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PHYSICAL PROPERTIES OF THE BINARY STAR 12 PERSEI

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ABSTRACT

We have obtained new radial velocities of the double-lined spectroscopic binary star 12 Persei, whose period is 331 days, and which has been resolved in recent years by speckle interferometry. We derive a solution for the orbital elements from the speckle and radial velocity data simultaneously, and find from that solution masses of 1.306 ± 0.035 and 1.172 ± 0.030 $M_{\odot}$ for the components, and an orbital parallax of $0''.04224 \pm 0''.00056$. We also determine spectroscopically the difference in magnitude between the components and, hence, their absolute magnitudes. We estimate their spectral types and individual colors by fitting standard-star colors to those observed and use those results to find effective temperatures, bolometric corrections, and radii, and hence surface gravities and mean densities for the components. Finally, we find projected rotational velocities. The stars seem to be well above the zero-age main sequence, but appear to have metallicities greater than the Sun; if so, they would lie closer to one appropriate to their metal content.

Key words: binaries: close — binaries: spectroscopic

1. INTRODUCTION

The bright star 12 Persei (=HR 788 = HD 16739; $\alpha = 2^h42^m14^s.9$, $\delta = 40°11'38''$ [J2000.0]; $V = 4.91$, F9 V) was found to be a double-lined spectroscopic binary by Campbell (1900). Its orbit is eccentric, and the period is about 11 months, during only a few of which the spectra are resolved. Thus, several seasons are required to obtain full phase coverage. As a result, the first published orbital solution was that of Colacevich (1935), subsequently revised by the same author (Colacevich 1941). Despite the lapse of about 40 years, that solution was still of only average quality, meriting only "c," given without comment, in the ranking system of Batten (1970). Indeed, by modern standards it appears rather poorly determined.

12 Per was one of the first binaries to be resolved by speckle interferometry, by C. R. Lynds in 1973, according to McAlister (1978), who used that observation, plus five of his own and one by A. Labeyrie, in conjunction with Colacevich's orbit, to obtain an orbital parallax and individual masses for the components. Since then, however, many additional speckle observations have been obtained, and they are listed by Hartkopf, McAlister, & Mason (1997).[3] In addition, a few radial velocities, of higher precision than those available to Colacevich, have been obtained with CORAVEL (Duquennoy, Mayor, & Halbwachs 1991) and used for a new spectroscopic orbit by Duquennoy & Mayor (1991). But those authors made no attempt to obtain a simultaneous solution of their radial velocities and the available speckle data.

2. NEW OBSERVATIONS

Such a solution, however, was the intent when, also in 1991, one of us (D. J. B.) persuaded another (C. D. S.) to begin observing 12 Per with the Dominion Astrophysical Observatory (DAO) 1.22 m telescope and coudé spectrograph. Observations have been obtained mainly with the radial velocity spectrometer (Fletcher et al. 1982) but also photographically on occasion. The four plates obtained all show double lines and have been measured with the Arcturus measuring machine at DAO, with the same set of lines as used for IAU standard stars (Scarfe, Batten, & Fletcher 1990). Observations of the same standards have permitted the spectrometer observations to be adjusted to the zero point of that paper. To date, 35 well-resolved spectrometer observations have been obtained, plus two at phases where the spectra were expected to be accurately superposed.

Independently, the third of us (F. C. F.) began observing 12 Per in 1995, and in the fall of 1996 obtained two series of well-resolved observations with the coudé feed telescope and coudé spectrograph of the Kitt Peak National Observatory (KPNO). The detector was a Texas Instruments CCD, and the observations cover a range of about 80 Å, centered at 6430 Å, except for one observation at 6700 Å, and have a resolution of 0.21 Å. Each was measured relative to either *o* Aql or *ι* Psc, with the cross-correlation program FXCOR (Fitzpatrick 1993).

The KPNO data are insufficient to define the orbit, unlike the DAO data. However, the KPNO spectra can be used to determine the magnitude difference between the components and other useful properties of the system. Thus the two sets of data are complementary, and on discovering our mutural interest in the system in 1997 June, we agreed at once to collaborate. All the new radial velocities are presented in Table 1, which includes in a footnote the adjust-

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[3] See http://www.chara.gsu.edu/DoubleStars/Speckle/intro.html.

