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SECONDARIES OF ECLIPSING BINARIES. IV. THE TRIPLE SYSTEM LAMBDA TAURI

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ABSTRACT

We have measured low-noise Reticon spectra to redetermine the velocity curve of the primary of this early-type semidetached system. The velocity curve of the secondary is determined for the first time. We find that $K_1 = 56.9 \pm 0.6$ km s^{-1}, $K_2 = 215.6 \pm 0.7$ km s^{-1}, $m_1 = 7.18 \pm 0.09\ m_\odot$, and $m_2 = 1.89 \pm 0.04\ m_\odot$.

The 33 day periodicity in the residuals, discovered in previous investigations, is confirmed and is present in the secondary velocities as well as those of the primary. The presence of the 33 day periodicity in the velocities of *both* components means that it can be unambiguously ascribed to orbital motion around a third body. The K and $f(m)$ for the 33 day orbit are 10.1 ± 0.7 km s^{-1} and $0.0034 \pm 0.0008\ m_\odot$. A suggestion by Mazeh and Shaham that the angle between the planes of the long- and short-period orbits might be as large as 30° must be rejected, because it can be shown from the photometry that the orbits are coplanar to within 7°. The mass of the third body is $0.7 \pm 0.2\ m_\odot$; it is most probably a K dwarf.

Subject headings: stars: eclipsing binaries — stars: individual

I. INTRODUCTION

Light variations of λ Tau [HR 1239 = HD 25204, $m_v = 3.4$, B3 V, $\alpha = 03^h55^m08^s$, $\delta = +12°12'$ (1900)] were detected in 1848, making it the third eclipsing binary to be recognized. Unfortunately, its brightness, which led to its initial discovery as a variable, makes photometric observations difficult. Only three extensive sets of observations, two by Stebbins (1920) and one more recently by Grant (1959), have been obtained photoelectrically. Photometric solutions with Grant's data have been computed by Hutchings and Hill (1971) and Cester *et al.* (1978). The eclipses are partial, and the system is semidetached.

Its relative brightness has led to numerous series of spectroscopic investigations at various observatories. Although observed as early as 1897 (Belopolsky 1898), the first extensive investigation of the spectroscopic orbit was by Schlesinger (1914). He determined a period of nearly 4 days for the primary. However, his velocity residuals from the computer curve were larger than expected and were attributed to motion of the eclipsing binary about a third body with a period of 34.6 days. McLaughlin (1937) revised this period to 30.0 days.

Ebbighausen and Struve (1956) reviewed these and other spectroscopic investigations. In addition to measuring or remeasuring many of these existing plates, they obtained a large number of new observations which they used to redetermine the elements of both the short and long period orbits. In all they used velocities spanning 55 years from six different observatories. From velocity residuals of the short-period orbit they determined a long period of 33.025 and a semiamplitude of 8.6 to 11.6 with the assumption of a circular orbit.

Ebbighausen and Struve (1956) noted that on some of the high dispersion plates obtained at Dominion Astrophysical Observatory (DAO) between 1935 and 1939, the secondary Mg II 4481 Å line can be seen. From measurements of this feature they obtained a rough mass ratio of the brighter star to the fainter star of 4.0 and suggested that its spectral type was late B or early A.

In addition to his photometry of λ Tau, Grant (1959) obtained high-dispersion spectroscopic observations to determine the spectral type, relative luminosity, and mass of the secondary and to search for lines of the third component. He detected no lines from the third star but did detect the secondary features of the Hα line and Ca II K line. From these as well as the Mg II line at 4481 Å, he determined a mass ratio of 3.75 which is in good agreement with that of Ebbighausen and Struve (1956).

The primary of λ Tau is usually classified as a B3 V star (Slettebak and Howard 1955; Olson 1968; Levato 1975). The secondary is apparently an overluminous mid-A subgiant (Grant 1959; Olson 1968). No lines from the third star have been detected (Grant 1959). The minimum mass of this star determined by Ebbighausen and Struve (1956) is 0.7 $m_\odot$, suggesting that it is a G or K dwarf.

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The presence of a third star may produce detectable perturbations in the motion of the short period pair. For λ Tau with a period ratio of about 8:1 the precession period of the line of nodes is expected to be 7–8 years (Söderhjelm 1975; Mazeh and Shaham 1976). Attempts to detect such an effect by examining the existing photometric data (Söderhjelm 1975) and the existing spectroscopic data (Mazeh and Shaham 1976) have produced conflicting results. This suggests the need for a new set of high-quality observations.

Because the scatter of velocities about the long-period computed curve is large (Ebbighausen and Struve 1956), there has always existed some doubt about the reality of the third component. This doubt was increased when Casini, Galeotti, and Guerrero (1968), from a recent series of spectroscopic observations, found no evidence of a third component in their velocity residuals. As a result of this, Batten (Batten, Fletcher, and Mann 1978) suggested that the case for the reality of the third body should be reopened.

We have obtained high signal-to-noise ratio Reticon observations of λ Tau at McDonald Observatory which confirm the period that Ebbighausen and Struve (1956) determined for the third component. In addition we have obtained high-quality orbital elements for both the primary and secondary of the eclipsing system.

II. OBSERVATIONS

The observations were made with the McDonald Observatory 2.7 m telescope coudé spectrograph and a 1024 element Reticon self-scanned silicon photodiode array (Vogt, Tull, and Kelton 1978). Their central wavelength was 4510 Å, and they covered 105 Å. The width of the spectrograph entrance slit was set so that the projected slit width was four diodes, which gave a resolution of 0.45 Å (velocity resolution of 30 km s^{-1}). The majority of the spectra had signal-to-noise ratios of between 400 and 500 to 1.

The central wavelength was chosen so as to include the primary 4471 Å He I and 4481 Mg II lines—in fact, these are the only lines of the primary that are present in these spectra—and the secondary 4481 Å Mg II and 4549 Å Ti II lines, as well as additional weaker secondary Ti II and Fe II lines between 4500 and 4535 Å. The He I, Mg II, and some of the Ti II and Fe II lines can be seen in Figure 1, which shows a section of two Reticon spectra observed at opposite quadratures.

