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ABSOLUTE DIMENSIONS AND MASSES OF ECLIPSING BINARIES.
IV. EE PEGASI IS A TRIPLE STAR

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ABSTRACT

A previously unknown faint companion with an orbital period of about 4 years has been discovered orbiting the 2.6 day eclipsing binary in the EE Pegasi system. The third star was discovered by its effects on the radial velocities and times of primary eclipse of the eclipsing pair. Spectroscopic observations of very high quality were obtained with the Reticon spectrometer of the 2.7 m reflecting telescope at McDonald Observatory. Radial velocities of high precision have been obtained for both stars of the eclipsing pair in this well-known, large light ratio, eclipsing binary system. Spectroscopic orbits derived from a three-body fit to the radial velocities have been combined with photometric orbits from photoelectric light curves to find very accurate masses and radii for components of the eclipsing binary: ($2.15 \pm 0.02\ M_\odot$, $2.09 \pm 0.03\ R_\odot$) for the A3m primary and ($1.33 \pm 0.01\ M_\odot$, $1.31 \pm 0.01\ R_\odot$) for the F5 secondary. The uncertainties are conservative standard errors. Theoretical evolutionary tracks indicate an age of about 3×10^8 years based on the observed masses, radii, and luminosities. The F5 secondary of the eclipsing pair is still very close to the zero-age main sequence. The A3m primary is about halfway through its main sequence lifetime. Both are rotating synchronously with the orbital period. The third star is probably a low-mass main-sequence star of spectral type K or M.

Subject headings: stars: eclipsing binaries — stars: evolution — stars: individual — stars: rotation

I. INTRODUCTION

EE Pegasi (HD 206155, SAO 126971, +08°4714) was discovered to be an eclipsing binary by Hoffmeister (1935). In the half-century since its discovery, EE Peg has been studied by many photometric and spectroscopic investigators, and our knowledge of its properties has gradually improved. From visual observations, Gomi (1940) found that the original estimate of the orbital period was twice the true value. Wellmann (1953) obtained both visual brightness estimates and photographic radial velocities of the primary and derived the first orbits. Bakos (1965) improved the orbits by obtaining additional radial velocities and the first photoelectric photometry of this system. Catalano and Rodonó (1970) published improved photoelectric light curves and a better photometric orbit and ephemeris. An excellent blue light curve obtained by Ebbighausen (1971) has been reanalyzed by Linnell (1973), who also gave an improved ephemeris, and by Mezzetti *et al.* (1980). Popper (1981) was able to measure radial velocities from the D lines of both components on 11 Å mm^{-1} spectrograms photographed on high signal-to-noise ratio plates at the Lick Observatory between 1973 and 1980. On the basis of these velocities and his discussion of Linnell's analysis of the light curve, the properties of the components were derived. These properties were included in the review of stellar masses (Popper 1980), although it was realized that small systematic effects might be present in the velocities of the secondary component because of possible blending in the D lines.

The coudé Reticon spectrometer of the 2.7 m telescope at McDonald Observatory was brought to bear on EE Peg in 1979 in the hope that weak lines of the secondary could be measured in the 6400 Å region, as had been possible for the similar large light ratio system YZ Cas (Lacy 1981). Lines of the secondary were easily found in spectra with a signal-to-noise ratio of about 300. Preliminary results were announced by Lacy and Evans (1979), Fekel, Lacy, and Tomkin (1980), and Lacy (1983). This series of Reticon observations has now been completed, and the data are discussed and analyzed in § II. Because we have found from that analysis that the EE Peg system is in fact a triple star, it is necessary to consider the effect of the light of the third component on the photometric orbits mentioned above. This is done in § III. The results of the new photometric and spectroscopic analyses are combined and interpreted by application of theoretical models in § IV.

II. SPECTROSCOPIC OBSERVATIONS AND ANALYSIS

Spectroscopic observations of EE Peg were obtained by Lacy with the Reticon spectrometer of the 2.7 m telescope at McDonald Observatory from 1979 to 1983. Vogt, Tull, and Kelton (1978) have described this device. The observations were centered at 6420 Å and have a width of about 100 Å. The spectrometer slit projected onto 4 diodes, or 0.44 Å, on the detector array at a dispersion of 4.4 Å mm^{-1}. Observations of a hollow cathode iron-neon source and the standard radial velocity stars o Peg and ι Psc were also made just before or after EE Peg was observed in order to fix the radial velocity zero point and to provide templates in the cross-correlation analyses employed to obtain radial velocities. The radial velocity reductions followed the precepts of Lacy (1981, 1982). The resultant radial velocities are listed in Table 1. Small portions of two representative observations are shown in Figure 1.

