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Period Changes in the SX Phoenicis Star DY Pegasi

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ABSTRACT. We report 69 new times of maximum light for the SX Phoenicis star DY Pegasi. Combining these new times with previous published maxima, we found the data to be well modeled with a triple linear fit. However, we also determined a refined constant period change of -6.00×10^{-12} days day^{-1}. From both spectroscopic and photometric measurements, we determined $-0.8 < [\mathrm{Fe/H}] < -0.6$. Using phase-averaged indices, we found $\langle T_{\mathrm{eff}} \rangle = 7660$ and $\langle \log g \rangle = 3.89$. From evolutionary models, a mass of $M = 1.5\ M_{\odot}$ and an age of 1.7 Gyr were determined.

1. INTRODUCTION

The SX Phoenicis variable DY Pegasi ($\alpha_{2000} = 23^{\mathrm{h}}08^{\mathrm{m}}51\overset{\mathrm{s}}{.}0$, $\delta_{2000} = +17°12'52''$, $\langle V \rangle = 10.36$, $\Delta V = 0.54$) was first reported as a variable star by Morgenroth (1934). The first extensive observations were made 4 yr later by Soloviev (1938). Since that time the star has received extensive attention. The early observations of DY Peg are well summarized in two papers, Quigley & Africano (1979) and Mahdy & Szeidl (1980). Since then there have been a number of additional times of maximum light published (Hobert et al. 1985; Mahdy 1987; Rodriguez et al. 1990; Agerer & Hübscher 1996, 1998; Agerer et al. 1999, 2001; Wilson et al. 1998; Van Cauteren & Wils 2000).

DY Peg has been observed by the *Hipparcos* satellite (HIP 114290). It was found to have a parallax of 0.36 ± 2.04 mas. Clearly the error is larger than the measured value, but it does provide a lower limit on the distance. DY Peg has also been recently observed by Solano & Fernley (1997), who determined a rotational velocity of $v \sin i = 23.6 \pm 8.3$ km s^{-1}. It is worth noting that within the observational errors, this is one of the fastest rotational velocities for a SX Phe star. Finally, Wilson et al. (1998) examined DY Peg with spectroscopy and infrared photometry. They found a mean radius of $2.09 \pm 0.25\ R_{\odot}$, with a total displacement of $0.073\ R_{\odot}$.

As part of our variable star observing program, we have obtained data on DY Peg. We have collected Strömgren $uvby\beta$ photometry using a photomultiplier, time-series ensemble photometry using a CCD, and spectroscopic observations using a CCD. In this paper we will look at the period change from $O - C$ analysis, the physical parameters determined from the Strömgren indices, and the evolutionary state of DY Peg.

2. PHOTOMETRIC OBSERVATIONS

Observations of DY Peg were made from 1988 July 19 to 1988 August 13 at the Brigham Young University (BYU) West Mountain Observatory 24 inch (610 mm) Telescope (WMO 24). Observations were made with a photomultiplier through the BYU $uvby\beta$ filters as described in Joner & Taylor (1995). Additional photomultiplier observations were secured 1989 June 23 on the 50 inch (1.27 m) telescope at the Kitt Peak National Observatory (hereafter KPNO). Once again observations were made through the BYU filter set. All Strömgren data were transformed to the Hyades-Coma standard system using techniques detailed in Joner et al. (1995).

Light curves of DY Peg were secured using a variety of telescope and CCD combinations. A summary of the telescopes, CCDs, and the resulting plate scale is found in Table 1. In all cases observations were made through a standard *V* filter modeled after Bessell (1990). In 1997 August, observations were made on two nights (JD 2,450,635 and 2,450,637) using the Burrell Schmidt Telescope (hereafter BST) at KPNO with the S2KA CCD. To improve readout time, only a $20' \times 20'$ sub-

[1] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. Observations made with the Burrell Schmidt Telescope of the Warner and Swasey Observatory, Case Western Reserve University.

[2] Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1
TELESCOPE AND CCD SPECIFICATIONS

Telescope	CCD	Pixel Size (μm)	Plate Scale (arcsec pixel^{-1})	Array Size (pixels)
BST	S2KA	21	2.07	600 × 600 (subframe)
DDT (Cas)	Apogee Ap8p	24	0.76	1024 × 1024
DDT (New)	Apogee Ap47p	13	1.32	1024 × 1024
	Meade Pictor 416	9	0.91	768 × 512
	Meade Pictor 1616	9	0.91	1536 × 1024
WMO 16 inch	SpectraSource HPC-1	12	0.61	1024 × 1024