An Fe-Ne discharge was observed immediately after each observation of λ Tau. The radial velocity standard stars Vega (A0 V) and π Cet (B7 V) were also observed at 4510 Å. These two standard stars were observed only once.

The observations are detailed in Tables 1 and 2. The photometric ephemeris: JD$_\odot$ (primary minimum) = 2,435,089.204 + 3.9529552E has been used to calculate the phases in the short-period orbit given in these tables and elsewhere in this paper. The epoch of this ephemeris is that of Grant (1959), and the period is a refinement of Stebbin's period of 3.952952 days obtained from Grant's epoch of primary minimum and Stebbin's (1920) epoch of JD 2,421,506.850.

III. RADIAL VELOCITIES

Primary velocities were measured from the 4471 Å He I and 4481 Å Mg II lines separately. There is no evidence of a 4471 Å He I line in the secondary, so this line provides primary velocities at all phases. The presence of the secondary 4481 Å Mg II line, which is about one-third as strong as it is in the primary (see Fig. 1), means that this line provides velocities at only those phases when it is resolved from the secondary Mg II line. The Mg II line of the primary, or secondary, was measured only in the observations in which it is resolved from the same line in the other component. Secondary velocities were measured from the 4481 Å Mg II line, a group of five Ti II and Fe II lines between 4500 and 4535 Å (hereafter "the Ti II and Fe II lines"), and the 4549 Å Ti II line. Each of these lines, or group of lines, were also measured separately. Spectroscopic information about the lines is given in Table 3.

The Ti II and Fe II lines of the secondary are weak (see Fig. 1), and in most observations some of them are poorly defined or even absent. The variability of their definition, which is too marked for it to be ascribed to variation of the signal-to-noise ratios of individual observations, must be due to intrinsic variations in the spectrum of λ Tau. At least two lines are well defined in all observations (made outside of secondary eclipse), three or four lines are well defined in most observations, and all five lines are well defined in a very few observations. Although these secondary Ti II and Fe II lines are weaker than the secondary Mg II line they have the advantage that, because the same lines are absent from the spectrum of the primary, they provide secondary velocities at all phases when the secondary is visible. This is not true of the secondary Mg II line, which can be reliably measured only when it is fully resolved from the stronger Mg II line of the primary.

In about 20% of the observations the profile of the 4549 Å Ti II line is very broad and shallow or extremely asymmetric and cannot be measured. In most of the remaining observations it provided secondary velocities consistent with the velocities from the other secondary lines; however, in some cases there are differences of up to 35 km s^{-1}. We think that the occasional anomalous behavior of the line is due to the fact that it is a blend of two Ti II lines and an Fe II line (see Table 3), and we did not make use of the velocities from this line.

The radial velocities were measured by cross-correlation of the profile of the line being measured with the profile of the same line in the standard star spectrum, in order to determine the wavelength shifts between the λ Tau spectra and the standard star spectrum. The heliocentric velocities of λ Tau were obtained after conversion of the wavelength shifts into velocity differences between λ Tau and the standard star, and with allowance made for the geocentric corrections, the contribution caused by instrumental offsets, and the