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TABLE 1

RETICON RADIAL VELOCITIES FOR EE PEGASI

HJD (2,440,000+)	ORBITAL PHASE[a]	PRIMARY		SECONDARY	
		RV(km s^{-1})	$O-C$[b]	RV(km s^{-1})	$O-C$[b]
4041.928......	0.914	22.2	0.6	−97.9	−0.3
4042.889......	0.280	−109.8	2.3	116.5[c]	−1.7
4174.676......	0.423	−66.7	0.1	44.8	2.4
4175.799......	0.850	46.3	−0.6	−148.6	−7.4
4178.658......	0.938	8.0	−0.5	−74.6	4.6
4179.689......	0.331	−102.2	1.3	103.3[c]	1.7
4180.710......	0.719	62.4	−0.1	−166.6	−0.2
4181.670......	0.084	−72.6	−2.1	50.9	2.6
4364.937......	0.815	56.0	0.5	−160.1	−1.5
4366.962......	0.585	19.2	0.2	−99.8	0.1
4449.928......	0.153	−100.1	0.2	93.1	1.1
4451.894......	0.901	25.4	0.1	−111.1	−0.6
4452.887......	0.279	−114.8	0.1	112.1[c]	−3.6
4568.603......	0.307	−106.9	0.1	112.7	0.0
4571.565......	0.434	−58.7	0.3	28.6[c]	−7.2
4736.936......	0.356	−88.6	0.0	95.7	−0.6
4737.946......	0.740	71.1	0.0	−164.0	−2.3
4832.819......	0.838	53.7	−3.5	−141.4	−0.1
4833.926......	0.259	−109.2	−0.9	130.8[c]	5.0
4894.629......	0.356	−89.8	0.2	92.1	−2.8
4895.649......	0.744	70.8	1.0	−160.7[c]	2.5
4974.571......	0.772	71.7	3.4	−161.9[c]	0.7
4979.560......	0.671	55.6[c]	−2.6	−149.1	−2.6
5100.978......	0.869	44.9	0.5	−122.4[c]	4.4
5185.973......	0.208	−106.1	2.2	...	...
5186.962......	0.584	21.5	−1.7	−101.1	−6.8
5271.642......	0.804	61.7	−0.1	−153.8	4.4
5272.561......	0.154	−95.6	0.5	96.8	0.1
5273.717......	0.593	25.1	−1.8	−100.5	1.5

[a] The orbital phase is relative to the short-period ephemeris.

[b] Both the long-period and short-period orbits have been subtracted from the observations to yield the residuals.

[c] Half-weight.

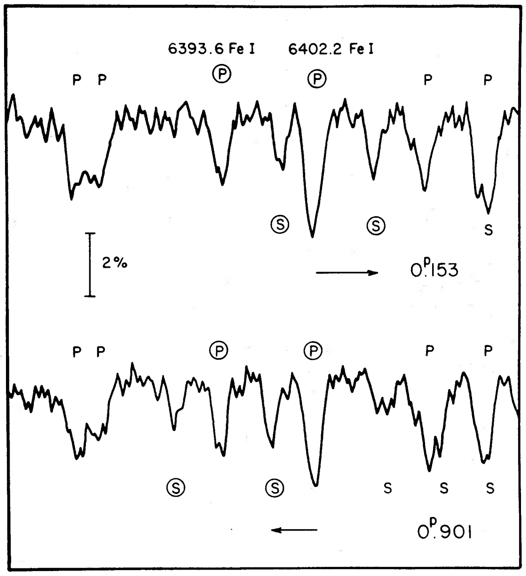

FIG. 1.—Portions of Reticon scans of EE Peg at opposite quadratures. Features due to the primary (P) component are labeled and identified above each scan, and those of the secondary (S) are shown below each scan. The circled features are some of those actually used in the cross-correlation analysis for radial velocities. The secondary's features are shifted relative to the primary's as indicated by the arrows below each scan. The bar shows the flux corresponding to 2% of the continuum.

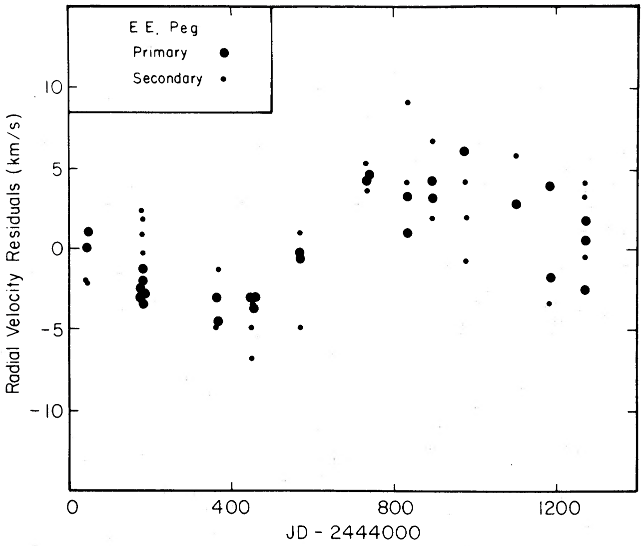

FIG. 2.—Radial velocity residuals from a preliminary two-body fit to the Reticon velocities. This figure shows the modulation of the center-of-mass velocity of the eclipsing binary by a third body in the system.