TABLE 1

Radial Velocities of 12 Persei

HJD (2,400,000+)	Phase	V_A (km s^{-1})	$O-C_A$ (km s^{-1})	V_B (km s^{-1})	$O-C_B$ (km s^{-1})	Notes[a]
48,440.972......	19.973	−40.5	−0.2	−4.2	−0.6	P
48,455.980......	20.019	−9.9	−0.1	−38.3	−0.8	SF
48,459.977......	20.031	−5.1	−0.1	−44.0	−1.1	SF
48,465.974......	20.049	−2.6	−0.2	−46.6	−0.8	SF
48,514.899......	20.197	−9.8	0.4	−36.7	0.4	P
48,520.942......	20.215	−11.3	−0.1	−35.9	0.1	SK
48,521.868......	20.218	−12.0	−0.7	−34.2	1.7	SF
48,529.907......	20.242	−12.8	−0.2	−34.2	0.3	SK
48,690.660......	20.728	−31.9	−0.1	−13.1	0.0	P
48,730.678......	20.848	−39.2	−0.9	−4.7	1.1	SK
48,768.984......	20.964	−42.8	−0.2			SK
48,780.972......	21.000	−23.8	−0.8	−23.8	−1.0	SK
48,800.972......	21.061	−2.3	−0.1	−47.0	−1.0	SK
48,819.957......	21.118	−5.3	0.0	−42.0	0.5	SK
48,822.979......	21.127	−5.7	0.3	−43.0	−1.2	SF
48,827.973......	21.142	−6.8	0.2	−41.0	−0.3	SK
49,029.640......	21.752	−32.2	0.7			SF
49,036.648......	21.773	−33.9	0.0	−10.0	0.7	P
49,041.613......	21.788	−35.1	−0.4	−9.9	−0.1	SK
49,057.628......	21.836	−38.6	−1.1	−7.0	−0.3	SF
49,084.657......	21.918	−43.8	−0.8	−1.0	−0.5	SK
49,174.964......	22.191	−9.3	0.6	−38.5	−1.0	SK
49,369.658......	22.779	−34.6	−0.3	−10.0	0.3	SK
49,381.622......	22.815	−36.8	−0.5	−7.8	0.3	SF
49,417.637......	22.924	−43.4	0.0	−0.2	−0.1	SK
49,691.736......	23.752	−32.2	0.7	−12.2	−0.4	SK
49,747.657......	23.921	−42.8	0.4	−0.2	0.1	SK
49,753.625......	23.939	−44.2	−0.2	0.2	−0.3	SK
49,803.668......	24.090	−2.7	0.8	−43.0	1.6	SK
50,025.804......	24.761	−33.1	0.3	−10.4	0.9	SK
50,046.768......	24.825	−36.6	0.2	−6.4	1.0	SK
50.066.694......	24.885	−40.6	0.2	−2.4	0.6	SK
50,124.610......	25.060	−2.2	0.0	−46.4	−0.3	SK
50,160.638......	25.169	−8.8	−0.2	−39.8	−0.9	SK
50,361.931......	25.777	−34.0	0.2	−10.9	−0.5	K
50,362.833......	25.780	−33.9	0.4	−10.3	0.0	K
50,363.865......	25.783	−34.0	0.5	−10.1	0.0	K
50,364.820......	25.786	−33.6	1.0	−10.0	−0.1	K
50,366.743......	25.792	−34.4	0.5	−10.4	−0.8	K
50,399.747......	25.891	−40.7	0.5	−3.0	−0.5	K
50,400.736......	25.894	−40.9	0.6	−2.9	−0.6	K
50,401.772......	25.897	−41.6	0.1	−3.2	−1.2	K
50,404.924......	25.907	−42.2	0.1	−2.0	−0.7	K
50,405.765......	25.909	−42.3	0.2	−0.1	1.0	SK
50,412.842......	25.931	−42.2	1.5	0.9	0.6	SK:
50,436.757......	26.003	−23.0	−2.2	−23.0	2.3	SK:
50,461.676......	26.078	−3.0	−0.2	−45.8	−0.4	SK
50,475.708......	26.121	−5.8	−0.3	−43.4	−1.1	SK
50,503.628......	26.205	−10.7	0.0	−36.7	−0.1	SK
50,510.609......	26.226	−12.5	−0.7	−35.1	0.3	SK