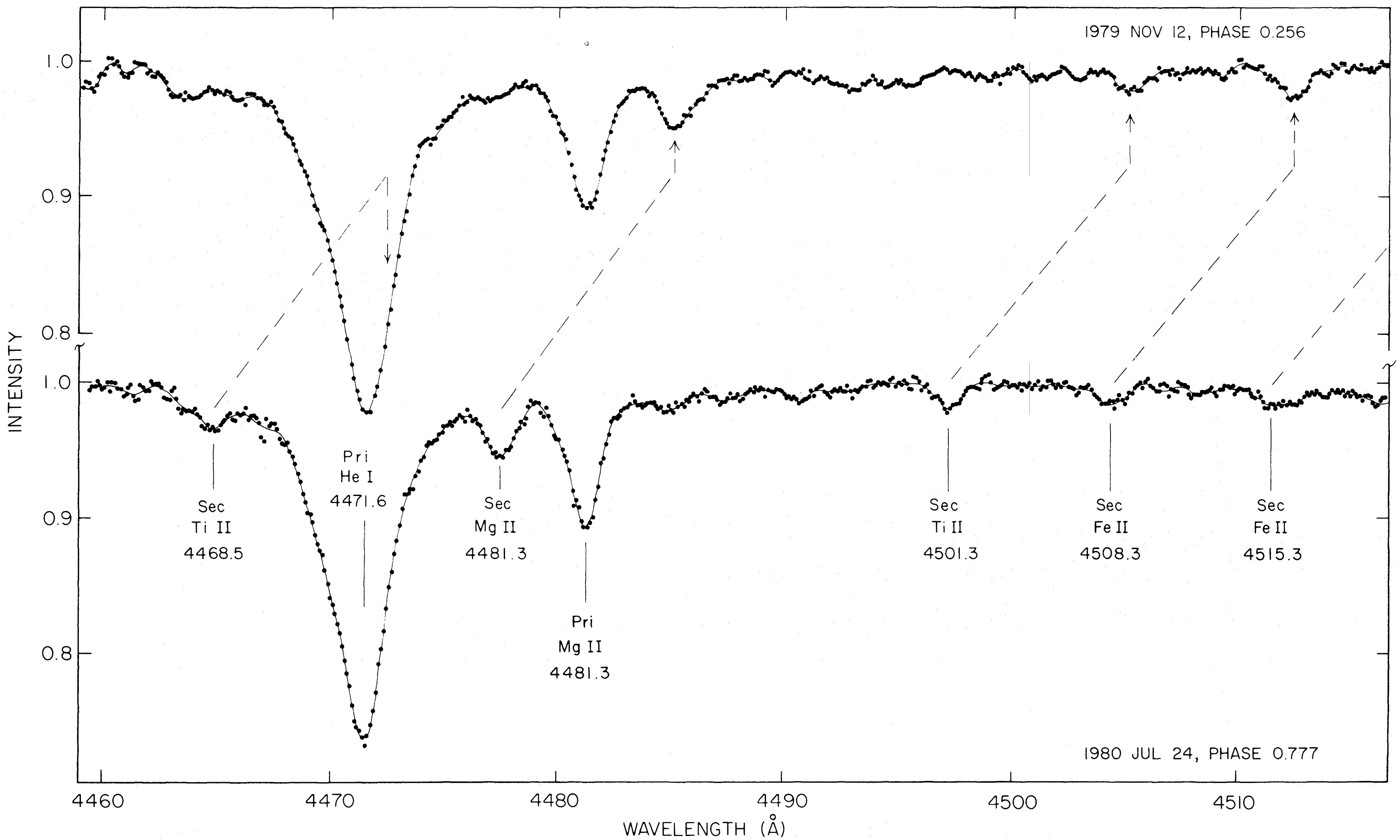

FIG. 1.—Two spectra at opposite quadratures plotted on an expanded intensity scale. The wavelength scale is for the primary. Secondary lines shown are Mg II 4481.3 Å, three lines from the group of five Ti II and Fe II lines between 4500 and 4535 Å, and a Ti II line at 4468.5 Å. This last line is blended with the primary He I line in the top spectrum; it has not been used for any radial velocity measurement. Note the absence of Ti II and Fe II lines from the primary. The phases are for the short-period orbit, calculated from the center of primary eclipse.

TABLE 1

OBSERVATIONS AND VELOCITIES OF λ TAURI: PRIMARY

UT Date	HJD 2444000+	Velocity[a] (km s^{-1}) He I	Velocity[a] (km s^{-1}) Mg II	Velocity[a] (km s^{-1}) Mean	O-C[b] (km s^{-1})	4 Day Orbit Phase[c]	4 Day Orbit Velocity[b] (km s^{-1})	33 Day Orbit Phase[b]	33 Day Orbit Velocity[b] (km s^{-1})
1979 Oct 31.392	177.898	-30	-32	-31.0	+1.9	0.215	-53.0	0.213	+22.0
1979 Nov 01.295	178.800	- 1	---	- 1.0	-0.5	0.443	-22.5	0.240	+21.5
1979 Nov 02.295	179.800	+78	+79	+78.5	+2.3	0.696	+55.2	0.270	+23.3
1979 Nov 04.448	181.953	-30	-37	-33.5	-0.3	0.241	-55.5	0.335	+22.0
1979 Nov 12.406	189.912	-38	-43	-40.5	+0.4	0.254	-55.3	0.576	+14.8
1979 Nov 13.364	190.869	+12	---	+12.0	+3.1	0.496	- 2.8	0.605	+14.8
1979 Nov 14.242	191.747	+66	+69	+67.5	-1.0	0.718	+56.1	0.631	+11.4
1979 Dec 06.316	213.821	-31	-35	-33.0	-2.3	0.303	-54.2	0.298	+21.2
1979 Dec 08.331	215.837	+82	+79	+80.5	+4.4	0.813	+56.5	0.359	+24.0
1979 Dec 09.078	216.583	+11	---	+11.0	---	0.001	---	0.382	---
1979 Dec 09.308	216.813	- 6	+14	+ 4.0	---	0.060	---	0.389	---
1979 Dec 10.145	217.651	-32	-36	-34.0	+0.5	0.272	-54.9	0.414	+20.9
1979 Dec 25.126	232.631	-23	- 7	-15.0	---	0.061	---	0.867	---
1979 Dec 28.165	235.670	+57	+54	+55.5	0.0	0.830	+51.6	0.958	+ 3.9
1979 Dec 31.236	238.741	+47	+46	+46.5	+2.4	0.607	+34.6	0.051	+11.9
1980 Feb 02.097	271.599	+44	+36	+40.0	+1.4	0.919	+29.2	0.044	+10.8
1980 Feb 03.058	272.559	-34	-36	-35.0	-0.5	0.162	-47.3	0.073	+12.3
1980 Feb 11.049	280.550	-29	-32	-30.5	-2.2	0.183	-51.7	0.315	+21.2
1980 Mar 02.085	300.584	-55	-60	-57.5	-4.4	0.252	-57.7	0.920	+ 0.2
1980 Mar 22.079	320.576	-33	-36	-34.5	+1.0	0.309	-51.9	0.524	+17.4
1980 Jul 22.468	442.965	-28	-33	-30.5	+3.4	0.270	-53.5	0.223	+23.0
1980 Jul 24.461	444.958	+81	+83	+82.0	+1.9	0.775	+58.8	0.283	+23.2
1980 Jul 28.463	448.960	+80	+75	+77.5	-0.5	0.787	+56.8	0.404	+20.7
1980 Aug 21.451	472.951	+66	+63	+64.5	+1.4	0.856	+47.0	0.129	+17.5
1980 Aug 23.435	474.935	-22	-24	-23.0	+1.5	0.358	-43.9	0.189	+20.9
1980 Aug 29.434	480.935	+60	+55	+57.5	-5.5	0.876	+38.6	0.370	+18.9
1980 Aug 30.389	481.889	-18	-11	-14.5	+1.8	0.117	-36.4	0.399	+21.9
1980 Sep 02.491	484.992	+56	+45	+50.5	-1.5	0.902	+33.1	0.492	+17.4
1980 Oct 22.434	534.939	+21	+12	+16.5	-0.4	0.538	+10.1	0.002	+ 6.4
1980 Oct 23.424	535.929	+66	+63	+64.5	-1.5	0.788	+56.3	0.032	+ 8.2
1980 Oct 24.460	536.965	-12	+ 8	- 2.0	---	0.050	---	0.063	---
1980 Oct 27.331	539.836	+70	+75	+72.5	-3.5	0.776	+56.0	0.150	+16.5
1980 Dec 01.373	574.878	+59	+64	+61.5	-2.4	0.641	+41.8	0.209	+19.7
1980 Dec 01.383	574.889	+60	+65	+62.5	-2.1	0.644	+42.7	0.209	+19.8
1980 Dec 31.173	604.677	-34	-37	-35.5	-1.0	0.180	-50.5	0.109	+15.0
1981 Jan 21.203	625.706	+ 3	---	+ 3.0	0.0	0.499	- 3.2	0.745	+ 6.2
1981 Feb 26.064	661.563	+23	+20	+21.5	-3.1	0.570	+20.2	0.828	+ 1.3
1981 Oct 13.497	891.002	+39	+41	+40.0	-0.6	0.613	+34.9	0.761	+ 5.1
1981 Oct 14.426	891.930	+55	+55	+55.0	+2.6	0.847	+49.5	0.789	+ 5.5
1981 Oct 17.467	894.971	+43	+43	+43.0	+4.6	0.617	+38.7	0.881	+ 4.3
1981 Oct 19.453	896.957	-35	-32	-33.5	+1.2	0.119	-37.2	0.941	+ 3.7
1981 Dec 15.309	953.815	+ 6	---	+ 6.0	-2.5	0.503	- 3.3	0.659	+ 9.3
1981 Dec 17.236	955.741	+13	---	+13.0	---	0.990	---	0.718	---
1981 Dec 17.383	955.888	-18	---	-18.0	---	0.027	---	0.722	---