Preliminary orbits were fitted to radial velocity curves obtained from the new spectroscopic data. The residuals from the orbits had a much larger scatter than velocities of the similar system YZ Cas (Lacy 1981). When the residuals were plotted as a function of time (Fig. 2), it became clear that the center-of-mass velocity of the eclipsing pair was being modulated by a long-period (4 year) orbit about the center of mass of a triple star system. Note that the same modulation is present in residuals of both the primary and secondary. This modulation is also apparent in Popper's (1981) primary velocities, listed in Table 2. The scatter of Popper's (1981) secondary velocities is too great to show the modulation clearly. All of Popper's (1981) original velocities have been reduced by 1.4 km s^{-1} in order to make his center-of-mass velocities agree with the Reticon observations (see below).

The elements of the 2.8 day and 4 year orbits have been found simultaneously by computing differential corrections to preliminary elements for both orbits. A modified version of the general least-squares computer program described by Daniels (1966) was employed. Separate solutions were made from the primary and secondary data of each of the series of radial velocities in Table 1 (Reticon) and 2 (image tube). The ephemeris used for the 2.8 day orbit was fixed to the value derived from the eclipse timings discussed in § III. Both the Reticon and the image-tube data resulted in solutions that were identical to within their estimated errors. The orbital eccentricity for the short-period orbit was found to be not significantly different from zero and was thereafter fixed at zero. Popper's (1981) primary velocities had a residual variance about twice that of the Reticon velocities and were therefore given half weight. His original velocities were shifted by −1.4 km s^{-1} to bring them into agreement with the Reticon's system. Because Popper's secondary velocities have a much larger residual variance than the new velocities, and because of possible systematic effects caused by slight bending between the lines of the components, these velocities were not used in the final orbits. The larger value of K_c found here is presumably a consequence, at least in part, of this blending.

Elements common to both the primary and secondary

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TABLE 2

IMAGE-TUBE RADIAL VELOCITIES OF EE PEGASI

HJD (2,440,000+)	ORBITAL PHASE[a]	PRIMARY[b] RV(km s^{-1})	PRIMARY[b] $O-C$[d]	SECONDARY[c] RV(km s^{-1})	SECONDARY[c] $O-C$[d]
1904.933......	0.817	63.6	0.8	−144.9	5.3
1904.943......	0.820	62.0	0.1	−149.0	−0.2
1905.802......	0.147	−91.4	−1.0	89.6	−7.5
1905.806......	0.149	−92.2	−1.3	90.1	−7.8
1941.801......	0.844	51.2	−3.6	−142.7	−4.3
1941.820......	0.852	53.9	1.4	−144.7	−10.1
1966.606......	0.282	−110.2	−3.0	110.4	−12.2
1966.617......	0.287	−108.7	−2.1	110.1	−11.6
1967.618......	0.667	55.8	−2.3	−152.6	−8.3
1967.627......	0.671	58.4	−0.7	−155.5	−9.7
2024.570......	0.337	−96.6	−0.1	97.8	−6.2
2024.588......	0.344	−94.1	0.4	83.5	−17.2
2231.005......	0.883	38.1	−0.3	−114.8	3.4
2231.912......	0.228	−109.4	0.9	109.3	−12.6
2231.922......	0.232	−109.5	1.1	114.1	−8.2
2557.883......	0.255	−112.0	1.5	117.7	−3.2
2702.740......	0.371	−89.5	0.3	89.4	9.5
2702.749......	0.375	−85.9	2.6	87.6	9.9
2740.624......	0.786	60.4	−1.3	−161.3	4.2
2944.006......	0.170	−108.0	−2.7	102.4	2.1
2972.013......	0.826	53.3	0.9	−162.7	−8.3
3000.922......	0.826	52.8	0.1	−152.7	1.9
3000.930......	0.829	52.5	0.6	−157.3	−4.0
3001.890......	0.194	−112.7	−1.9	104.2	−5.2
3001.897......	0.197	−111.0	0.3	102.8	−7.4
3121.588......	0.737	65.8	−1.3	−159.8	5.5
3121.595......	0.740	66.8	−0.4	−162.1	3.4
3122.637......	0.137	−88.9	0.7	81.6	−6.4
3122.658......	0.145	−92.0	0.5	89.9	−2.7
3293.985......	0.332	−97.0	−0.9	110.5	2.5
3293.995......	0.336	−97.9	−2.9	111.9	5.7
3329.002......	0.656	56.4	0.8	−122.0	15.7
3329.012......	0.659	59.4	2.6	−125.2	14.4
3357.931......	0.663	63.6	6.1	−125.2	16.2
3357.941......	0.667	61.7	3.1	−130.4	12.8
3411.730......	0.133	−82.6	3.0	88.6	0.4
3411.738......	0.136	−83.2	3.5	80.2	−9.8
3439.698......	0.774	69.8	1.0	−155.2	6.5
3439.706......	0.777	69.9	1.4	−154.1	7.2
3716.874......	0.236	−111.6	−0.6	120.0	−2.6
3716.882......	0.239	−113.0	−1.8	119.3	−3.5
3741.781......	0.713	62.9	−2.0	−156.2	5.6
3741.793......	0.717	66.6	1.2	−148.4	14.4
3742.805......	0.102	−78.9	−3.2	75.6	10.6
3742.822......	0.109	−83.4	−4.9	70.7	1.1
4007.021......	0.633	39.4	−2.8	−121.2	9.1
4038.987......	0.795	61.3	−0.3	−164.9	−2.8
4039.002......	0.801	61.7	1.0	−157.8	2.8
4039.994......	0.179	−101.8	3.0	108.5	2.0
4040.009......	0.184	−105.4	0.8	108.5	−0.2