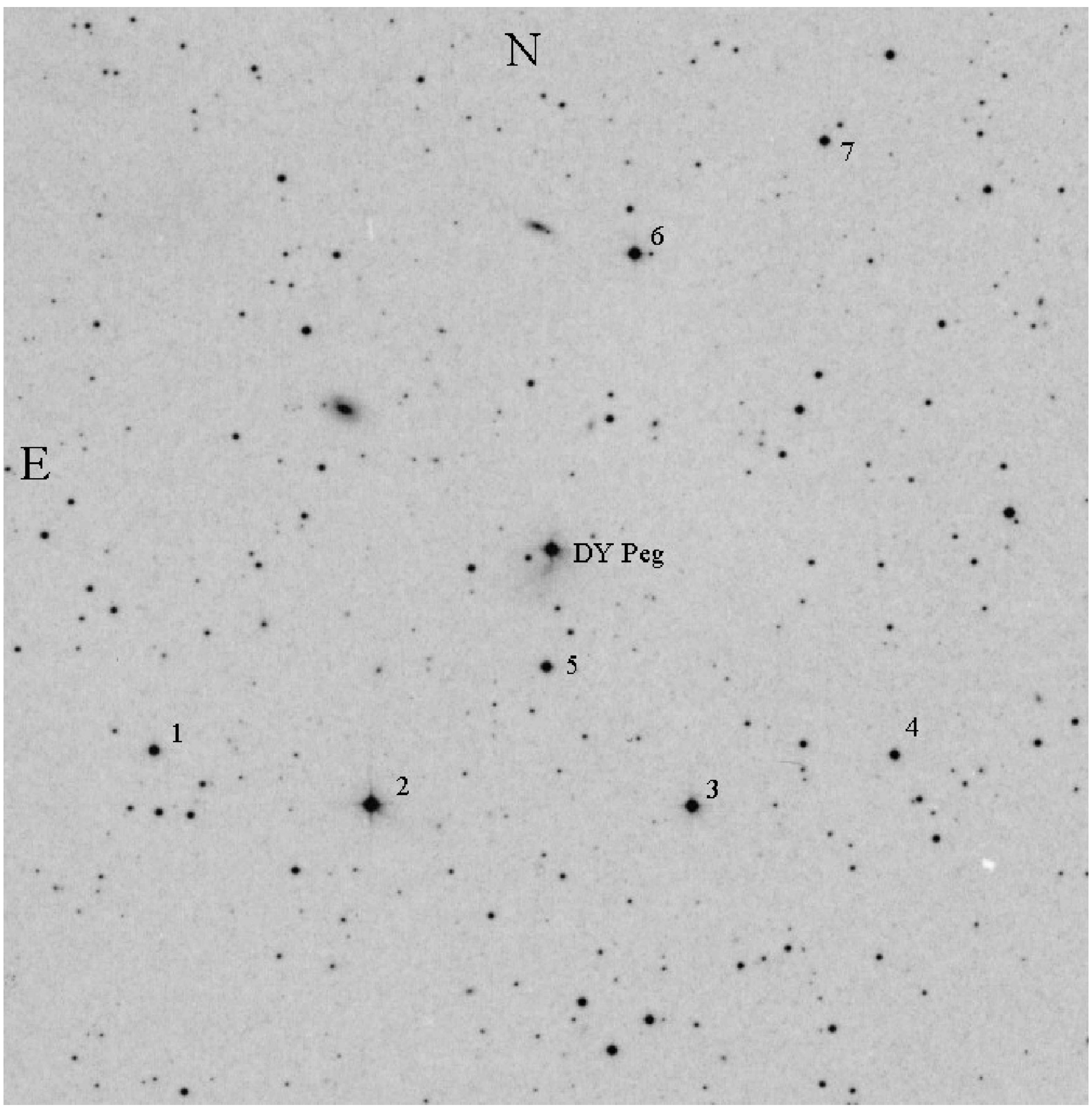

FIG. 1.—DY Pegasi field with comparison stars numbered. The field is 20 arcmin^2.

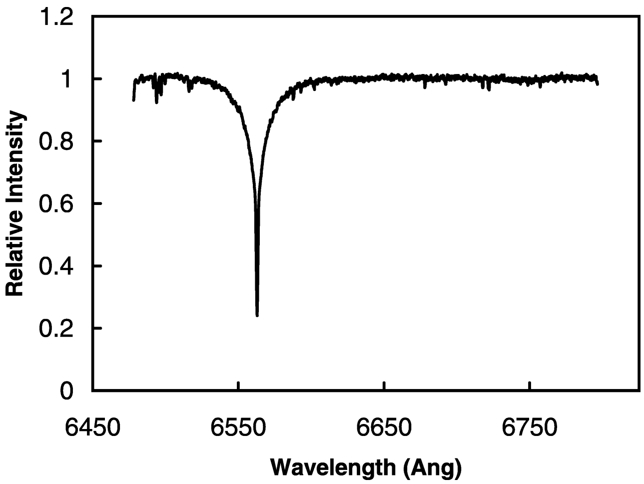

FIG. 2.—Individual and combined spectra of DY Peg.

section of the chip was used. Further details on observing methodology can be found in Hintz et al. (1997).

From 1998 to 2003, observations were made with the David Derrick 16 inch (406 mm) Telescope (hereafter DDT) of the Orson Pratt Observatory on the BYU campus. Observations were made with a Meade Pictor 416, Meade Pictor 1616, or Apogee Ap47p CCD at the Newtonian focus of the telescope, or with an Apogee Ap8p CCD at the Cassegrain focus. During this same time period, a few observations were also obtained using the BYU West Mountain Observatory 16 inch (406 mm) telescope (WMO 16) and a SpectraSource HPC-1 CCD.

A sample of the DY Peg field is shown in Figure 1, with comparison stars numbered and DY Peg labeled. From each CCD frame, we determined instrumental magnitudes for DY Peg and available comparison stars in the field. We used the methods detailed in Hintz et al. (1997) to select a set of comparison stars from those measured. These differential magnitudes and the HJD values were then used to plot the light curves for all nights.

A few additional times of maximum light were determined from data provided by B. Martin & M. Andersen (1998, private communication). These data were taken with an 8 inch (203 mm) telescope and a Lynxx2 CCD. In Table 5 the times of maximum light determined from this data are labeled CAN. Two times of maxima were determined from data supplied by J. H. Peña (1998, private communication).

3. SPECTROSCOPIC OBSERVATIONS

Spectra of DY Peg were obtained at the coudé feed telescope at KPNO on three nights in 1995 June, using the coudé spectrograph. The spectrograph was configured with the 632 line mm^{-1} "A" grating in first order, centered at 6640 Å. The 1080 mm focal length camera was used with the long focal length collimator and the red corrector to provide a reciprocal dispersion of 0.1 Å pixel^{-1} and a resolving power of 40,000. The detector was a Loral 3072 × 1024 thinned CCD, providing spectra coverage of approximately 6500–6800 Å.

Spectra were obtained sequentially for approximately 4 hr per night. Exposure times were set at 900 s the first night, and reduced to 600 s on the subsequent two nights to provide better sampling of the light/radial velocity curve. Observations of the radial velocity standard HD 213014 were interspersed among the spectra of DY Peg to monitor any drift in the coudé spectrograph.

A total of 47 spectra were obtained during the three consecutive nights of observing. The spectra were reduced following standard procedures, including bias correction and trim, bias subtraction, division by a flat-field image, extraction of a one-dimensional spectrum, wavelength calibration using a ThAr spectrum, and continuum normalization, all using NOAO IRAF tasks. The signal-to-noise ratio (S/N) of the individual spectra is approximately 25 : 1.

After reductions, the position of Hα was measured precisely, and the spectra were shifted to zero velocity and co-added to produce a single phase-averaged spectrum with a S/N of 180 : 1. In Figure 2 we show the combined spectra.

The equivalent widths of spectral lines measured in the phase-averaged spectrum are included in Table 2. The widths of the spectral features are consistent with the $v \sin i = 23.6$ km s^{-1} given by Solano & Fernley (1997).

TABLE 2
SPECTRAL FEATURES IN AVERAGED SPECTRUM OF DY PEG

Spectral Feature	Species	Excitation Potential	log *gf*	Equivalent Width (mÅ)
6516.083	Fe II	2.89	−3.22	37
6587.622	C I	8.54	−1.22	31
6592.92	Fe I	2.73	−1.473	16
6677.997	Fe I	2.69	−1.418	25
6717.687	Ca I	2.71	−0.524	23
6721.844	Si I	5.86	−0.94	37
6743.58	S I	7.86	−0.57	6
6748.779	S I	7.87	−0.35	13
6757.195	S I	7.87	−0.19	18

TABLE 3
CONSTANT PERIOD CHANGE DETERMINATIONS FOR DY PEG

Reference	Period Change (days day^{-1})
Quigley & Africano (1979)	-6×10^{-12}
Mahdy & Szeidl (1980)	-10.4×10^{-12}
Mahdy (1987)	-6.34×10^{-12}
Jiang & Zhao (1982)	-6.3×10^{-12}
Peña & Peniche (1986)	-6.03×10^{-12}
Blake et al. (2000)	-3.72×10^{-11}
Derekas et al. (2003)	-5.51×10^{-12}
Current paper	-6.00×10^{-12}