[a] Primary velocities measured during primary eclipse (phases -0.08 to +0.08) were excluded from the orbital solutions.

[b] O-C and decomposition of the observed velocities into velocities in the 4 day and 33 day orbits are for the mean velocities and the orbital solution for all elements with the 4 day period fixed. Phases in the 33 day orbit are for the P and T of the same solution.

[c] Photometric phases.

TABLE 2

OBSERVATIONS AND VELOCITIES OF λ TAURI: SECONDARY

HJD 2444000+	Velocity[a] (km s^{-1})		O-C[b] (km s^{-1})	4 Day Orbit		33 Day Orbit	
	Mg II	Ti II + Fe II		Phase[c]	Velocity[b] (km s^{-1})	Phase[b]	Velocity[b] (km s^{-1})
177.898	+228	+231	-2.1	0.215	+208.9	0.139	+22.1
178.800	---	+116	---	0.443	---	0.166	---
179.800	-169	-183	+1.6	0.696	-208.2	0.196	+25.2
181.953	+234	+240	-0.4	0.241	+216.3	0.262	+23.7
189.912	+220	+233	+0.1	0.254	+217.8	0.503	+15.2
190.869	---	---	---	0.496	---	0.532	---
191.747	-178	-199	+1.4	0.718	-212.3	0.559	+13.3
213.821	+225	+234	+1.1	0.303	+209.1	0.228	+24.9
215.837	-152	-162	+1.1	0.813	-185.9	0.290	+23.9
216.583	---	+ 28	-2.6	0.001	+ 6.7	0.312	+21.3
216.813	---	+100	-1.3	0.060	+ 78.2	0.319	+21.8
217.651	+230	+235	-3.5	0.272	+215.1	0.345	+19.9
232.631	---	+ 89	+5.1	0.061	+ 83.2	0.799	+ 5.8
235.670	-154	-168	+3.0	0.830	-173.3	0.891	+ 5.3
238.741	---	-143	-2.6	0.607	-152.2	0.984	+ 9.2
271.599	---	- 82	-1.4	0.919	- 91.4	0.981	+ 9.4
272.559	+183	+198	+4.6	0.162	+182.6	0.010	+15.4
280.550	+211	+223	+4.3	0.183	+196.8	0.253	+26.2
300.584	+211	+217	-3.7	0.252	+215.8	0.860	+ 1.2
320.576	+212	+223	+0.5	0.309	+206.0	0.467	+17.0
442.965	+232	+239	-2.3	0.270	+215.9	0.180	+23.1
444.958	-169	-180	+0.9	0.775	-204.7	0.240	+24.7
448.960	-161	-173	+6.1	0.787	-197.1	0.362	+24.1
472.951	-118	-134	-0.6	0.856	-154.2	0.089	+20.2
474.935	+188	+201	+5.4	0.358	+174.7	0.150	+26.3
480.935	---	-117	-3.3	0.876	-137.4	0.332	+20.4
481.889	+144	+161	-1.6	0.117	+140.7	0.361	+20.3
484.992	---	- 93	-1.2	0.902	-109.7	0.455	+16.7
534.939	---	---	---	0.538	---	0.970	---
535.929	-177	-187	+0.6	0.788	-199.4	0.000	+12.4
536.965	---	+ 83	+0.1	0.050	+ 67.7	0.031	+15.3
539.836	-171	-184	-1.8	0.776	-205.4	0.118	+21.4
574.878	-125	-157	-0.3	0.641	-181.1	0.181	+24.1
574.889	-134	-160	-1.3	0.644	-183.6	0.182	+23.6
604.677	+200	+211	-1.5	0.180	+191.5	0.085	+19.5
625.706	---	---	---	0.499	---	0.723	---
661.563	---	-105	---	0.570	---	0.811	---
891.002	-110	-157	-4.2	0.613	-158.8	0.771	+ 1.8
891.930	-139	-164	-6.1	0.847	-164.2	0.800	+ 0.2
894.971	-122	-153	+3.7	0.617	-158.7	0.892	+ 5.7
896.957	+133	+149	-1.9	0.119	+142.5	0.952	+ 6.5
953.815	---	+ 23	---	0.503	---	0.677	---
955.741	---	+ 1	+2.0	0.990	- 5.0	0.735	+ 6.0
955.888	---	+ 47	+2.2	0.027	+ 41.1	0.740	+ 5.9

[a] Secondary velocities measured during secondary eclipse (phases 0.42 to 0.58) were excluded from the orbital solutions.

[b] O-C and decomposition of observed velocities into velocities in the 4 day and 33 day orbits are for the Ti II + Fe II velocities and the orbital solution for all elements with the 4 day period fixed. Phases in the 33 day orbit are for the P and T of the same solution.