[a] The orbital phase is relative to the short-period ephemeris.

[b] All primary image-tube velocities were given half-weight in computing the orbits.

[c] Secondary image-tube velocities were not used in computing orbits because of their large standard error compared with the Reticon velocities.

[d] Both the long-period and short-period orbits have been subtracted from the observations to yield the residuals.

orbital solutions were then merged, weighted according to their estimated uncertainties, and fixed (secondary) or used as preliminary elements (primary) for the final series of differential corrections on the combined data set. The resulting elements and uncertainties are listed in Table 3 (short-period orbit) and Table 4 (long-period orbit). All uncertainties cited in this paper are standard deviations.

The fit of the model to the data is displayed in Figures 3 and 4. In these figures, the residual error has been split evenly between the short-period and long-period decompositions of the observed velocities.

The minimum mass of the third body (corresponding to an edge-on orbit) is set at 0.3 $M_\odot$ by the mass function and the mass of the eclipsing pair (derived below). The maximum mass of the third body cannot be estimated without making some assumption about its nature. High signal-to-noise ratio Reticon spectra of EE Peg have been carefully searched for any sign of absorption lines due to the third component.

We are confident we could have detected features due to the third component if they had been stronger than one-fourth of the depth of features of the secondary. Since absorption features that are strong in the secondary spectrum gradually become stronger in later spectral types, it is conservative to say that the third component must be fainter than one-fourth of the luminosity of the secondary. The mass-luminosity relation for main-sequence stars then places the upper limit of 0.7 $M_\odot$ for the mass of the third component, if it is a main-sequence star, as are the members of the eclipsing system. Such a star would contribute less than 2% of the total light and have an orbit with an inclination of greater than 28°.

Rotational velocities of both components of the eclipsing binary have been estimated from 62 unblended Reticon line profiles. Profiles of the nonrotating standard stars o Peg and ι Psc were synthetically broadened by convolving them with the rotational broadening function of Gray (1976) for a variety of different values of $V \sin i$. These synthetically broadened profiles were then matched to the observed profiles of the binary components to yield rotational velocities of 40 ± 1 km s^{-1} for the primary and 26 ± 2 km s^{-1} for the secondary. These do not differ significantly from the synchronous velocities of 40 ± 1 km s^{-1} and 25 ± 1 km s^{-1} respectively. Previous estimates of the rotational velocity of the primary have been made by Abt and Hudson (1971), Koch, Olson, and Yoss (1965), and Levato (1974) as 30, 45 ± 6, and 40 km s^{-1} respectively.

The procedure used here for determining rotational velocities produces results that differ systematically from the approximate methods employed previously on YZ Cas (Lacy 1981) in the sense that the primary's rotational velocity was previously overestimated by about 20%. It now appears that both components of YZ Cas are rotating synchronously.

III. PHOTOMETRIC REANALYSIS

The eclipse ephemeris is considered first. Published observations of the dates of primary eclipse and a new ephemeris are listed in Table 5. Only a single epoch of primary minimum is given by Ebbighausen (1971), the zero epoch of his ephemeris, although it was based on at least two dates of eclipse in 1968–1969. The information needed to determine the two dates actually observed has kindly been supplied to us by Ebbighausen (1982). The table also lists some of the recent visual observations in the *Bedeckungsveränderlichen Beobachter der Scweizerischen Astronomischen Gesellschaft* (*BBSAG*) *Bulletin.*

Catalano and Rodonó (1970) pointed out three very discrepant visual observations. These and two more recent examples are listed in Table 6. In all five cases the reported dates agree quite closely with the early visual ephemeris of Wellmann (1953) and disagree completely with the new ephemeris in Table 4 and those of Ebbighausen (1971) and Catalano and Rodonó (1970). Wellmann's (1953) ephemeris was based on the assumption that there were 1791 cycles between his mean observation and that by Gomi (1940). The more recent and