TABLE 4
ARCHIVAL MAXIMA OF DY PEGASI

HJD (2,400,000.0+)	Detector	Reported In[a]	Cycle	HJD (2,400,000.0+)	Detector	Reported In[a]	Cycle	HJD (2,400,000.0+)	Detector	Reported In[a]	Cycle
29193.4456	pg	Sc	0	29194.4691	pg	Sc	14	30976.4250	pg	St	24449
30976.4967	pg	St	24450	30987.3619	pg	St	24599	31022.0744	pg	St	25075
31086.3238	pg	St	25956	31104.2638	pg	St	26202	31288.5472	pg	St	28729
31290.5170	pg	St	28756	31306.4861	pg	St	28975	31310.4978	pg	St	29030
31314.4391	pg	St	29084	31317.4288	pg	St	29125	31318.4481	pg	St	29139
31318.5228	pg	St	29140	31320.4892	pg	St	29167	31328.5124	pg	St	29277
31330.4801	pg	St	29304	31671.4834	pg	St	33980	31764.3924	pg	St	35254
31797.3563	pg	St	35706	31824.2672	pg	St	36075	32011.5414	pg	St	38643
32092.4147	pg	St	39752	32093.3646	pg	St	39765	32172.2697	pg	St	40847
32379.5271	pg	St	43689	32380.5477	pg	St	43703	32381.4948	pg	St	43716
32382.5174	pg	St	43730	32385.5809	pg	St	43772	32386.5267	pg	St	43785
32387.5496	pg	St	43799	32394.5505	pg	St	43895	32398.5607	pg	St	43950
32406.5103	pg	St	44059	32408.0396	pg	St	44080	32409.4989	pg	St	44100
32410.5200	pg	St	44114	32411.4686	pg	St	44127	32413.4370	pg	St	44154
32414.6057	pg	St	44170	32415.4786	pg	St	44182	32421.4592	pg	St	44264
32425.3979	pg	St	44318	32427.4403	pg	St	44346	32428.3876	pg	St	44359
32432.3978	pg	St	44414	32433.4201	pg	St	44428	32434.3681	pg	St	44441
32751.8884	pm	Ir	48795	32751.9613	pm	Ir	48796	32752.9092	pm	Ir	48809
34626.4620	pg	Al	74500	34661.3915	pm	MB	74979	34661.4644	pm	MB	74980
34662.3403	pm	MB	74992	34662.4150	pm	MB	74993	34662.4857	pm	MB	74994
34662.5589	pm	MB	74995	34689.3228	pm	MB	75362	34689.3968	pm	MB	75363
34690.3437	pm	MB	75376	34690.4165	pm	MB	75377	34690.4897	pm	MB	75378
34691.2919	pm	MB	75389	34691.3646	pm	MB	75390	34691.4376	pm	MB	75391
34692.2401	pm	MB	75402	34692.3138	pm	MB	75403	34692.3858	pm	MB	75404
34692.4585	pm	MB	75405	34693.2613	pm	MB	75416	34693.3338	pm	MB	75417
34693.4057	pm	MB	75418	34693.4789	pm	MB	75419	34695.3021	pm	MB	75444
34695.3756	pm	MB	75445	34695.4487	pm	MB	75446	34696.2515	pm	MB	75457
34696.3242	pm	MB	75458	34697.3966	pm	MB	75459	35070.2901	pm	De	80586
35745.5885	pm	HG	89846	35745.6611	pm	HG	89847	35745.7343	pm	HG	89848
35745.8069	pm	HG	89949	35760.6847	pm	HG	90053	35760.7576	pm	HG	90054
35761.7794	pm	HG	90068	35762.5808	pm	HG	90079	35762.6536	pm	HG	90080
35762.7266	pm	HG	90081	35762.8003	pm	HG	90082	35770.6031	pm	HG	90189
35770.6753	pm	HG	90190	35770.7488	pm	HG	90191	35771.5523	pm	HG	90202
35771.6229	pm	HG	90203	35771.6958	pm	HG	90204	35773.6654	pm	HG	90231
35773.7375	pm	HG	90232	35780.5941	pm	HG	90326	35780.6664	pm	HG	90327
36155.3623	pm	Br	95465	36160.3214	pm	Br	95533	36160.3939	pm	Br	95534
37164.5170	pm	MS	109303	37165.5375	pm	MS	109317	37167.4320	pm	MS	109343
37168.5276	pm	Br	109358	37174.4348	pm	Br	109439	37178.3734	pm	MS	109493
37178.4451	pm	MS	109494	38276.8624	pm	KM	124556	38655.8598	pm	Fi	129753
40895.6447	pm	WN	160466	40897.6138	pm	WN	160493	41535.5012	pm	MS	169240
41937.4701	pm	GH	174752	41937.5444	pm	GH	174753	41957.3785	pm	GH	175025
41957.4538	pm	GH	175026	41957.5243	pm	GH	175027	41957.5998	pm	GH	175028
41963.4324	pm	MS	175108	41984.3615	pm	MS	175395	42279.4210	pm	MS	179441
42739.2955	pm	He	185747	43085.6951	pm	QA	190497	43085.7684	pm	QA	190498
43085.8403	pm	QA	190499	43088.6860	pm	QA	190538	43088.7582	pm	QA	190539
43089.7064	pm	QA	190552	43305.9329	pm	QA	193517	43307.8308	pm	QA	193543
43307.9023	pm	QA	193544	43348.8143	pm	QA	194105	43348.8867	pm	QA	194106
43348.9598	pm	QA	194107	43350.7833	pm	QA	194132	43350.8554	pm	QA	194133
43350.9288	pm	QA	194134	43351.8042	pm	QA	194146	43351.8765	pm	QA	194147
43353.7728	pm	QA	194173	43353.8459	pm	QA	194174	44113.5179	pm	MS	204591
45611.5704	pm	Me	225133	45624.6242	pm	Me	225312	45643.5851	pm	Me	225572
46007.7789	pm	Ho	230566	46018.7999	pm	Ho	230717	46019.5916	pm	Ho	230728
46019.6634	pm	Ho	230729	46021.6357	pm	Ho	230756	46022.5835	pm	Ho	230769
46052.6290	pm	Ho	231181	46054.6000	pm	Ho	231208	46055.6180	pm	Ho	231222
46056.6393	pm	Ho	231236	46645.4466	pm	Ma	239310	46645.5195	pm	Ma	239311
46646.4675	pm	Ma	239324	46646.5408	pm	Ma	239325	46647.4155	pm	Ma	239337
46649.3849	pm	Ma	239364	46649.4578	pm	Ma	239365	46649.5307	pm	Ma	239366
46653.4688	pm	Ro	239420	46653.5419	pm	Ro	239421	46653.6150	pm	Ro	239422
46654.4168	pm	Ro	239433	46654.4901	pm	Ro	239434	46654.5619	pm	Ro	239435
46654.6352	pm	Ro	239436	46655.6571	pm	Ro	239450	46656.4581	pm	Ro	239461
46656.5313	pm	Ro	239462	46656.6052	pm	Ro	239463	46656.8237	pm	Wi	239466
46656.8961	pm	Wi	239467	46656.9690	pm	Wi	239468	47002.8586	pm	Wi	244211

TABLE 4 (*Continued*) ARCHIVAL MAXIMA OF DY PEGASI

HJD (2,400,000.0+)	Detector	Reported In[a]	Cycle	HJD (2,400,000.0+)	Detector	Reported In[a]	Cycle	HJD (2,400,000.0+)	Detector	Reported In[a]	Cycle
47003.8068	pm	Wi	244224	47003.8798	pm	Wi	244225	47006.8694	pm	Wi	244266
47008.8389	pm	Wi	244293	47030.7892	pm	Wi	244594	47034.8002	pm	Wi	244649
47050.7714	pm	Wi	244969	50052.1988	pm	A1	286025	50052.2710	pm	A1	286026
50453.2928	pm	A3	291525	50750.3215	pm	A2	295598	50762.2811	pm	A2	295762
51137.2674	pm	A3	300904	51158.4139	pm	A3	301194	52125.5619	pm	DK	314456
52126.5833	pm	DK	314470	52134.5332	pm	DK	314579	52134.6062	pm	DK	314580
52137.5228	pm	DK	314620	52137.5955	pm	DK	314621	52158.3805	pm	DK	314906
52161.4431	pm	DK	314948								