[c] Photometric phases.

TABLE 3
LINES MEASURED IN λ TAURI

Line	λ (Å)	χ (eV)	Component
He I	4471.48	20.87	Pri
	4471.69	20.87	
Mg II	4481.14	8.86	Pri and Sec
	4481.34	8.86	
Ti II	4501.28	1.12	Sec
Fe II	4508.29	2.85	Sec
Fe II	4515.34	2.84	Sec
Fe II	4522.64	2.84	Sec
Ti II	4533.97	1.24	Sec
Ti II	4549.47[a]	2.83	Sec
	4549.64	1.58	
	4549.82	1.18	

[a] This is an Fe II line.

heliocentric radial velocity of the standard star. (The instrumental offsets had been calculated by cross-correlation of the Fe-Ne spectra with the Fe-Ne spectrum that accompanied the standard star observation.) These heliocentric velocities are listed in Tables 1 and 2; they are rounded to the nearest km s^{-1} because the asymmetries in the profiles of both the primary and secondary lines show that it is probably not meaningful to quote more accurate velocities.

The star π Cet was the standard for the measurement of the primary He I line, and Vega was the standard for the measurement of the primary Mg II line and all secondary lines.[2] Heliocentric velocities of +15.4 and −13.9 km s^{-1} from Wilson (1953) were used for π Cet and Vega, respectively. The velocity of π Cet obtained by cross-correlation of its Mg II line with Vega's is +15.2 km s^{-1}, which is in excellent agreement with Wilson's value of +15.4 km s^{-1} and confirms that the radial velocity of π Cet at the time of our observation was the same as Wilson's value.

[2] It would have been preferable to have used the same standard star for all measurements; however, this was not possible because in π Cet the Ti II lines are absent and in Vega the He I line—which *is* present with a depth of 5%—is affected by other weak lines. Other candidate standard stars that we observed also lacked some of the required lines, or they had excessively broad lines.

IV. ANALYSIS

Inspection of the velocities from the He I and Mg II lines of the primary, given in Table 1, shows that outside of primary eclipse they are reasonably consistent with each other. For the analysis of the primary velocities we have adopted the mean velocities for these two lines.

There is no such consistency in the Mg II and Ti II + Fe II line velocities of the secondary; comparison of the results in Table 2 shows that the Mg II line velocities are always of smaller magnitude than the Ti II + Fe II line velocities. Orbital solutions of the secondary velocities (see Table 4) yield semiamplitudes of 200.1 ± 1.3 and 215.6 ± 0.7 km s^{-1} for the Mg II and Fe II + Ti II lines, respectively; thus the secondary semiamplitude for the Mg II line is 16 km s^{-1} smaller than it is for the Ti II + Fe II lines.[3] Which set of velocities is most representative of the orbital motion of the secondary? Two considerations suggest that it is the Ti II + Fe II line velocities.

First, the inspection of each λ Tau observation, which had been done as a preliminary to the measurement of

[3] The same effect may be present in the eclipsing binary V822 Aql. This system, which has a period of 5.3 days and component of spectral type B3 and B9, is very similar to λ Tau in some respects. Popper (1981) says that the secondary Si II and Fe II lines, which—like the Ti II and Fe II lines in λ Tau—are much weaker than the secondary 4481 Å Mg II line, "tend to give velocities, both positive and negative, somewhat larger than does λ4481." Although Popper's findings are based on a small number (seven) of observations and he does not give any velocities for the Si II and Fe II lines, the sense of the discrepancy is the same as we find for the Ti II + Fe II and Mg II lines in λ Tau.

TABLE 4
ORBITAL ELEMENTS

ELEMENT	SOLUTION				
	Primary	Secondary Ti II + Fe II	Secondary Mg II	Primary $e_s = 0$	Secondary Ti II + Fe II $e_s = 0$
V_0 (km s^{-1})	13.1 ± 0.5	14.0 ± 0.9	17.5 ± 5.0	13.4 ± 0.5	14.2 ± 1.5
K_s (km s^{-1})	56.9 ± 0.6	215.6 ± 0.7	200.1 ± 1.3	56.8 ± 0.6	213.4 ± 1.7
e_s	0.025 ± 0.015	0.046 ± 0.004	0.037 ± 0.011	0.0	0.0
ω_s (deg)	7 ± 28	77 ± 7	50 ± 28	...	...
T_s (HJD 2,444,000+)	658.4 ± 0.3	684.8 ± 0.1	601.6 ± 0.3	...	...
P_s (days)			3.9529552 (fixed)		
K_l (km s^{-1})	10.1 ± 0.7	10.8 ± 0.8	17.3 ± 15.9	10.5 ± 0.7	15.2 ± 3.0
e_l	0.16 ± 0.07	0.21 ± 0.08	0.48 ± 0.31	0.15 ± 0.06	0.27 ± 0.16
ω_l (deg)	236 ± 24	261 ± 22	203 ± 25	241 ± 24	149 ± 32
T_l (HJD 2,444,000+)	667.3 ± 2.1	667.8 ± 1.8	633.7 ± 1.6	667.4 ± 2.1	659.3 ± 2.6
P_l (days)	33.09 ± 0.06	32.96 ± 0.06	33.47 ± 0.11	33.07 ± 0.05	33.15 ± 0.09

NOTE.—A solution for V_0 and K_s for the secondary Ti II + Fe II velocities with all other elements fixed with their values for the primary $e_s > 0$ solution [ω_s(sec) = ω_s(pri) + 180°] gives $V_0 = 19.5 \pm 2.2$ km s^{-1} and $K_s = 214.8 \pm 2.7$ km s^{-1}.

the radial velocities, showed that the individual lines in the group of five Ti II and Fe II lines had very similar shifts with respect to the same lines in the standard star (Vega). In other words, the Ti II and Fe II lines all yield the same velocity. This mutual consistency suggests—but does not prove—that the Ti II and Fe II lines provide a more truthful measure of orbital motion than the Mg II line.