[a] Codes for types of observations: (P) DAO photographic; (SF) DAO spectrometer with F star mask; (SK) DAO spectrometer with K star mask; (K) KPNO CCD. The following amounts have been added to the raw DAO spectrometer data to give the results in this table, which are in the system of Scarfe et al. 1990: SF, −0.8 km s^{-1}; SK, 0.4 km s^{-1}. A colon following the above code indicates an observation rejected from the final solution because it produced a large residual in a preliminary one.

ments made to observations obtained with each of the DAO spectrometer masks. The speckle interferometric observations used in our solutions are set out in Table 2.

3. ORBITAL SOLUTIONS AND DYNAMICAL PARAMETERS

Orbital elements have been derived from the radial velocities and the speckle data, both separately and simultaneously, by means of programs developed at the University of Victoria (Barlow, Fekel, & Scarfe 1993). No adjustment between DAO and KPNO data was necessary, since the standard stars used by F. C. F. are among those observed by Scarfe et al. (1990). The CORAVEL data were also included without any adjustment, since for stars similar in type to the Sun none is necessary (Scarfe et al. 1990). The individual observations in each of the data sets were all weighted equally. However, since the secondary star's velocities are less precise than those of the primary, they were given relative weights of 0.4 in the solutions. The orbital period was obtained from a preliminary solution of all the primary star's radial velocities, including those of Colacevich (1941), but those early data are of much lower precision and they were not included in any subsequent

TABLE 2

Speckle Interferometric Data

Besselian Year	Phase	Position Angle (deg)	$O-C_\theta$ (deg)	Separation (arcsec)	$O-C_\rho$ (arcsec)	Weight
1973.9380......	0.590	129.3	3.8	0.055	0.002	1.00
1975.7131......	2.549	132.8	0.4	0.053	0.000	1.00
1975.9561......	2.817	85.6	0.2	0.048	0.000	1.00
1976.8523......	3.806	87.0	−0.6	0.048	−0.001	1.00
1976.8599......	3.815	85.5	−0.4	0.046	−0.002	1.00
1976.9227......	3.884	71.5	1.2	0.041	−0.001	1.00
1977.0867......	4.065	227.6	1.6	0.035	0.002	1.00
1977.4874......	4.507	136.6	−2.7	0.056	0.003	1.00
1977.7338......	4.779	93.6	0.8	0.050	0.000	1.00
1977.7419......	4.788	90.6	−0.5	0.052	0.003	1.00
1978.1490......	5.237	186.1	1.7	0.050	−0.001	1.00
1978.6099......	5.746	99.4	0.5	0.047	−0.004	1.00
1978.6155......	5.752	98.1	0.3	0.048	−0.003	1.00
1978.6182......	5.755	96.5	−0.8	0.050	−0.001	1.00
1979.5299......	6.761	96.2	0.0	0.052	0.002	1.00
1980.7180......	8.072	225.0	2.0	0.036	0.002	1.00
1980.7744......	8.134	205.0	0.2	0.042	−0.003	0.25
1981.6711......	9.124	206.0	−1.3	0.048	0.005	0.25
1981.6821......	9.136	202.0	−2.4	0.046	0.001	0.25
1981.6847......	9.139	200.0	−3.8	0.048	0.003	0.25
1981.6875......	9.142	201.0	−2.1	0.046	0.001	0.25
1981.7010......	9.157	200.2	0.4	0.051	0.004	1.00
1982.7659......	10.332	167.2	−1.0	0.050	−0.003	1.00
1983.7131......	11.377	152.1	−8.6	0.058	0.005	0.00
1983.8239......	11.500	139.3	−1.3	0.054	0.001	0.25
1983.9551......	11.644	118.8	2.3	0.053	0.001	0.25
1984.0576......	11.757	94.7	−2.1	0.039	−0.011	0.00
1984.0602......	11.760	96.0	−0.3	0.048	−0.002	1.00
1984.7046......	12.471	144.6	−0.6	0.053	0.000	1.00
1984.8431......	12.624	120.5	0.6	0.054	0.001	0.25
1985.8376......	13.722	106.6	3.4	0.049	−0.002	1.00
1986.8862......	14.879	69.4	−2.2	0.042	−0.001	1.00
1986.8888......	14.882	69.1	−1.8	0.041	−0.001	1.00
1987.7626......	15.846	79.8	0.4	0.047	0.001	1.00
1988.6581......	16.834	79.4	−2.5	0.048	0.001	1.00
1988.6635......	16.840	80.2	−0.5	0.048	0.002	1.00
1990.7551......	19.148	201.0	−0.7	0.044	−0.002	1.00
1991.8937......	20.405	156.1	−0.1	0.052	−0.001	1.00