[a] (A1) Agerer & Hübscher 1996; (A2) Agerer & Hübscher 1998; (A3) Agerer et al. 1999; (Al) Alania 1956; (Br) Broglia 1961; (De) Detre & Chang 1960; (DK) Derekas et al. 2003; (Fi) Fitch et al. 1966; (GH) Geyer & Hoffman 1974; (He) Heiser 1976; (HG) Hardie & Geilker 1958; (Ho) Hobert et al. 1985; (Ir) Iriarte 1952; (KM) Karetnikov & Medvedev 1964; (Ma) Mahdy 1987; (MB) Masani & Broglia 1954; (Me) Meylan et al. 1986; (MS) Mahdy & Szeidl 1980; (QA) Quigley & Africano 1979; (Ro) Rodriguez et al. 1990; (Sc) Schneller 1938; (St) Steinmetz 1946; Steinmetz 1948; (Wi) Wilson et al. 1998; (WN) Warner & Nather 1972.

TABLE 5
NEW MAXIMA OF DY PEGASI

HJD (2,400,000.0+)	Detector	Telescope	Cycle	HJD (2,400,000.0+)	Detector	Telescope	Cycle
47362.8959	pm	WMO 24	249148	47363.8437	pm	WMO 24	249161
47363.9167	pm	WMO 24	249162	47364.7917	pm	WMO 24	249174
47364.8642	pm	WMO 24	249175	47382.8045	pm	WMO 24	249421
47383.7521	pm	WMO 24	249434	47387.8371	pm	WMO 24	249490
47701.8572	pm	KPNO	253796	47701.9304	pm	KPNO	253797
48896.7539	pm	Peña	270167	48896.8072	pm	Peña	270168
49995.6805	CCD	CAN	285250	49995.7538	CCD	CAN	285251
49998.6704	CCD	CAN	285291	49998.7435	CCD	CAN	285292
50665.8725	CCD	BST	294440	50665.9451	CCD	BST	294441
50667.9141	CCD	BST	294468	51027.7319	CCD	DDT	299402
51027.8052	CCD	DDT	299403	51047.7139	CCD	DDT	299676
51094.6784	CCD	DDT	300320	51094.7512	CCD	DDT	300321
51098.6166	CCD	DDT	300374	51098.6897	CCD	DDT	300375
51098.7622	CCD	DDT	300376	51380.9137	CCD	DDT	304245
51408.6986	CCD	DDT	304626	51408.7721	CCD	DDT	304627
51408.8450	CCD	DDT	304628	51408.9175	CCD	DDT	304629
51420.7317	CCD	DDT	304791	51420.8047	CCD	DDT	304792
51442.6827	CCD	WMO 16	305092	51442.7559	CCD	WMO 16	305093
51451.6524	CCD	DDT	305215	51451.7253	CCD	DDT	305216
51451.7979	CCD	DDT	305217	51451.8711	CCD	DDT	305218
51461.6430	CCD	DDT	305352	51461.6432	CCD	WMO 16	305352
51461.7161	CCD	DDT	305353	51461.7159	CCD	WMO 16	305353
51461.7894	CCD	DDT	305354	51461.8622	CCD	DDT	305355
52113.8965	CCD	DDT	314296	52161.7360	CCD	DDT	314952
52161.8085	CCD	DDT	314953	52161.8820	CCD	DDT	314954
52491.8720	CCD	DDT	319479	52491.9440	CCD	DDT	319480
52494.9355	CCD	DDT	319521	52499.9651	CCD	DDT	319590
52501.8621	CCD	DDT	319616	52501.9351	CCD	DDT	319617
52503.7580	CCD	DDT	319642	52503.8315	CCD	DDT	319643
52503.9041	CCD	DDT	319644	52505.7266	CCD	DDT	319669
52505.7995	CCD	DDT	319670	52519.6575	CCD	DDT	319860
52519.7290	CCD	DDT	319861	52519.8025	CCD	DDT	319862
52519.8750	CCD	DDT	319863	52902.6643	CCD	DDT	325112
52902.9567	CCD	DDT	325116	52903.6859	CCD	DDT	325126
52911.7808	CCD	DDT	325237				

TABLE 6
COEFFICIENT ERRORS FOR ALL EQUATIONS

Equation	Epoch Error	Period Error	Period Change Error
1	0.00021	1.0×10^{-9}	...
2	0.00015	2.4×10^{-9}	6.7×10^{-15}
3	0.00020	2.9×10^{-9}	...
4	0.00022	1.6×10^{-9}	...
5	0.00022	2.1×10^{-9}	...
6	0.00018	8.0×10^{-9}	...

4. PERIOD CHANGES

The existence of a changing period in DY Peg has been well established since the work of Quigley & Africano (1979) and Mahdy & Szeidl (1980). Published constant period change determinations are collected in Table 3. Of all these, only the result of Blake et al. (2000) is found to be radically different. However, two publications have suggested the possibility of alternative models. Mahdy & Szeidl (1980) stated that the period change up to that point could be fit equally well by two linear fits. Derekas et al. (2003) argued that the parabolic fit does not fully describe the $O-C$ diagram, especially for the last 25,000 cycles. This result encouraged us to take a careful look at both the parabolic fit and alternative models.

We collected 208 published times of maximum light (Table 4) and determined 69 new times of maximum light (Table 5). For our analysis we only included new times of maximum light determined from *V*- or *y*-filter observations to minimize errors due to phase differences. From all times of maximum light, we determined the best linear fit to the data. From the $O-C$ diagram of this initial fit, we found one archival data point with an unusually large error (2,446,018.7999). This point was removed from the data set, and a new ephemeris was calculated (see eq. [1]). The errors for all equations in this section are collected in Table 6.

$$\mathrm{HJD_{max}} = 2{,}429{,}193.4506 + 0.072926308E \quad (1)$$

The standard deviation per datum for this fit is $\sigma = 0.0017$. The $O-C$ diagram determined from equation (1) is shown in Figure 3. The expected parabolic shape was evident in the $O-C$ diagram, therefore we proceeded with a second-order polynomial fit. This yielded an ephemeris of

$$\mathrm{HJD_{max}} = 2{,}429{,}193.4464 + 0.072926383E - 2.187 \times 10^{-13}E^2 \quad (2)$$

This model gave a significantly better standard deviation of $\sigma = 0.0008$. From this second-order fit, we determined a constant period change of -4.37×10^{-13} days cycle^{-1}, or -6.00×10^{-12} days day^{-1}. This period change matches well with the previous studies, except for Blake et al. (2000).