The second consideration is the possibility that the secondary velocities include a rotational contribution. We will outline why we think that the Mg II line velocities are much more affected than the Ti II + Fe II line velocities. A rotational effect is expected because the heating of the secondary by the much brighter primary means that the side of the secondary illuminated by the primary is hotter than the "dark" side of the secondary. Hutchings and Hill (1971) find that for λ Tau the surface temperature of the secondary at the point directly beneath the primary is 1400 K higher than it is at the point on the "dark" side of the secondary farthest away from the primary. As a result the variation of strength of a spectral line over the observed hemisphere of the secondary is asymmetric, except at phases 0.0 and 0.5, and so the velocity obtained by measuring the line will include a rotational component. The large rotational velocity of the secondary—$V \sin i \approx 80$ km s^{-1} is derived from the line widths—means that its influence might well be significant. The effect is greatest at quadrature and is illustrated in Figure 2 for the phase 0.25 quadrature, which for the sake of simplicity we will discuss from here on. The 8.9 eV Mg II line is strongest on the side of the secondary facing the primary; thus the rotational contribution to the measured Mg II line velocity favors the half of the observed hemisphere of the secondary that is illuminated by the primary. This rotational contribution is opposed to the orbital motion—see Figure 2 and recall that orbital and rotational motions must be in the same sense—so the Mg II line velocity will be less than the orbital velocity. By the same argument the magnitude of the observed Mg II line velocity at phase 0.75 will also be less than the magnitude of orbital motion. In other words, we expect that the Mg II line velocities will tend to underestimate the secondary's orbital motion. The asymmetry of the profile of the secondary Mg II line at phase 0.25, when its deepest point is shifted to the blue side of the profile (see Fig. 1), is consistent with this explanation. At phase 0.75 we expect that the deepest point of the profile will be shifted to the red, however at this phase profile asymmetries are masked because the line is sandwiched between the He I and Mg II lines of the primary. The Ti II and Fe II lines have excitation potentials of only 1.1 to 2.8 eV (see Table 3) so that the strengthening of these lines on the side of the secondary facing the primary is much less than it is for the 8.9 eV Mg II line. This means that although the Ti II + Fe II line velocities may not be completely free of a rotational contribution, it will be much smaller than it is for the Mg II line; in other words, the Ti II + Fe II line velocities will also tend to underestimate the secondary's orbital motion, but the effect will be less than it is for the Mg II line. This explains why the secondary Ti II + Fe II semiamplitude of 215.6 ± 0.7 km s^{-1} is *larger* than the secondary Mg II semiamplitude of 200.1 ± 1.3 km s^{-1}. We decided to do separate orbital element solutions for the Ti II + Fe II line velocities and the Mg II line velocities and prefer the elements for the Ti II + Fe II line solution.

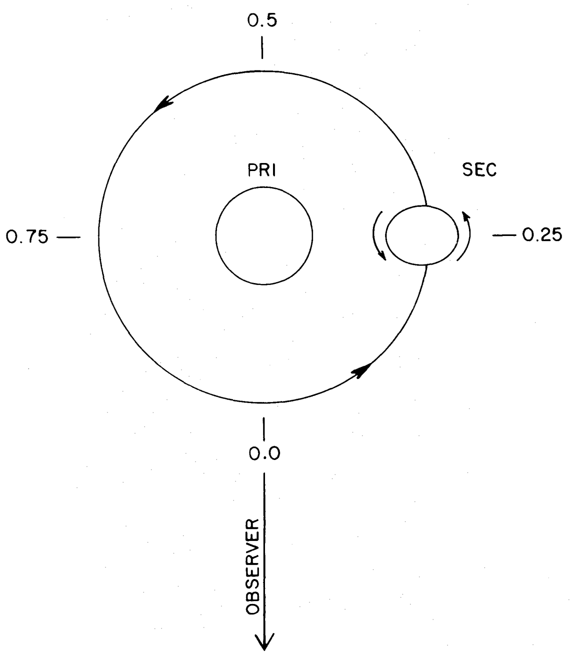

FIG. 2.—The effect of rotation on the observed secondary velocities

The residuals for the solution of the primary velocities clearly have a 33 day periodicity with an amplitude of about 10 km s^{-1}. The same periodicity and amplitude is also present in the residuals for the solution of the secondary velocities—both the Ti II + Fe II and the Mg II line velocities. The presence of the identical 33 day periodicity in the velocities of *both* the primary and secondary is conclusive evidence of orbital motion of the center of mass of the eclipsing pair around a third star. It cannot be attributed to some obscure low-amplitude pulsation of the primary. (The B3 V spectral type of the primary and the 10 km s^{-1} amplitude are suggestive of the pulsational variability of β CMa stars.)

The elements for the 4 and 33 day orbits of the primary were found simultaneously by evaluating differential corrections to the elements for both orbits in a modified version of the general least-squares computer routine described by Daniels (1966). All elements were solved for, except the period of the 4 day orbit which was fixed with the precisely determined photometric value. Separate solutions of the secondary Ti II + Fe II and Mg II line velocities were made in the same way. (Primary velocities measured during primary eclipse, phases -0.08 to $+0.08$, and secondary velocities measured during secondary eclipse, phases 0.42 to 0.58, were excluded from the solutions.) The results are given