Note.—The two CHARA observations given zero weight were rejected from the final solution because of their large residuals from a preliminary one. The large residual was in the position angle for the earlier observation and in the separation for the later one.

solutions, for all of which the period was held fixed. The elements common to the separate solutions of the velocity and speckle data agree well, and the simultaneous solution represents both sets of data satisfactorily. Indeed, the standard errors of an observation of unit weight from that solution are $\sigma_\theta = 1^\circ\!.5$, $\sigma_\rho = 0''\!.0020$, and $\sigma_V = 0.48$ km s^{-1}, almost unchanged from those from the individual solutions of the position angles, separations, and radial velocities, which are $\sigma_\theta = 1^\circ\!.3$, $\sigma_\rho = 0''\!.0018$, and $\sigma_V = 0.48$ km s^{-1}, respectively. The final elements from the simultaneous solution are presented in Table 3. Figure 1 shows the radial velocity curves derived from those elements, plotted through the radial velocity data, and Figure 2 the apparent ellipse from the same elements, plotted through the speckle data.

Table 4 presents a variety of astrophysical properties of the 12 Per system. Dynamical properties of the system are given in the first part of the table, and parameters of the

TABLE 3

Orbital Parameters of 12 Persei

Parameter	Value
Period (days)	330.9821 ± 0.0125
HJD of periastron	2,449,111.81 ± 0.14
Major semiaxis (arcsec)	0.05338 ± 0.00052
Velocity amplitude of primary (km s^{-1})	20.94 ± 0.10
Velocity amplitude of secondary (km s^{-1})	23.34 ± 0.15
Eccentricity	0.6574 ± 0.0024
Inclination (deg)	126.77 ± 0.56
Argument of primary star's periastron (deg)......	269.29 ± 0.34
Position angle of ascending node (deg)	49.29 ± 0.42
Systemic velocity (km s^{-1})	−22.93 ± 0.05

