/\Delta v = 0.10 \pm 0.02$, will place important constraints on the modal interpretation. Therefore in an attempt to confirm this ratio we ob-

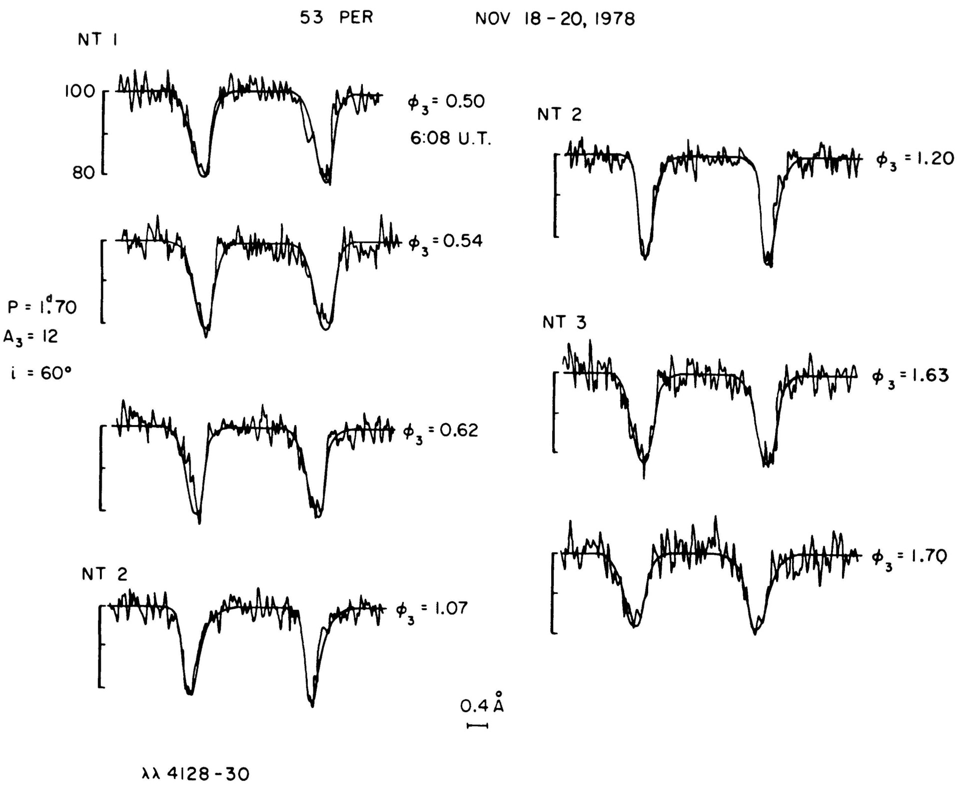

FIG. 1.—Spectroscopic line profiles obtained for 53 Per on 1978 November 18–20. *Solid line*, traveling wave fits to the data, assuming $-m = l = 3$ and $i = 60°$.

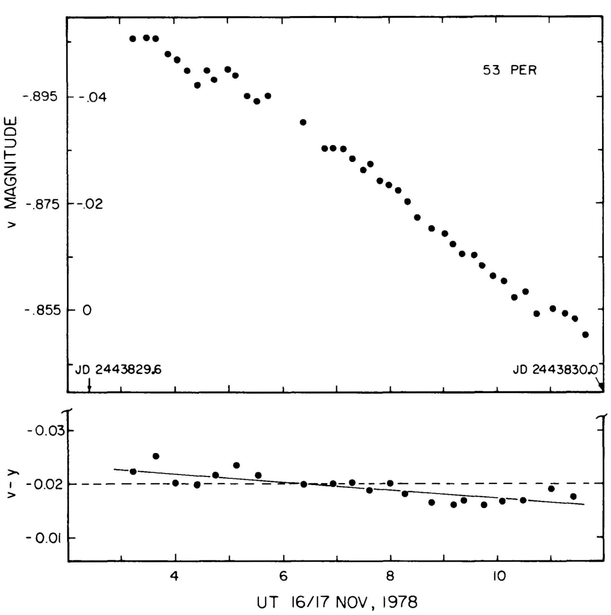

FIG. 2.—Strömgren light and color curves of 53 Per for the night of 1978 November 17. Magnitudes are relative to the standards (*outer ordinate scale*) or relative to the zero point taken from BS (*inner ordinate scale*).

tained additional photometry on three nights in December and January. The results are shown in Figures 3 through 5. Inclement weather prevented us from acquiring data during intervening nights. Nevertheless, a few statements can be made from these observations: (1) only incomplete portions of a cycle are represented on any of these nights; (2) the slopes are rather shallow. These remarks point to a period which is much longer than 6 hours. It is probably 1.88 or 1.74 days, as it was in late 1977. Continuing: (3) the mean amplitude is small compared with that in Figure 2, suggesting that two modes are beating together, again as in 1977; and (4) the color variation is imperceptible on any given night. In fact, if one combines the extreme light levels of December 23 and January 1, one can compute a ratio $\Delta(v - y)/\Delta v = 0.09 \pm 0.025$. This is in excellent agreement with the value 0.10 ± 0.02 obtained from Figure 2. It also agrees with the lack of color variations inferred from Percy's (private communication) negative results in 1978 October, namely, $\lesssim 0.12$. The mean of these three attempts, $+0.10 \pm 0.02$, fully confirms the BS value.