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TABLE 3

Spectroscopic Orbit of the Eclipsing Binary in EE Pegasi

Quantity	Wellman 1953	Bakos 1965	Popper 1981	This Paper
Semiamplitude:				
K_h (km s^{-1})	86.3 ± 2.9	86.2 ± 0.4	90.1 ± 0.5	89.4 ± 0.3
K_c (km s^{-1})	...	...	140.2 ± 1.3	144.4 ± 0.7
Mass ratio	...	...	1.56 ± 0.02	1.61 ± 0.01
Center-of-mass velocity:				
γ_h (km s^{-1})	−24.5 ± 3.6	−13.4 ± 0.4	−20.5 ± 0.5	−22.7 ± 0.2[a]
γ_c (km s^{-1})	...	...	−17.7 ± 1.1	−22.1 ± 0.6[a]
Eccentricity e	0.067 ± 0.028	0.003 ± 0.004	0	0.000 ± 0.004
Standard errors:				
ϵ_h (km s^{-1})[b]	8.3	8.0	3.6	1.4
ϵ_c (km s^{-1})[b]	...	...	8.2	2.9

[a] In Figures 3 and 4, the center-of-mass velocity is attributed solely to the long-period orbit.

[b] The standard errors correspond to single observations of unit weight.

TABLE 4

Spectroscopic Orbit of the Eclipsing Binary's Center of Mass in EE Pegasi

Quantity	Value and Standard Error
Orbital period P (days)	1464 ± 20
Semiamplitude K (km s^{-1})	4.4 ± 0.6
Eccentricity e	0.52 ± 0.11
Longitude of periastron ω (degrees)	−85 ± 11
Epoch of periastron (JD)	2443120 ± 24
Center-of-mass velocity γ (km s^{-1})	−22.6 ± 0.2
Mass function $f(m)$ ($M_\odot$)	0.0083 ± 0.0023
Mass of 3d body ($M_\odot$)	$0.3 \leq M_3 \leq 0.7$[a]
Light of 3d body $L_3/(L_1 + L_2)$	<0.02[a]
Inclination of orbital plane of long-period orbit (degrees)	>28[a]

[a] This value assumes that the third body is a normal main-sequence star.

accurate photometric ephemerides show that there were actually 1790 cycles in this interval, so the period derived by Wellmann (1953) was systematically too short. The two most recent discrepant visual observations in Table 6 can be easily explained as 1 day errors in recording the universal time, but the three earlier discrepant observations have no obvious explanation. Recent visual observations given in the *BBSAG Bulletin* agree well with the photoelectric ephemerides and show a scatter which is about the typical order-of-magnitude greater than photoelectric observations. Figure 5 displays the residuals from the new ephemeris. Much greater weight was given to the photoelectric observations than to the visual observations in computing the new ephemeris. The somewhat greater than expected scatter in the photoelectric eclipse timings is real and is due to the light-travel time across the orbit of the eclipsing pair around the center of mass of the triple star system.

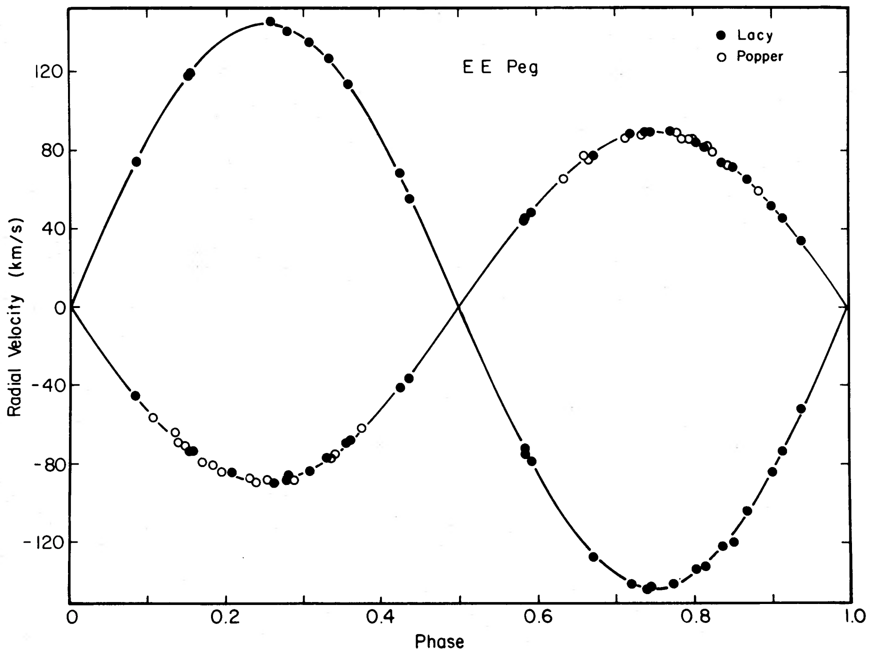

Fig. 3.—Radial velocities of the eclipsing binary components of EE Peg. The long-period modulation due to the third body has been removed, along with the three-body center-of-mass velocity (see Fig. 4).