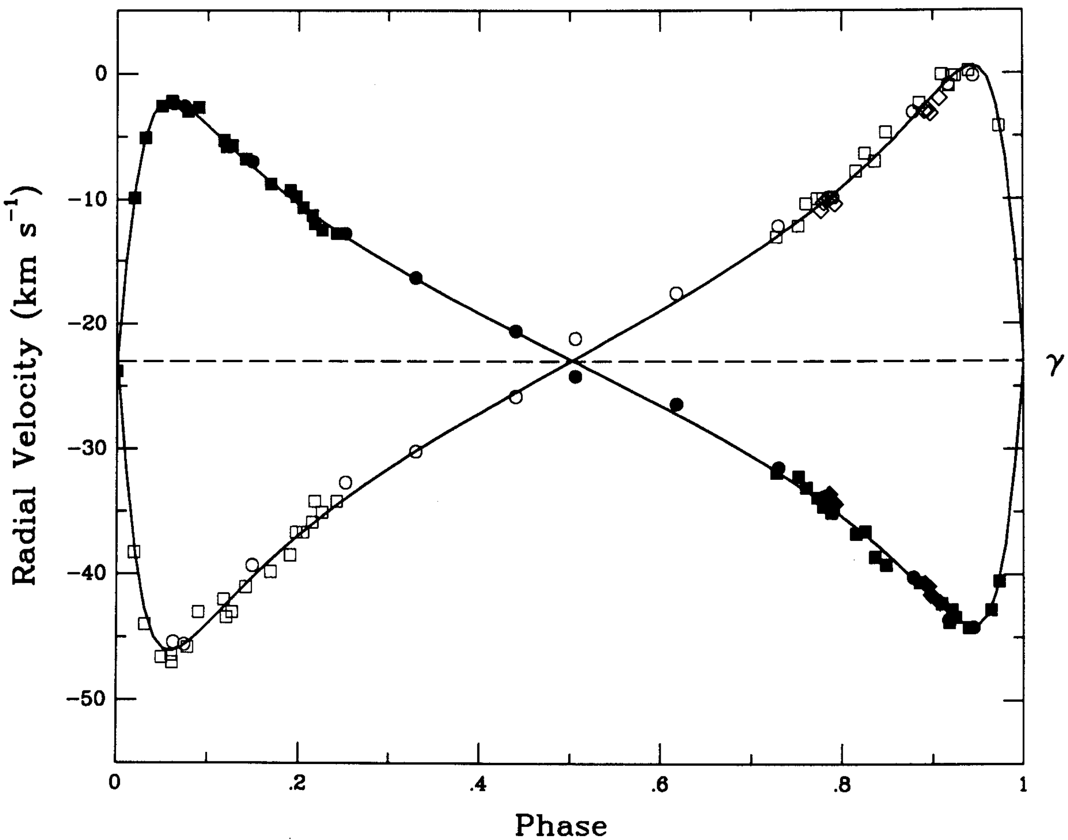

FIG. 1.—Radial velocity curves of 12 Persei. Filled symbols represent velocities of the primary star, and open ones those of the secondary. The CORAVEL velocities of Duquennoy et al. (1991) are shown as circles, the DAO data as squares, and the KPNO ones as diamonds. The curves represent velocities calculated from the solution of Table 3, while the dashed line gives the systemic velocity.

individual stars in the second part. The orbital parallax, 0".04224 ± 0".00056, provides one of the most accurately determined stellar distances known, and the masses are also among the most accurately known for any stars. The orbital parallax agrees well with the trigonometric value of 0".0418 ± 0".0067 (van Altena, Lee, & Hoffleit 1995), and fairly well with the preliminary value of 0".045 ± 0".002 found for the orbital parallax by McAlister (1978). It also agrees with the new trigonometric parallax found from observations by the *Hipparcos* satellite, which is 0".04052 ± 0".00125 (ESA 1997), within the sum of the uncertainties of each. However, our new orbital parallax has an uncertainty under half that of the *Hipparcos* result, and we consider it to supersede the latter. The masses of the primary and secondary star are 1.306 ± 0.035 and 1.172 ± 0.030 $M_{\odot}$, respectively. The uncertainties are thus under 3%, a significant improvement over the preliminary results of McAlister (1978). We discuss the masses further below, but note here that the size and direction of the orbital angular momentum vector, ***J***, are also well determined from the orbit.

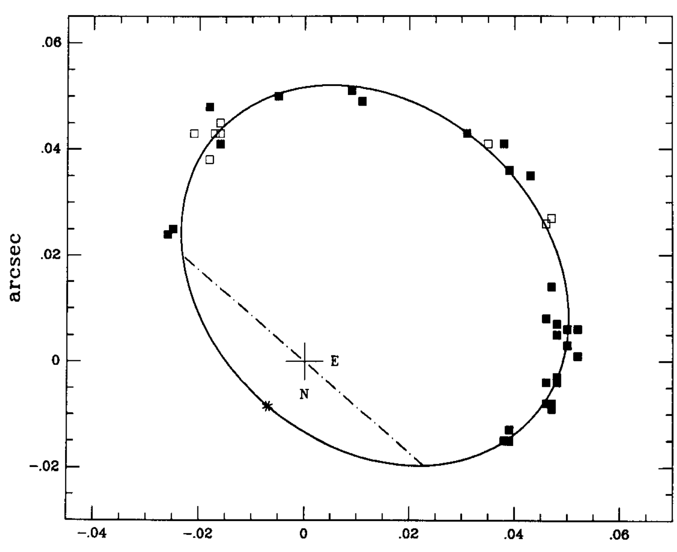

FIG. 2.—Apparent relative orbit of 12 Persei. Filled squares represent CHARA observations, weighted 1.0 in the solutions, and open ones those from other sources, weighted 0.25. The primary star is at the origin, with the coordinate directions shown. The ellipse represents the elements of Table 3, the line of nodes is shown as a sequence of dots and dashes, and the asterisk marks the location of periastron.