III. CONSTRAINTS ON MODAL IDENTIFICATION

a) Line Profile Variations: $m = -l$, $l \leq 4$

The star 53 Per exhibits profile variations characteristic of its variable class. Its profiles vary in shape but

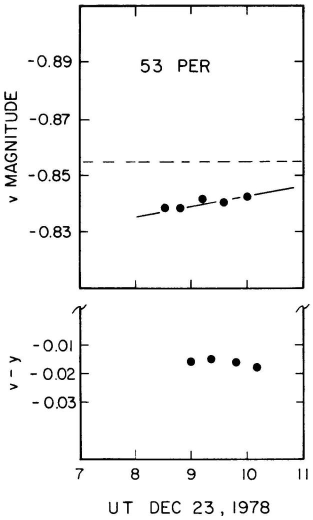

FIG. 3.—Light and color curves for 1978 December 23

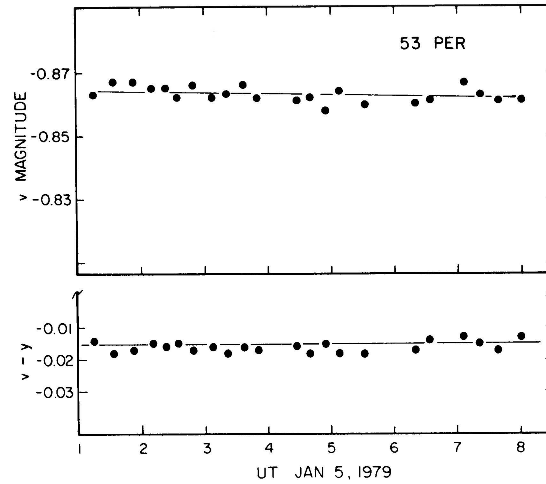

FIG. 5.—Light ana color curves for 1979 January 5

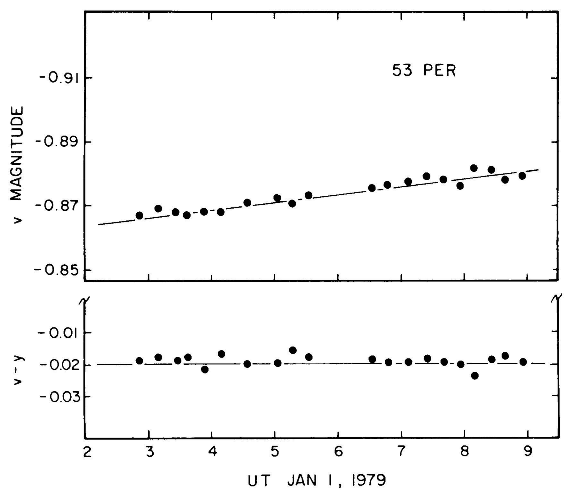

FIG. 4.—Light and color curves for 1979 January 1

barely in radial velocity. The behavior of the profiles shown in Figure 1 is no exception. Furthermore, the amplitude of the variations (10 to 12 km s^{-1}) is as large as can be produced in a nonradial pulsator of its rotational velocity. According to our theoretical modeling experiments, these constraints suggest that $m = \pm l$, where $l > 4$. If $l \leq 4$, zonal cancellations across the disk are found to reduce substantially the amplitude of the variations. In addition, as one proceeds to modes having $|m| < l$, the amplitude of the variations decreases but the radial velocities increase. It is concluded that a low-order sectorial mode is one of those present in 53 Per.

Profile variations also provide a unique tool for the analysis of nonradial modes in that they specify the sense of the traveling wave's motion. The profiles of 53 Per always vary with time in the direction of red asymmetry–narrow-line–blue asymmetry–broad-line phases. This behavior is an unmistakable signature of a direct traveling wave, $m < 0$.