Although the data are reasonably fitted with a parabola, we elected to explore the alternatives suggested by Mahdy & Szeidl

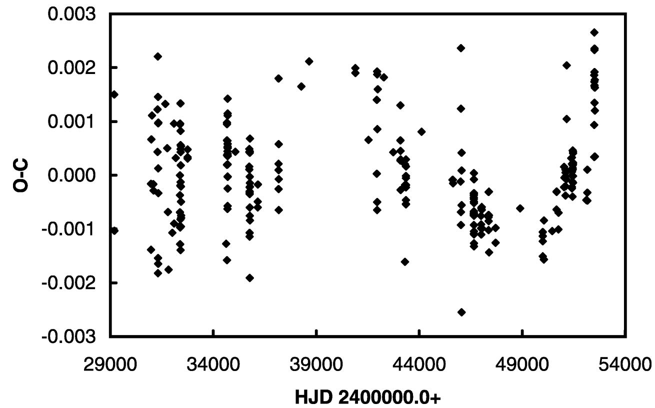

FIG. 4.—$O-C$ diagram from a double linear fit as given by eqs. (3) and (4).

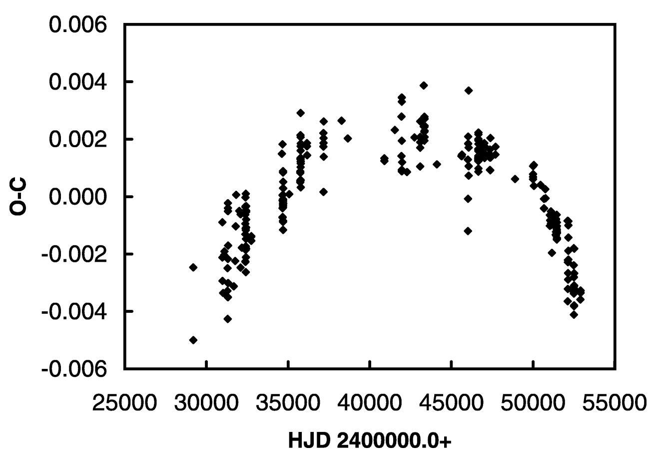

FIG. 3.—$O-C$ diagram from the single linear fit given in eq. (1).

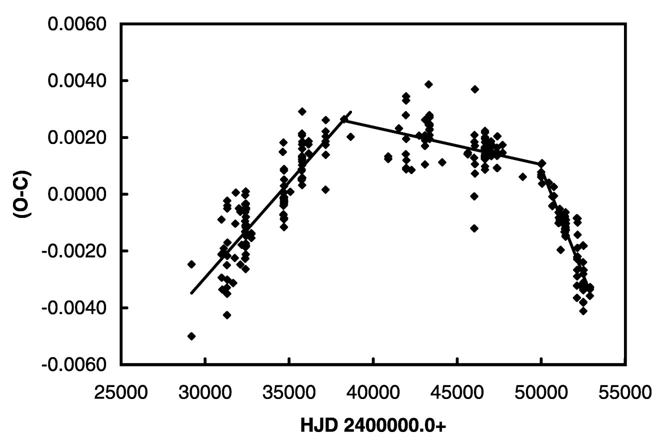

FIG. 5.—$O-C$ diagram with a triple linear fit as given by eqs. (3), (5), and (6).

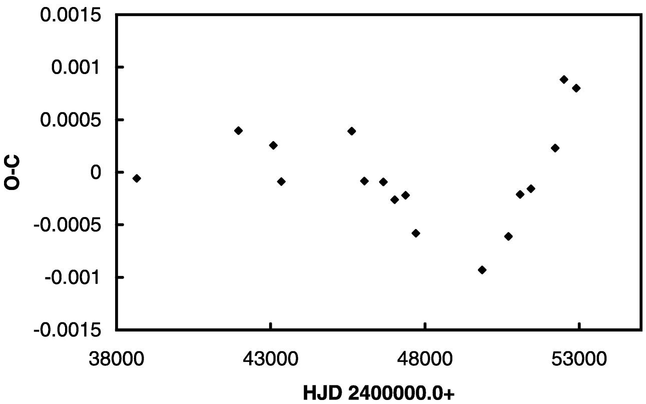

FIG. 6.—Seasonally averaged $O - C$ diagram from the parabolic fit given in eq. (2).

(1980) and Derekas et al. (2003). Using the break at HJD 24,380,000.0 suggested by Mahdy & Szeidl (1980), we determined two linear fits as shown in equations (3) and (4),

$$\mathrm{HJD_{max}} = 2{,}429{,}193.4471 + 0.072926357E, \quad (3)$$

$$\mathrm{HJD_{max}} = 2{,}438{,}276.8643 + 0.072926275E. \quad (4)$$

The total standard deviation for the double-line model is $\sigma = 0.0009$. We compared the variances for the parabolic fit and double linear fit using a standard F-test with a 95% confidence interval. From this test we concluded that the parabolic fit is significantly better than the double linear fit. Our additional times of maximum light strongly indicate that the double linear fit suggested by Mahdy & Szeidl (1980) should be removed from further consideration. In Figure 4 we show the $O - C$ diagram for the double linear fit. An examination of this diagram shows that a case can be made for a second period break at about HJD 2,449,000.0. Therefore, we examined the possibility of fitting the data after HJD 2,438,000 with two linear segments, or a double-break model. For this model we kept equation (3) and found two additional equations given by equations (5) and (6),

$$\mathrm{HJD_{max}} = 2{,}438{,}276.8623 + 0.072926298E, \quad (5)$$

$$\mathrm{HJD_{max}} = 2{,}450{,}052.1985 + 0.072926197E. \quad (6)$$

The overall standard deviation for the three linear fits is $\sigma = 0.0007$. The standard F-test in this case does not show a significant difference in the sample variances between the parabolic fit and the triple linear fit, although the newest data are fitted better with the triple linear fit. The triple linear solution is shown in Figure 5.

Since the parabolic solution and triple linear solutions were similar in error, we chose to examine the residuals from the two solutions to find a compelling reason to select one over the other. The residuals from the parabolic fit show a pattern for data after HJD 2,444,000.0. To clarify this shape, we used seasonal averages and found the curve shown in Figure 6. Although one might be inclined to see a sine curve in this data, we feel that there is insufficient data to support that conclusion. It is also interesting to note that the bottom of the apparent "sine" curve is at the location of our second period break. When we examined the residuals for the triple linear solution, we found no patterns in the residuals, only scatter about the zero line. Because of the lack of a pattern in the residuals, we prefer the triple linear solution.

Given the triple linear fit detailed above, a case can be made for DY Peg showing a set of period breaks like those seen in CY Aquarii (Powell et al. 1995). However, Fu & Sterken (2003) argue that CY Aqr can be equally well fitted with a light-time orbital solution. The alternative model for the changes seen in the period of DY Peg is a constant period change with an orbital component.

5. THE COMPOSITION OF DY PEG

It seems appropriate to provide an estimate of the metallicity from the available line measurements of the phase averaged-spectrum detailed earlier. The line list used for the analysis described here is tabulated in Table 2.

Oscillator strengths (gf-values) used for the lines in Table 2 have been taken from the sources in the literature. Values for Fe I lines were taken from O'Brian et al. (1991). For the Fe II λ6516 line, Biémont et al. (1991) and Heise & Kock (1990) are in good agreement at $\log g = -3.45$ and -3.44, respectively, but this value gives a discrepant solar iron abundance. The gf-value for C I λ6587 was taken from Lambert et al. (1982), who iterated it from the solar equivalent width. For Si I λ6721 and for the S I triplet near λ6750, log gf-values were taken from Wiese et al. (1969). For the Ca I line, the gf-value from Smith & Raggett (1981) was used, with the caution from Smith (1981) that the line appears to be blended on either side.