4. SPECTRAL TYPES, MAGNITUDE DIFFERENCES, AND ROTATIONAL VELOCITIES

In order to take advantage of the accurately determined distance to find the absolute magnitudes of the individual components of 12 Per, it is necessary to know the difference in magnitude between them. If they are assumed to be identical in spectral type, the DAO spectrometer traces indicate approximate agreement with the magnitude difference of 0.3 given by Colacevich (1941), and used by McAlister (1978), but this is a rather uncertain result.

However, the KPNO spectra permit further information to be gained. One approach is to match the observed spectrum by adding the spectra of stars of known type, but it

TABLE 4

Physical Properties of 12 Persei

A. Dynamical Properties

Parameter	Value
Orbital major semiaxis (AU)	1.264 ± 0.011
Orbital parallax (arcsec)	0.04224 ± 0.00056
Distance (pc)	23.68 ± 0.31
Distance modulus (mag)	1.872 ± 0.029
Mass ratio	0.897 ± 0.007
Angular momentum ($M_\odot$ AU^2 yr^{-1})	5.19 ± 0.23
Galactic latitude of $\boldsymbol{J}$ (deg)	202.2 ± 0.6
Galactic longitude of $\boldsymbol{J}$ (deg)	-29.2 ± 0.4

B. Properties of Individual Stars

Parameter	Primary	Secondary
Mass ($M_\odot$)	1.306 ± 0.035	1.172 ± 0.030
Absolute visual magnitude	3.55 ± 0.03	4.12 ± 0.03
Absolute bolometric magnitude	3.47 ± 0.03	4.00 ± 0.04
Effective temperature (K)	6125 ± 80	5800 ± 70
Radius ($R_\odot$)	1.58 ± 0.05	1.37 ± 0.04
Surface gravity (m s^{-2})	144 ± 9	172 ± 11
Log g (cgs)	4.16 ± 0.03	4.24 ± 0.03
Mean density ($\rho_\odot$)	0.33 ± 0.03	0.46 ± 0.04

proved not to be entirely satisfactory. While spectral types of F8 + G2 seemed about right, the best combination, HR 7560 (F8 V) plus 16 Cyg A (G1.5 V), resulted in a fit whose lines were not quite strong enough to reproduce the 12 Per double-lined spectrum at 6430 Å. Thus we conclude that the system is slightly metal-rich (perhaps [Fe/H] = 0.1) relative to those standards and also the Sun.

Another approach is to measure equivalent widths of lines in well-resolved double-lined spectra, in the present case of six pairs of Fe I or Ca I lines in three different spectra. These yielded an average continuum ratio of 0.686 ± 0.006. Since the lines of the secondary are intrinsically stronger than those of the primary, this results in a minimum value of the magnitude difference. To correct approximately for the effect of differing spectral type on the line strengths, the ratio of the equivalent widths of the same lines in the spectra of HR 7560 and 16 Cyg A was measured, yielding the result 0.892 ± 0.011. Thus the luminosity ratio is $0.686(0.892) = 0.612$ (± 0.009), which in turn gives $\Delta m(6430\ \text{Å}) = 0.533 \pm 0.016$. We convert this to $\Delta V = 0.57 \pm 0.02$ using the mean colors of Johnson (1966a) for stars of types F8 V and G2 V. For the $B-V$ index these would be 0.54 and 0.63 mag, respectively, and we assign an uncertainty of 0.02 mag to each, corresponding to an uncertainty of 1 spectral subclass.

We may also use Johnson's (1996a) mean colors to check that those of 12 Per (Johnson 1966b) are well represented by our spectral types and the above magnitude difference. The results are summarized in Table 5. These are acceptable results for all but the $U-B$ color.