The above conditions impose the constraints on modes observed at all times so far in 53 Per:

$$m \approx -l\,, \quad l = 1, 2, 3, \quad \text{or} \quad 4\,. \tag{1}$$

b) m-mode Splitting: $\Delta m = 1$

The double-mode solution BS found for their 1977 photometric data gives a frequency splitting, $\Delta\sigma = 0.54 \pm 0.04$ (est. error) radians per day. Applying this value to the standard rotational m-mode splitting equation (Ledoux 1951), and inserting $V_{\rm rot} \sin i = 17 \pm 1.5$ km s^{-1}, $R_0 = 4 \pm 0.5\, R_\odot$, and $C = 0.15$, one can solve for sin i as a function of the difference between the two m-modes, Δm,

$$\Delta\sigma = \frac{\Delta m(1 - C)(V_{\rm rot} \sin i)}{R_0 \sin i}\,. \tag{2}$$

For $\Delta m = 1$, one finds sin $i = 0.83$, and $i = 56°(+12°, -9°)$. However, for $\Delta m > 1$, unphysical values of Δm result. Therefore equation (2) leads unambiguously to the condition

$$\Delta m = 1 \tag{3}$$

between the two modes represented in the photometric data.

It is encouraging that Smith and McCall suggested, on the basis of line profile analysis, that sin i is rather large too, but probably not unity. It turns out that the derived inclination value can put additional constraints on the mode identification. For example, BS find the ratio of amplitudes of modes 1 and 2 to be near 0.8. If one makes the assumption of equipartition of energy in the two modes, and if one adopts the above value, $i \approx 60°$, one can use this amplitude ratio to admit only the following modes (see BS, Fig. 9):

$$l = 2\,, \quad m = \pm 2, \pm 1$$
$$l = 3\,, \quad m = \pm 3, \pm 2\,. \tag{4}$$

This condition merely expresses the requirement that the apparent amplitude of adjacent m-modes will be influenced by the observer's aspect. Since the modes in question will indeed be identified with $l = 3$, $m = -2$ and -3 further on, the equipartition argument seems approximately correct in retrospect (see also Fitch and Wiśniewski 1979).

c) *The Dominance of Light Variations by Geometry*

i) *Phase Correspondence*

Light variations can be produced by three causes in a nonradially pulsating star: temperature (i.e., compression) variations, changes in the projected surface area, and in the local surface normal. The latter two are geometric effects which generally produce the same sign in light variation (except for $l = 1$ when they cancel). For most reasonable limb darkening laws the projected area component is the dominant geometric effect. Table 1 gives the light variations in magnitude for each of the three effects for $l = 1$ through 5. These values are computed on the basis of linear, adiabatic, nonradial theory, and in the blackbody approximation (see BS for computational details); the values are also computed for a spectroscopic amplitude of 12 km s^{-1} and a 1.88 day period. Note that all m-modes associated with an order l will attain these amplitudes if each is viewed from the proper aspect.

For all orders Table 1 predicts that absurdly large light amplitudes will be produced by the temperature effect. BS found that when effects due to radiative diffusion losses at the surface are included, these amplitudes are decreased by a factor of 2 or 3. In view of this trend, we suggested that the observed light variations might be explained by a more complete nonadiabatic treatment of energy transport in the stellar envelope.

In § II it was pointed out that to within the errors 53 Per exhibits broad lines at maximum light phase. This phase correspondence is in accord with the positive entries in Table 1. For orders $l = 1$, 2, and 3, negative temperature and light amplitudes are predicted because horizontal motions in long-period pulsators create pressure variations which are out of phase with the geometric variations. These negative temperature amplitudes can only be brought into accord with the observations if they are greatly reduced or if a nonadiabatic phase lag of half a cycle occurs in the star. In our opinion the latter alternative is unlikely because theoretically predicted phase lags are considerably smaller than this (Dziembowski and Saio, private communication) and because it would be fortuitous for a phase lag to be precisely half a cycle. Thus without exception the observed light variations must be identified with positive entries in Table 1. This constraint rules out geometrical effects associated with the $l =$ 1, 4, and 5 modes from producing the observed light variations.

TABLE 1

LINEAR, ADIABATIC MAXIMUM AMPLITUDES OF NONRADIAL MODES FOR 53 PERSEI (in magnitudes)

A.

l	B_1	B_2	B_3
1..........	+0.0352	−0.0352	−2.65:
2..........	+0.0486	+0.0934	−3.31:
3..........	+0.0172	+0.0292	−1.20:
4..........	+0.01530	−0.0556	+1.56:
5..........	−0.0106	−0.0182	+0.87

B.