A microturbulence of 2 km s^{-1} was adopted following Roby & Lambert (1990), but the observed lines are so weak as to make the microturbulence irrelevant to the determination of abundances.

A model atmosphere representing the average temperature and luminosity of DY Peg was computed using the grid of models available from Kurucz (1979). Abundances were determined using the synthetic spectrum program of Sneden (1974), varying the abundances of each element to obtain a match to the observed equivalent width. The line list includes a single line of Fe II, as well as three lines of Fe I. On average we found the metallicity to be [Fe/H] $= -0.8$, in good agreement with Burki & Meylan (1986). In addition, the star may exhibit a slight (0.15 dex) excess of the α-elements calcium and sulfur. The abundance of carbon may exhibit a more sig-

TABLE 7
STRÖMGREN MEASUREMENTS

HJD (2,440,000.0+)	y	$(b-y)$	m_1	c_1	β	HJD (2,440,000.0+)	y	$(b-y)$	m_1	c_1	β
7362.7841	10.560	0.1924	0.1542	0.8270	2.7746	7363.9166	10.014	0.1464	0.1339	1.0102	2.8897
7362.7862	10.571	0.2097	0.1520	0.7620	2.6698	7363.9186	10.010	0.1474	0.1425	1.0000	2.8805
7362.7885	10.596	0.2229	0.0974	0.8088	2.7183	7363.9240	10.115	0.1561	0.1420	1.0129	2.8301
7362.8333	10.230	0.1429	0.1769	0.9457	2.8274	7363.9261	10.169	0.1535	0.1566	0.9825	2.8652
7362.8371	10.299	0.1596	0.1553	0.9563	2.8291	7363.9284	10.237	0.1571	0.1604	0.9513	2.8274
7362.8391	10.372	0.1611	0.1590	0.9170	2.7909	7364.7780	10.487	0.2065	0.1430	0.7693	2.7364
7362.8447	10.428	0.2088	0.1426	0.8366	2.7451	7364.7800	10.449	0.1829	0.1490	0.7986	2.7690
7362.8468	10.436	0.2101	0.1258	0.8763	2.7355	7364.7819	10.351	0.1780	0.1498	0.8240	2.7750
7362.8487	10.474	0.1851	0.1768	0.8191	2.7314	7364.7870	10.124	0.1180	0.1640	0.9593	2.8272
7362.8543	10.477	0.2432	0.1218	0.7913	2.7396	7364.7890	10.076	0.1309	0.1321	0.9874	2.8007
7362.8562	10.536	0.2127	0.1353	0.8272	2.7376	7364.7910	10.053	0.1021	0.1803	0.9846	2.8709
7362.8581	10.547	0.1999	0.1885	0.7577	2.7221	7364.7938	10.054	0.1079	0.1790	1.0182	2.8620
7362.8641	10.563	0.2414	0.1257	0.7809	2.7290	7364.7959	10.106	0.1146	0.1425	1.0525	2.8273
7362.8660	10.564	0.2337	0.1571	0.7277	2.7301	7364.8012	10.176	0.1614	0.1257	1.0269	2.8174
7362.8679	10.580	0.2461	0.1239	0.7684	2.7327	7364.8032	10.217	0.1619	0.1399	0.9769	2.8445
7362.8735	10.604	0.2207	0.1500	0.7516	2.7601	7364.8073	10.311	0.1638	0.1699	0.8996	2.8044
7362.8756	10.577	0.2317	0.1354	0.7457	2.7375	7364.8547	10.376	0.1651	0.1612	0.8509	2.7572
7362.8776	10.570	0.2208	0.1425	0.7568	2.7427	7364.8566	10.254	0.1813	0.1370	0.8813	2.8543
7362.8832	10.472	0.1907	0.1546	0.7951	2.8393	7364.8585	10.182	0.1364	0.1640	0.9259	2.8518
7362.8852	10.400	0.1922	0.1319	0.8473	2.8156	7364.8639	10.035	0.1161	0.1588	1.0396	2.8390
7362.8871	10.307	0.1787	0.1430	0.8495	2.8486	7364.8658	10.013	0.1386	0.1433	1.0139	2.8711
7362.8890	10.208	0.1665	0.1478	0.9118	2.7949	7364.8679	10.047	0.1200	0.1867	1.0055	2.8155
7362.8922	10.082	0.1388	0.1462	0.9983	2.8670	7364.8700	10.082	0.1431	0.1407	1.0224	2.8412
7362.8942	10.045	0.1270	0.1569	0.9819	2.8835	7364.8731	10.154	0.1472	0.1486	1.0081	2.8091
7362.8962	10.027	0.1267	0.1660	0.9899	2.8739	7364.8787	10.273	0.1701	0.1496	0.9534	2.8336
7362.9015	10.117	0.1229	0.1657	1.0039	2.8307	7364.8808	10.336	0.1777	0.1510	0.9361	2.7561
7362.9035	10.159	0.1291	0.1799	0.9700	2.8687	7364.8830	10.391	0.1692	0.1592	0.9273	2.7980
7362.9054	10.173	0.1771	0.1252	0.9517	2.8151	7364.8890	10.463	0.1918	0.1714	0.8400	2.7781
7362.9077	10.238	0.1670	0.1438	0.9511	2.8377	7364.8911	10.469	0.2297	0.1062	0.8498	2.7814
7362.9124	10.314	0.1315	0.1992	0.9013	2.8143	7364.8930	10.521	0.2069	0.1666	0.8087	2.7681
7363.7725	10.065	0.0865	0.1818	1.0627	2.8608	7364.8988	10.537	0.2410	0.1203	0.7967	2.7056
7363.7744	10.114	0.0731	0.1963	1.0557	2.8774	7364.9009	10.537	0.2547	0.1231	0.7491	2.7298
7363.7767	10.135	0.1145	0.1659	1.0418	2.8187	7364.9030	10.549	0.2468	0.1254	0.7531	2.6742
7363.8323	10.424	0.1848	0.1659	0.7897	2.7292	7364.9089	10.590	0.2510	0.1204	0.7696	2.7130
7363.8345	10.328	0.1810	0.1401	0.8545	2.8139	7364.9109	10.572	0.2528	0.1117	0.7736	2.7476
7363.8364	10.238	0.1509	0.1657	0.9149	2.8105	7364.9128	10.612	0.2157	0.1522	0.7633	2.7249
7363.8414	10.071	0.1107	0.1690	1.0182	2.8423	7364.9148	10.594	0.2272	0.1494	0.7666	2.6986
7363.8433	10.026	0.1351	0.1474	1.0045	2.8588	7364.9178	10.595	0.2308	0.1297	0.7897	2.7376
7363.8456	10.053	0.1166	0.1556	1.0378	2.8715	7364.9200	10.528	0.2570	0.0965	0.7902	2.7846
7363.8492	10.103	0.1385	0.1431	1.0342	2.8669	7364.9221	10.507	0.2482	0.1110	0.8006	2.7277
7363.8512	10.134	0.1648	0.1335	0.9782	2.8161	7382.7316	10.088	0.0978	0.1848	0.9988	2.8663
7363.8568	10.305	0.1333	0.1935	0.9276	2.7941	7382.7339	10.085	0.1171	0.1724	1.0053	2.8265
7363.8588	10.326	0.1785	0.1315	0.9230	2.8202	7382.7358	10.112	0.1319	0.1389	1.0267	2.8533
7363.8608	10.351	0.1994	0.1046	0.9447	2.7735	7382.7422	10.219	0.1708	0.1369	0.9749	2.8677
7363.8659	10.444	0.1953	0.1432	0.8599	2.7555	7382.7442	10.298	0.1259	0.1914	0.9706	2.7829
7363.8678	10.440	0.2317	0.1073	0.8625	2.7899	7382.7464	10.322	0.1731	0.1507	0.9504	2.7672
7363.8698	10.491	0.2119	0.1398	0.8171	2.7527	7382.7518	10.402	0.2047	0.1240	0.8755	2.7720
7363.8753	10.535	0.2088	0.1524	0.8139	2.7080	7382.7537	10.443	0.1935	0.1269	0.9021	2.7642
7363.8773	10.531	0.2317	0.1409	0.7725	2.7103	7382.7558	10.450	0.2008	0.1557	0.8410	2.7453
7363.8793	10.552	0.2303	0.1357	0.7880	2.7109	7382.7690	10.551	0.2444	0.0996	0.8001	2.7872
7363.8852	10.561	0.2412	0.1353	0.7625	2.7512	7382.7712	10.600	0.2029	0.1532	0.8020	2.7507
7363.8875	10.582	0.2219	0.1567	0.7657	2.6903	7382.7733	10.591	0.2182	0.1554	0.7654	2.7431
7363.8896	10.571	0.2389	0.1254	0.7784	2.7217	7382.7865	10.578	0.1952	0.1661	0.7728	2.7608
7363.8951	10.578	0.2194	0.1540	0.7410	2.7467	7382.7886	10.527	0.2129	0.1481	0.7687	2.7520
7363.8969	10.557	0.2429	0.1067	0.7656	2.7176	7382.7906	10.533	0.1772	0.1827	0.7898	2.7926
7363.8988	10.548	0.2432	0.1067	0.7743	2.7243	7382.7958	10.315	0.1852	0.1337	0.8813	2.8563
7363.9048	10.426	0.2159	0.1279	0.8184	2.7858	7382.7978	10.227	0.1454	0.1797	0.8803	2.8373
7363.9068	10.388	0.1639	0.1565	0.8629	2.8013	7382.7999	10.127	0.1290	0.1690	0.9704	2.8725
7363.9088	10.253	0.1860	0.1296	0.8951	2.7754	7382.8018	10.082	0.1332	0.1332	1.0233	2.8839
7363.9110	10.150	0.1491	0.1459	0.9234	2.8172	7382.8047	10.047	0.1138	0.1594	1.0408	2.8515
7363.9145	10.041	0.1242	0.1623	1.0085	2.8619	7382.8066	10.060	0.1071	0.1877	1.0084	2.8583
7382.8084	10.094	0.1202	0.1616	1.0216	2.8438	7387.8570	10.457	0.1880	0.1542	0.8627	2.6939