Finally, from the same three spectra the mean values of the projected rotational velocity $v \sin i$ are 6.9 km s^{-1} for the primary star and 5.4 km s^{-1} for the secondary, both with estimated uncertainties less than 1.0 km s^{-1}. The pseudosynchronous period of rotation is 51.6 days, which would imply rotational velocities of 1.2 and 1.1 km s^{-1} for the primary and secondary, respectively, assuming the radii found below. The measured values of $v \sin i$ imply rotation periods of about 9 and 10 days for the primary and secondary, respectively. Thus the stars' rotation speeds are well above the pseudosynchronous value, not unexpectedly for such a long orbital period, despite the system's age, about which we shall have more to say below.

TABLE 5

Results of 12 Persei Spectral Types

Type	$U-B$	$B-V$	$V-R$	$R-I$
F8 + G2	0.08	0.57	0.50	0.30
12 Per	0.14	0.59	0.50	0.30

5. LUMINOSITIES, EFFECTIVE TEMPERATURES, AND RADII

Adopting the distance modulus and visual magnitude difference obtained above, we readily calculate absolute visual magnitudes for both stars. We then interpolate in the tables of VandenBerg (1992) for solar metal abundance, despite the slightly higher value that appears to be appropriate for 12 Per, to obtain estimates of the stars' bolometric corrections and effective temperatures. These were in turn used to determine stellar radii from the bolometric luminosities and effective temperatures, and surface gravities and mean densities from those radii and the masses. The process was iterated to obtain consistency between those gravities and the ones at which VandenBerg's tables were read. The results are included in Table 4.

The components of 12 Per appear to have bolometric luminosities consistent with their masses. Moreover, the derived effective temperatures agree within their uncertainties with those given for main-sequence stars of the same spectral types and color indexes by Popper (1980), Gray (1992), and Flower (1996). The bolometric corrections derived from VandenBerg's (1992) tables, and evident in Table 4, are further from zero than those given by Flower (1996). Use of the latter values would lead to lower luminosities, smaller radii, larger surface gravities, and higher densities for the stars, but in every case the required change would be smaller than the uncertainty given in Table 4.

However, the masses, luminosities, and radii of the components of 12 Per are all larger than expected for main-sequence stars of their effective temperatures. Therefore they may well be somewhat evolved, and poised to leave the main sequence. We note that Andersen (1992) gives 1.3 $M_\odot$ and 1.2 $R_\odot$ for the mass and radius of a zero-age main-sequence star of type F6, and 1.5 $M_\odot$ and 2.5 $R_\odot$ for those of a terminal-age main-sequence star of the same type. Moreover, comparison with the canonical parameters from Table B1 of Gray (1992, p. 431) does indeed suggest that if the spectral types are approximately right, then the stars must be somewhat evolved in order to have the masses, radii, and luminosities in Table 4. But they appear to be similarly offset, despite their substantial difference in mass, which makes such a conclusion for both stars questionable because the more massive star should be offset significantly further than the less massive one, as a result of their different evolutionary timescales.

The offset from the main sequence for the components of 12 Per would be somewhat smaller, however, if their metal content were higher, as we suspected it to be on other grounds discussed above. Presumably, to fit the spectrum of 12 Per with standard stars of earlier spectral type would require a somewhat greater metallicity. At a wavelength of 6430 Å, there are quite modest spectral line changes between late F and early G types. Thus we suspect that changing the metal abundance [Fe/H] by 0.1 to 0.2 could produce stronger lined standards at earlier spectral types, by perhaps 2 subclasses, and still yield a good fit to the spectrum of 12 Per. Such an adjustment would make the components lie closer to the zero-age main sequence and, thus, appear younger. It might therefore help us avoid the apparent evolutionary inconsistency that the assumption of solar abundances leads us into, when we attempt to understand the location of the components of 12 Per on the Hertzsprung-Russell diagram.

Finally we note that, despite the large sizes of the stars, the sum of their radii is scarcely more than 5% of the projected minimum apparent separation of their centers, which occurs almost exactly at periastron. There is thus no possibility of an eclipse in this system, and indeed none has been detected.

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