Model Parameters
$R_0 = 4R_\odot$ $M = 7M_\odot$ $\log T_e = 4.204$; $\lambda = 4100$ Å B_1 = surface normal effect B_2 = surface area effect B_3 = temperature effect $P = 1.88$ days $A = 12$ km s^{-1}, $i = 60°$

ii) *The Color-to-Light Ratio*

One advantage of conducting simultaneous photometric and spectroscopic observations is that the geometric component of the light variations represents the integral of the spectroscopic velocity amplitude over the pulsation cycle. (Incidentally, this relationship holds true even if the oscillations are so nonlinear that spherical harmonic functions do not adequately describe the shape of the star.) It will now be shown that geometric effects indeed appear to dominate the light curve.

The well-established color-to-light ratio, $\Delta(v - y)/\Delta v = 0.10 \pm 0.02$, is appreciably different from the theoretical ratio, 0.18, predicted from temperature variations due to radial pulsation in a B star. (This value is also *observed* for pairs of stars of slightly differing temperature and luminosity along the main sequence.) At first glance, geometric variations might be thought to produce color-free light variations. However, this will not be quite true because of the complicated hill/valley zonal structure on the star's surface, coupled with the wavelength dependence of the limb darkening functions. According to our modeling, these complicating effects will ensure that some color term will continue to be present, i.e., $\Delta(v - y)/\Delta v > 0$. We have attempted to compute $\Delta(v - y)/\Delta v$ ratios for the geometric contributions with different l values, but we were unsuccessful in obtaining unambiguous values because the atmospheric temperature structure near the boundary is not well known. Moreover, the overall color-to-light ratio due to all contributors cannot be determined until the true amplitude and phasing of the competing term (the temperature effect) becomes much better established. In view of these considerations, the observed ratio of +0.10 implies that the geometric component produces most, or nearly all, of the light variations. This statement is valid regardless of the question of a phase lag for temperature variations: if the temperature effect is substantial it becomes impossible to produce both the color-to-light ratio and the observed amplitudes found during 1977 and 1978 November. The simplest solution is to postulate that the amplitude of the temperature component is vanishingly small. In that event there is no longer a need for introducing a phase lag which is large and which has a special value. Moreover, we can then produce a ratio of 0.10 easily for reasonable values of l by considering only geometric effects. In view of this simplification we will drop the concept of a competing temperature component from further discussion, although its effect may still be nonnegligible.

In summary, Table 1, the phase correspondence, and the dominance of geometrical effects, lead to the following modal constraint:

$$l = 2, \quad \text{or} \quad 3 . \tag{5}$$

Note that the inclusion of geometric effects at all expressly forbids $l = 1$, at least in the linear approximation.

d) Identification of the Order: $l = 3$

The conclusion that geometry produces most of the light variations provides the last link in the mode identification argument, for we may now compare the photometric amplitudes derived in Table 1 from the 1978 November spectroscopic observations with the light amplitude found at the same time. This amplitude may be estimated simply by fitting the v filter light curve from Figure 2 to a sine curve having a $\sim$1.8 day period. The result is 0.057 ± 0.005 mag. Let us compare this value with the predicted amplitude arising from the only two possible pulsation orders remaining, $l = 2$ and 3. Table 1 predicts a geometric amplitude of 0.142 mag for $l = 2$. This value is nearly 3 times larger than the observed amplitude, so $l = 2$ can be ruled out. On the other hand, an amplitude of 0.046 mag is predicted for $l = 3$. Similarly, there is substantial agreement between the amplitude in the 1977 light curves (0.050 mag; BS) and the predicted amplitude, 0.040, assuming $l = 3$. These predicted values are in considerably closer agreement with the observations than $l = 2$. Considering the error in estimating the star's inclination and our neglect of temperature-induced light variations, these predicted amplitudes probably fall within the errors of our analysis.

It is concluded that sectorial modes of only one order,

$$l = 3 , \tag{6}$$

can produce a geometric light variation in agreement with the observations. The value $l = 1$ produces *no* geometric light variations, and the modes $l = 4$ and 5 produce variations of the wrong sign. Moreover, $l = 1$ cannot produce the phase correspondence and color-to-light ratio.

There is only one pair of modes which simultaneously satisfies all the modal constraints imposed by equations (1), (3), (4), (5), and (6). That is the identification

$$l = 3 , \quad m = -2 \quad \text{and} \quad -3 , \tag{7}$$

which we take to be the active pair of modes in the envelope of 53 Per during late 1977 and 1978. If these are g modes, a k value near 25 is indicated (Buta and Smith 1979).

There is an irony that the first mode identification of a profile-variable B star should include an odd l value, against which there has been some prejudice in the past. Note also that, whereas the presence of the $l = 2$ mode might have suggested a number of physical mechanisms for pulsational instability associated with a dipole geometry (e.g., duplicity), no such mechanism comes to mind for $l = 3$. Finally, the above identification is valid only during those times indicated, and it may not pertain at all to those epochs when 53 Per has exhibited other periods, particularly those which are subintegral multiples of 1.9 days.

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