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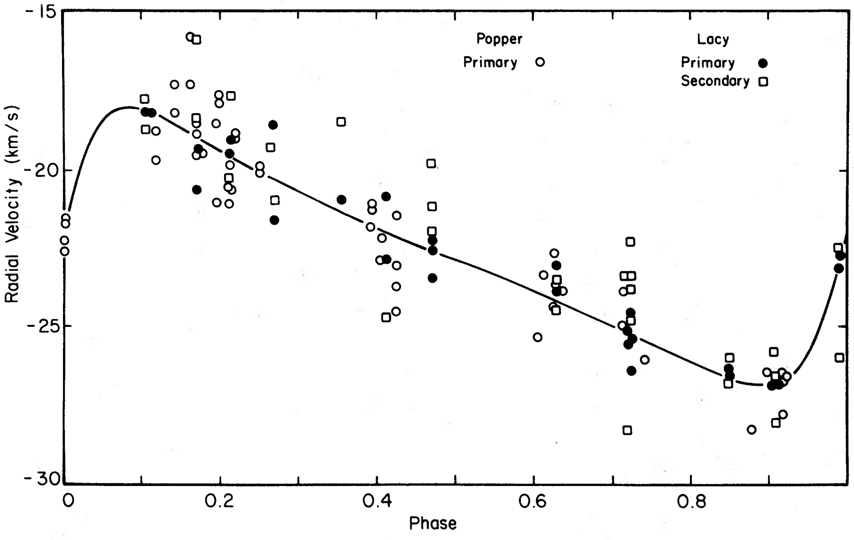

FIG. 4.—Radial velocities of the long-period modulation due to a third body in EE Peg. The three-body center-of-mass velocity is included in this figure.

TABLE 5

OBSERVATIONS OF PRIMARY MINIMA FOR EE PEGASI

Reference	Method[a]	HJD (2,400,000+)	E	$O-C$[b] (days)
Gomi 1940	v	29176.986	−4227	+0.0127
Wellmann 1953 mean	v	33928.7905	−2419	+0.0058
Bakos 1965	pe	34606.863	−2161	−0.0009
Bakos 1965	pe	34622.633	−2155	−0.0002
Bakos 1965	pe	34635.770	−2150	−0.0043
Bakos 1965	pe	34643.656	−2147	−0.0029
Catalano and Rodonó 1970	pe	38299.508	−756	+0.0031
Catalano and Rodonó 1970	pe	39324.509	−366	+0.0009
Ebbighausen 1982	pe	40068.290	−83	−0.0031
Catalano and Rodonó 1970	pe	40462.526	67	+0.0007
Ebbighausen 1982	pe	40504.576	83	−0.0007
Scarfe *et al.* 1973	pe	41174.7726	338	+0.0013
Mauron 1974	v	42286.524	761	+0.0181
Ralincourt 1977	v	43093.368	1068	+0.0003
Hevesi 1977	v	43382.467	1178	−0.0043
Hevesi 1977	v	43390.374	1181	+0.0181
Poretti 1978	v	43779.338	1329	+0.0064
Nezry 1978	v	43771.458	1326	+0.0110
Buzzoni 1979	v	43829.255	1348	−0.0127

[a] Methods are v = visual observations and pe = photoelectric.

[b] $C = 2.62821423E + 2440286.4349$.

TABLE 6

DISCREPANT VISUAL OBSERVATIONS OF MINIMA

REFERENCE	REPORTED DATES OF MINIMUM (2,400,000+)	$O-C$ (days) This Paper	$O-C$ (days) Wellman 1953
Marks 1962	37204.358	+0.818	+0.010
Dueball and Lehmann 1965	37569.440	+0.579	−0.026
Virkhristjuk 1964	38281.309	+0.202	−0.006
Braune and Mundry 1973	40469.402	−1.008	+0.004
Flin 1972	41559.494	+1.003	−0.005

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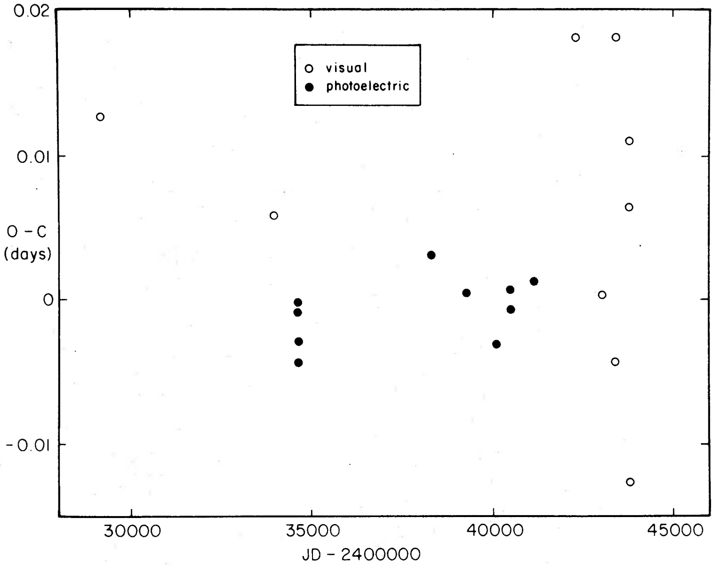