TABLE 7 (Continued) Strömgren Measurements

HJD (2,440,000.0+)	y	(by)	m_1	c_1	β	HJD (2,440,000.0+)	y	(by)	m_1	c_1	β
7382.8138 ……	10.188	0.1414	0.1532	1.0016	2.8620	7701.8531 ……	10.106	0.1492	0.1478	0.9662	2.8680
7382.8160 ……	10.239	0.1434	0.1753	0.9720	2.8096	7701.8545 ……	10.080	0.1303	0.1544	1.0444	2.8404
7382.8180 ……	10.275	0.1655	0.1494	0.9415	2.8406	7701.8561 ……	10.060	0.1374	0.1373	1.0467	2.8799
7382.8201 ……	10.334	0.1416	0.1851	0.9333	2.8121	7701.8605 ……	10.064	0.1441	0.1523	1.0045	2.8361
7382.8222 ……	10.330	0.1923	0.1356	0.8887	2.7873	7701.8620 ……	10.087	0.1448	0.1487	1.0193	2.8492
7383.7258 ……	10.625	0.1923	0.1900	0.7431	2.7930	7701.8635 ……	10.121	0.1538	0.1392	1.0304	2.8345
7383.7278 ……	10.616	0.2186	0.1647	0.7339	2.7661	7701.8677 ……	10.220	0.1581	0.1493	1.0153	2.8214
7383.7297 ……	10.621	0.2217	0.1485	0.7537	2.7611	7701.8692 ……	10.251	0.1731	0.1547	0.9422	2.7976
7383.7356 ……	10.544	0.2179	0.1518	0.7529	2.7056	7701.8707 ……	10.287	0.1826	0.1467	0.9336	2.8103
7383.7381 ……	10.568	0.1748	0.1806	0.7849	2.8040	7701.8753 ……	10.373	0.1963	0.1376	0.9136	2.8006
7383.7403 ……	10.459	0.2025	0.1558	0.7640	2.7396	7701.8768 ……	10.413	0.1981	0.1230	0.8995	2.8009
7383.7465 ……	10.195	0.1475	0.1648	0.9160	2.8179	7701.8783 ……	10.425	0.2122	0.1250	0.8890	2.7407
7383.7485 ……	10.086	0.1480	0.1398	0.9901	2.8442	7701.8828 ……	10.457	0.2315	0.1173	0.8365	2.7476
7383.7507 ……	10.087	0.1012	0.1781	1.0031	2.8339	7701.8843 ……	10.482	0.2193	0.1264	0.8394	2.7596
7383.7529 ……	10.047	0.1307	0.1309	1.0469	2.8306	7701.8858 ……	10.488	0.2162	0.1382	0.8221	2.7614
7383.7549 ……	10.101	0.1116	0.1538	1.0557	2.8696	7701.8902 ……	10.523	0.2390	0.1181	0.8139	2.7374
7383.7570 ……	10.084	0.1237	0.1687	1.0288	2.8579	7701.8917 ……	10.539	0.2361	0.1275	0.8085	2.7759
7383.7592 ……	10.165	0.0996	0.1958	1.0124	2.8079	7701.8932 ……	10.540	0.2466	0.1193	0.7923	2.7415
7383.7649 ……	10.267	0.1562	0.1515	0.9819	2.7932	7701.9026 ……	10.600	0.2281	0.1429	0.7745	2.7340
7383.7670 ……	10.327	0.1665	0.1490	0.9331	2.8096	7701.9041 ……	10.600	0.2350	0.1309	0.7799	2.7325
7383.7866 ……	10.576	0.2316	0.1237	0.7899	2.7831	7701.9056 ……	10.587	0.2431	0.1179	0.7887	2.7367
7383.8011 ……	10.593	0.2387	0.1381	0.7481	2.7057	7701.9131 ……	10.554	0.2169	0.1463	0.7537	2.7558
7383.8031 ……	10.605	0.2203	0.1447	0.7601	2.7641	7701.9146 ……	10.514	0.2328	0.1246	0.7636	2.7492
7383.8052 ……	10.571	0.2601	0.1098	0.7594	2.7511	7701.9161 ……	10.492	0.2311	0.1194	0.7704	2.7761
7387.8313 ……	10.153	0.1219	0.1841	0.9645	2.8436	7701.9234 ……	10.216	0.1706	0.1369	0.9227	2.8354
7387.8345 ……	10.021	0.1286	0.1430	0.9995	2.8674	7701.9250 ……	10.144	0.1631	0.1302	0.9613	2.8520
7387.8367 ……	10.018	0.1207	0.1453	1.0560	2.8922	7701.9265 ……	10.097	0.1444	0.1425	0.9898	2.8570
7387.8386 ……	10.000	0.1348	0.1185	1.0670	2.8825	7701.9308 ……	10.047	0.1278	0.1580	1.0262	2.8706
7387.8407 ……	10.051	0.1355	0.1450	1.0489	2.8601	7701.9323 ……	10.053	0.1390	0.1453	1.0351	2.8742
7387.8428 ……	10.103	0.1284	0.1609	1.0260	2.8936	7701.9337 ……	10.080	0.1364	0.1400	1.0508	2.8699
7387.8461 ……	10.112	0.1572	0.1653	0.9678	2.7955	7701.9380 ……	10.157	0.1588	0.1519	0.9818	2.8198
7387.8516 ……	10.302	0.1901	0.1183	0.9213	2.8074	7701.9394 ……	10.195	0.1737	0.1235	1.0095	2.8170
7387.8549 ……	10.313	0.1866	0.1434	0.9145	2.8255	7701.9409 ……	10.233	0.1681	0.1371	0.9903	2.8155