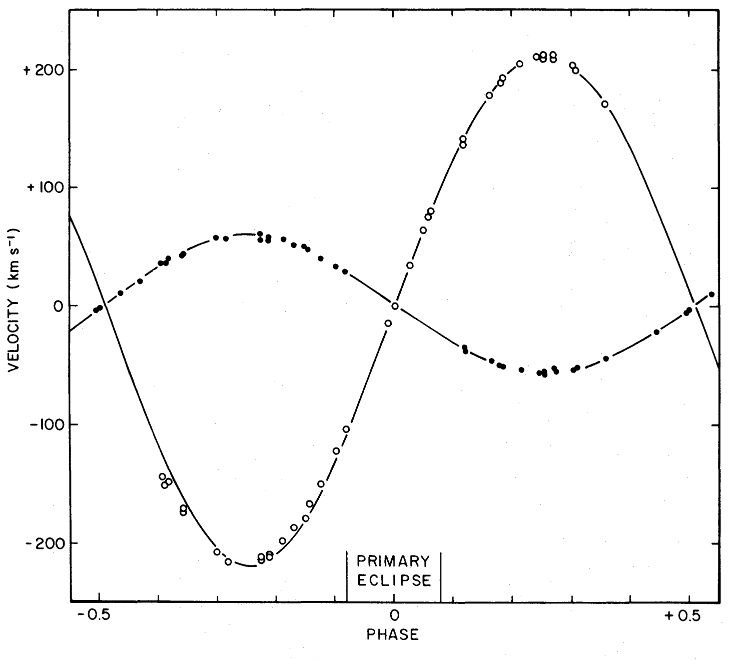

FIG. 3.—The primary and secondary velocities for the short-period orbit of λ Tau. Each point is *not* an observed velocity, but is the short-period component from the decomposition of the observed velocity into short- and long-period components. Primary velocities are from the $e_s > 0$ orbital solution with the short period fixed. Secondary velocities are from the orbital solution of the Ti II + Fe II velocities for V_0 and K_s with all other elements fixed with the values from the same primary solution [$\omega_s(\text{sec}) = \omega_s(\text{pri}) + 180°$]. These short-period velocities do not include V_0. The zero of phase is the center of primary eclipse.

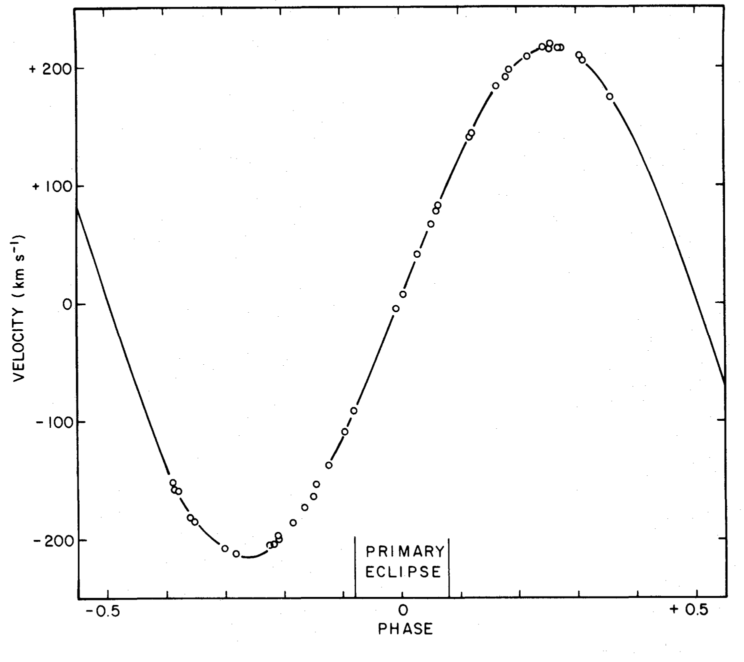

FIG. 4.—Secondary velocities for the short-period orbit of λ Tau from the $e_s > 0$ orbital solution of the Ti II + Fe II velocities with the short period fixed. These short-period velocities do not include V_0. The zero of phase is the center of primary eclipse.

in Table 4, and the velocity curves for the 4 and 33 day orbits are shown in Figures 3, 4, and 5.

The 33 day orbit is due to the motion of the center of mass of the primary and secondary around the center of mass of the system, so in principle the primary and secondary velocities should yield identical long-period elements. The solutions of the primary and secondary (Ti II + Fe II) velocities do indeed give very similar elements for the long-period orbit; they both show that the period is 33.0 days and the semiamplitude is 10.5 km s^{-1}. The results confirm the values of 33.025 days and $8.6 \leq K \leq 11.6$ km s^{-1} determined by Ebbighausen and Struve (1956). The eccentricity—0.16 ± 0.07 and 0.21 ± 0.08 from the primary and secondary velocities, respectively—is only about twice its associated error; however, the agreement of the two results and also the agreement of ω—i.e., $236° \pm 24°$ and $261° \pm 22°$ for the primary and secondary respectively—indicate that it must be real. We think that the primary velocities are probably more reliable than the secondary velocities and will adopt the long period orbital elements for the solution of the primary.

The eccentricity of the short-period orbit for the primary solution is 0.025 and is not much larger than its associated error of 0.015, which suggests that it is of marginal reality. (The 0.046 ± 0.004 eccentricity from the solution of the secondary Ti II + Fe II velocities can be disregarded, even though it is much larger than its associated error. The gap in secondary velocity coverage of the short-period orbit from phase 0.36 to 0.61 means that the solution will tend to produce a spuriously large eccentricity.) Results of solutions of the primary and secondary (Ti II + Fe II) velocities with the short-period orbit assumed to be circular are given in Table 4. Comparison with the nonzero eccentricity solutions shows that the primary and secondary short-period semiamplitudes do not change significantly, the long-period elements for the primary solution are unaffected, while the long-period semiamplitude and eccentricity for the secondary solution become somewhat larger.