FIG. 5.—Residuals from times of primary eclipse according to the ephemeris of Table 5

The spectroscopic orbit of the eclipsing pair around the center of mass which was discussed in § II above can be used to predict the effect of the light-travel time on the dates of minimum light. This has been done, and the results are shown in Figure 6. The phases are relative to the 4 year orbit. The trend of the observed times of eclipse shows some resemblance to the variation predicted from the spectroscopic data. The eclipse timing errors are not small enough for us to consider it useful to use these data to constrain the long-period orbit, however.

A summary of the published photometric orbital elements of EE Peg is given in Table 7. Because we concluded from the spectroscopic study above that the third component could possibly contribute up to about 2% of the system's luminosity, we have reanalyzed Ebbighausen's (1971) data using the Nelson-Davis-Etzel program (EBOP) and the methods of Popper and Etzel (1981) assuming no third light ($L_3 = 0$) and 2.5% third light ($L_3 = 0.025$). The principal effect of including third light is to increase the inclination by about 0°.5. The increase in i, as well as the small effects on the values of r, are in the expected directions. The reanalyses are in good agreement with the original analysis by Ebbighausen (1971) and subsequent computer analyses. The adopted solution, which is basically a weighted average, is listed in Table 7 along with our estimates of the uncertainties. These estimates are based on the least-squares results of the EBOP program and the consistency shown between independent analysis of the same data sets.

Ebbighausen's (1971) observations are of sufficient quality

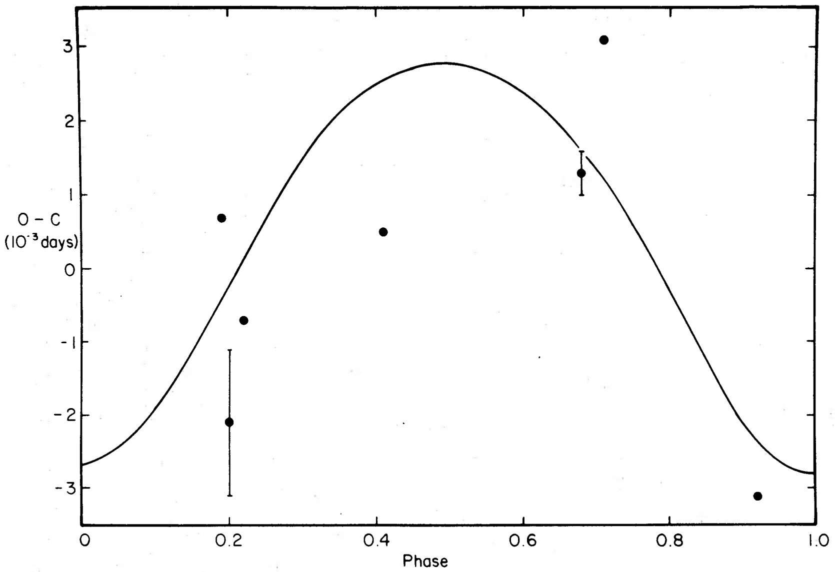

FIG. 6.—Photoelectric residuals from times of primary eclipse according to the ephemeris of Table 5. The phases are relative to the long-period modulation produced by the third body. The curve is the predicted propagation delay across the orbit of the eclipsing binary around the three-body center of mass. The predicted curve is based solely on the radial velocity information and is not a fit to the eclipse timing residuals. Two typical uncertainties are shown as bars. These uncertainties were either quoted by the original source or computed from the internal scatter about the mean.