nificant excess (+0.5 dex), but it is difficult to be confident of a measurement based on a single, high excitation line.

6. STRÖMGREN INDICES

All Strömgren observations are collected in Table 7. We phased the Strömgren data using equation (5). Average indices were then determined for 10 equal phase points. From the average indices, we determined an $E(by) = 0.039 \pm 0.008$. Using the excesses we determined intrinsic indices $(by)_0$, $(c_1)_0$, and $(m_1)_0$. These intrinsic values are reported in Table 8.

Using an average value of m_1 for the entire cycle, we determined the δm_1 value using the tables of Crawford (1979). We found $\delta m_1 = 0.039 \pm 0.005$. We then used the equations in McNamara & Powell (1985) to obtain a metal estimate. We found [Fe/H] $= -0.6 \pm 0.2$. In McNamara (1997) a value of [Fe/H] $= -0.65$ is reported for DY Peg. These two values estimate a little higher metal content than the value from Burki & Meylan (1986) or from the spectral estimate given above, but all values agree within the stated errors. It should be pointed out that the relations in McNamara & Powell (1985) are for stars cooler than DY Peg.

Adopting [Fe/H] $= -0.8$, we plotted the intrinsic c_1 and (by) values in a grid of model atmospheres from Kurucz (1994).

TABLE 8
Intrinsic Indices by Phase for DY Peg

Phase	y	$(by)_0$	$(m_1)_0$	$(c_1)_0$	β	$T_{\rm eff}$	log g
0.0 ……	10.053	0.085	0.170	1.009	2.859	8230	4.01
0.1 ……	10.136	0.102	0.167	1.000	2.840	8050	3.91
0.2 ……	10.294	0.125	0.168	0.932	2.817	7870	3.95
0.3 ……	10.420	0.160	0.153	0.869	2.768	7530	3.83
0.4 ……	10.488	0.178	0.152	0.812	2.750	7430	3.80
0.5 ……	10.553	0.189	0.146	0.781	2.733	7340	3.74
0.6 ……	10.583	0.194	0.154	0.756	2.735	7330	3.77
0.7 ……	10.594	0.191	0.152	0.751	2.739	7360	3.85
0.8 ……	10.510	0.173	0.157	0.769	2.760	7500	4.05
0.9 ……	10.233	0.120	0.165	0.897	2.826	7980	4.13

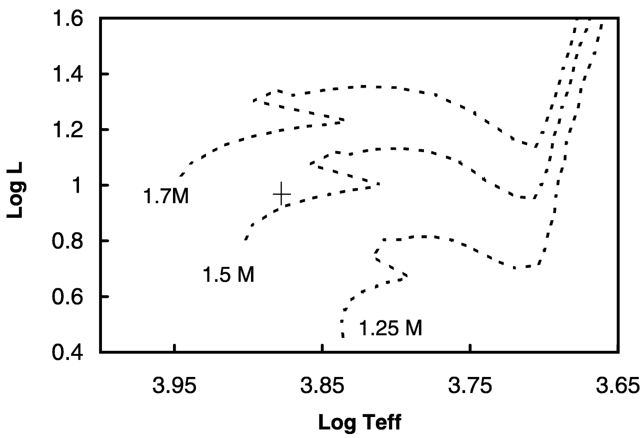

FIG. 7.—Evolutionary models for three 1.25 $M_{\odot}$, 1.5 $M_{\odot}$, and 1.7 $M_{\odot}$ stellar models. The position of DY Peg is marked by a cross.

From these models we determined surface temperature ($T_{\rm eff}$) and surface gravity at the 10 phase points. The values are reported in Table 8. Averaging over the 10 phase points, we found $\langle T_{\rm eff}\rangle = 7660 \pm 100$ and $\langle \log g\rangle = 3.89 \pm 0.04$.

We used the period-luminosity relation from Petersen & Høg (1998) to determine the absolute magnitude of DY Peg to be $M_V = 2.34$. We used this magnitude, the $T_{\rm eff}$, and a grid of evolutionary models from Schaerer et al. (1993) for $Z = 0.008$ to estimate the age and mass of DY Peg. The tracks for models of mass $M = 1.7\ M_{\odot}$, 1.5 $M_{\odot}$, and 1.25 $M_{\odot}$ are plotted in Figure 7 along with a cross marking the position of DY Peg. The cross falls just a little above the evolutionary track for $M = 1.5\ M_{\odot}$. We estimate a mass of 1.54 $M_{\odot}$ for DY Peg. From the position of the cross along the $M = 1.5\ M_{\odot}$ path, we estimate the age of DY Peg to be about 1.7 Gyr, which seems young for a Population II star. From this point on the evolutionary track, we determined a period change of $+1.43 \times 10^{-10}$ yr^{-1}, based on the slope of the evolutionary track and the period-luminosity relation of Petersen & Høg (1998). This predicted change is in the opposite sense of, and is of substantially different value than, the value determined in the parabolic fit given above.

7. CONCLUSION

We find that the period changes in DY Peg are best modeled as two period breaks. Our parabolic fit is similar to that found by many previous authors. However, in the parabolic fit, we found a pattern in the residuals. This pattern might be interpreted by some as a sine curve caused by a binary component, but we interpret this pattern as evidence that the data should be fitted with three linear segments around two period breaks. It is clear that DY Peg should continue to be monitored in order to examine both possibilities raised by this paper.

With regard to the physical characteristics of DY Peg, we find that the metal content is likely a little lower than in some earlier works and in the region of [Fe/H] $= -0.8$. We also find average values of $\langle T_{\rm eff}\rangle = 7660$ and $\langle \log g\rangle = 3.89$. Finally we estimate the mass of DY Peg at 1.5 $M_{\odot}$ with an age of 1.7 Gyr.

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