TABLE 7

Photometric Orbital Elements of EE Pegasi

Reference	r_h	r_c	i (degrees)	L_g	L_s	x_g	P (days)	Wavelength (Å)
Bakos 1965	0.166	0.141	88.57	0.784	0.216	0.6	2.6282253	4800
Catalano and Rodonó 1970	0.182	0.107	89.1	0.924	0.076	0.6	2.628208	4340
Ebbighausen 1971	0.1695	0.1074	88.61	0.921	0.079	0.55	2.6282284	4400
Linnell 1973	0.1712	0.1076	88.69	0.9200	0.0807	0.61	2.62821249	4400
Mezzetti *et al.* 1980	0.173	0.108	88.5	0.895	0.105	0.70	2.62823	4400
This paper ($L_3 = 0$)	0.1735	0.1080	88.85	0.9206	0.0794	0.69	2.62821423	4400
This paper ($L_3 = 0.025$)	0.1728	0.1090	89.41	0.9184	0.0816	0.69	2.62821423	4400
Adopted solution	0.172	0.108	88.6	0.920	0.079		2.62821423	4400
Standard errors	0.002	0.001	0.2	0.003	0.002		0.0000005	

and weight to carry out a solution in which the limb-darkening coefficients are adjusted along with the other parameters. The results are $x_g = 0.62 \pm 0.03$ and $x_s = 0.75 \pm 0.15$. The values of the other parameters in this solution do not differ significantly from those shown in Table 7. The difference between the observed and theoretical values of x_g is in the same sense and of about the same size as found by Popper and Etzel (1981) for other well-observed A and F type detached binaries.

IV. DISCUSSION

The photometric orbit given in Table 7 and the spectroscopic orbit in Table 3 have been combined to yield the absolute dimensions and masses shown in Table 8. These are known to very high accuracy—not many eclipsing binary masses and radii are known to ±1%. In order to make a detailed comparison with the theory of stellar evolution, it is necessary to estimate absolute magnitudes of the eclipsing binary components. This has been done using the color indices of Popper and Dumont (1977) and the surface brightness methods of Popper (1980) on the adopted photometric orbit. The light of the system was split up under the assumption that both components of the eclipsing binary obeyed Popper's (1980, Table 1) surface brightness relation. The color indices do not appear to be significantly reddened, so no correction has been made for interstellar extinction. The resulting radiative properties are listed in Table 8. The most important differences between these properties and those derived earlier (Popper 1981) are consequences of the larger orbital velocity of the secondary component.

The values of $B-V$ for the components have been chosen in such a way that they are consistent with the blue light ratio of the adopted photometric solution (Table 7), the observed value of $B-V$ outside eclipse (+0.11), and the visual surface brightness scale of Popper (1980). These new values are a slight improvement over the estimates of Popper (1981) which implied a color outside eclipse that was slightly redder (+0.13) than the observed value. Spectral types of A3m for the primary and F5 for the secondary are assigned based on their color indices, the color index–spectral type relation of Popper (1980, Table 1), and the metallic-lined nature of the primary's spectrum (Popper 1981).

It should be noted that the radiative properties have been derived by indirect means because EE Peg lacks a good light curve in V, which is needed to pin down the difference in color index between the components and verify the value inferred from the surface brightness ratio. The agreement is not always as good as desired. One of the major potential problems with large light ratio binaries now becoming available to high signal-to-noise ratio detectors is the difficulty in obtaining definitive radiative properties of the fainter component, i.e., color index, surface flux density, effective temperature, etc. Good light curves in two or more well-calibrated colors are still badly needed.

The theoretical evolutionary models of Hejlesen (1980) can match well the observed absolute properties of the eclipsing binary components of EE Peg over only a limited range of ages and compositions. The best agreement is achieved at a composition of $(X, Z) = (0.70 \pm 0.03, 0.035 \pm 0.005)$ and an age of

TABLE 8

Physical Properties and Standard Errors of EE Pegasi

Property	Primary	Secondary
Mass ($M_\odot$)	2.15 ± 0.02	1.33 ± 0.01
Radius ($R_\odot$)	2.09 ± 0.03	1.31 ± 0.01
Surface gravity log g (cgs units)	4.13 ± 0.01	4.33 ± 0.01
Rotational velocity (km s^{-1})	40 ± 1	26 ± 2
Synchronous velocity (km s^{-1})	40 ± 1	25 ± 1
Apparent visual magnitude (V)	7.09 ± 0.01	9.40 ± 0.10
Color index ($B-V$)	0.08 ± 0.01	0.44 ± 0.05
Absolute visual magnitude (M_V)	1.35 ± 0.10	3.6 ± 0.2
Absolute bolometric magnitude ($M_{\rm bol}$)	1.3 ± 0.1	3.6 ± 0.2
Effective temperature log T_e	3.94 ± 0.01	3.81 ± 0.02
Spectral type	A3m	F5
Distance (pc)	142 ± 8	
Composition (from models):		
X	0.70 ± 0.03	
Y	0.26 ± 0.03	
Z	0.035 ± 0.005	
Age (years)	$(3.0 \pm 0.2) \times 10^8$	

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$(3.0 \pm 0.2) \times 10^8$ years. The uncertainties represent the range of values over which the models can match the observations. Both stars are still in the core hydrogen-burning main-sequence band. The secondary is still close to the zero-age main sequence, but the primary, which is 60% more massive, is about halfway through its main-sequence lifetime. The relation of the primary component of EE Peg to other metallic-lined components of eclipsing binaries has been discussed earlier (Popper 1981).

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