Solutions of the primary and secondary (Ti II + Fe II) velocities in which the short period was allowed to vary, instead of being fixed, gave short periods of $3^{d}.95311 \pm 0^{d}.00014$ and $3^{d}.95298 \pm 0^{d}.00004$, respectively. The good agreement of these spectroscopically determined periods with the $3^{d}.9529552$ photometric period, which is

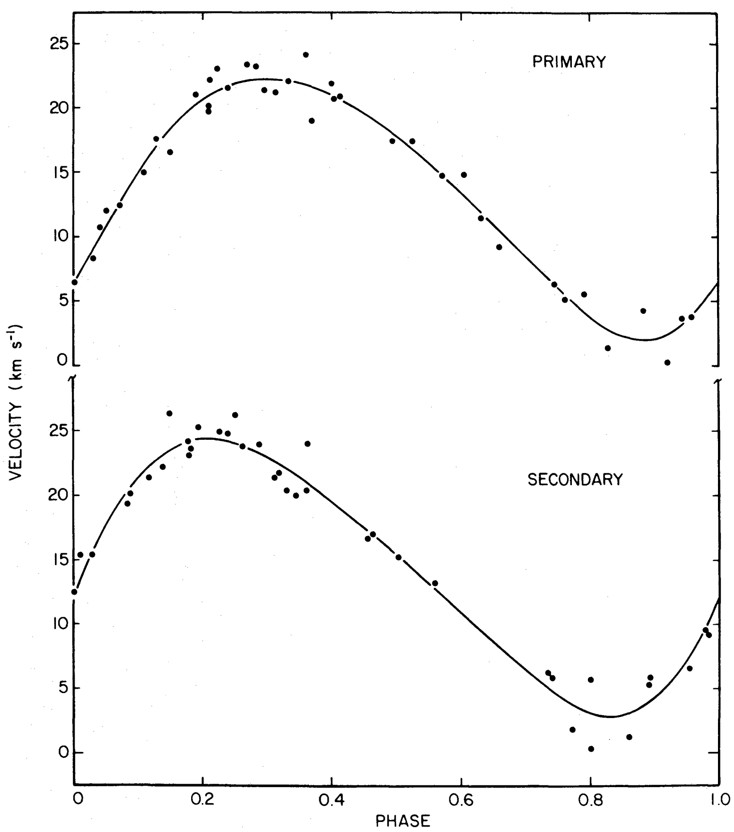

FIG. 5.—Velocities for the long-period orbit of λ Tau derived from the primary velocities and the Ti II + Fe II secondary velocities. Both velocity curves are from the $e_s > 0$ orbital solutions with the short period fixed. The phases are for the P_l and T_l of these solutions and are the same as the phases in the second-last columns of Tables 1 and 2. These long-period velocities include V_0.

based on minima observed in 1916 (Stebbins 1920) and 1954 (Grant 1959), is evidence that there has been no large change in the period.

V. RESULTS

The primary and secondary semiamplitudes of 56.9 ± 0.6 and 215.6 ± 0.7 km s^{-1}, respectively, combined with the photometrically determined inclination and fractional radii yield the masses and dimensions of the primary and secondary. Unfortunately the two most recent photometric solutions of λ Tau (Hutchings and Hill 1971; Cester *et al.* 1978) do not agree. Hutchings and Hill find $i = 81\overset{\circ}{.}3 \pm 0\overset{\circ}{.}3$, $r_1 = 0.345$, and $r_2 = 0.206$ while Cester *et al.* determine $i = 76° \pm 0\overset{\circ}{.}5$, $r_1 = 0.30$, and $r_2 = 0.25$. (These fractional radii are for the radius in the direction of orbital motion. The results quoted for Cester *et al.* are the means of their B and V solutions.) The corresponding Roche lobe fractional radius of the secondary (Plavec and Kratochvil 1964), which is set by the mass ratio $q = m_2/m_1$ $(=K_1/K_2) = 0.264$, is 0.262. Thus the Cester *et al.* fractional radius of the secondary is consistent with the secondary filling its Roche lobe, i.e., consistent with λ Tau being a semidetached system, while the Hutchings and Hill radius requires that it be a detached system.

The irregular changes in the profiles and strengths of the secondary lines discussed in § III are characteristic of a semidetached system, not a detached system. High-resolution extreme-ultraviolet observations by Polidan and Peters (1980), which reveal the presence of a gas stream, provide further spectroscopic evidence that the system is semidetached. Also, if it is supposed that the system is detached, then mass transfer has yet to occur, which makes it very difficult to explain why the radius of the secondary is 3 times greater than that of a normal main-sequence star of the same mass. It cannot be due to evolution, because the much more massive primary would evolve long before the secondary. These considerations suggest that the system must be semidetached, and we have therefore adopted the Cester *et al.* solution for calculation of the masses and dimensions. These results are given in Table 5.

TABLE 5

MASSES AND DIMENSIONS OF ECLIPSING PAIR

$f_1(m)$	$0.0754 \pm 0.0025\ m_\odot$
$f_2(m)$	$4.10 \pm 0.04\ m_\odot$
$a_1 \sin i$	$3.093 \pm 0.033 \times 10^6$ km
$a_2 \sin i$	$11.72 \pm 0.04 \times 10^6$ km
Inclination	76°
m_1	$7.18 \pm 0.09\ m_\odot$
m_2	$1.89 \pm 0.04\ m_\odot$
Separation	$21.3\ R_\odot$
r_1	0.30
r_2	0.25
R_1	$6.4\ R_\odot$
R_2	$5.3\ R_\odot$

NOTE.—The fractional radii r_1 and r_2 are the radii in the direction of orbital motion and are from Cester *et al.* 1978.

The 33 day orbit must be coplanar, or nearly coplanar, with the 4 day orbit, because the constancy of eclipse depth sets an upper limit of 7° on departure from coplanarity (Söderhjelm 1975). This means that the mass function,

$$m_3{}^3 \sin^3 i/[(m_1 + m_2) + m_3]^2 = 0.0034 ,$$

of the 33 day orbit of the eclipsing pair can be used to determine the mass of the third star because we know both i and $m_1 + m_2$, the total mass of the eclipsing pair. We find $m_3 = 0.7\ m_\odot$. If the third star is a main-sequence star, then it must be a K dwarf and will be exceedingly faint compared to the eclipsing pair. This is consistent with our failure to detect the 8806 Å Mg I line, which is strong in the spectra of cool stars, of the third star on a low-noise Reticon spectrum of λ Tau. It is also consistent with the fact that the photometric solutions do not require any third light.

VI. SPECTRAL TYPE OF THE SECONDARY

Although Hill *et al.* (1975) classified the primary as B2 V, most investigators have classified it as B3 V (Slettebak and Howard 1955; Olson 1968; Levato 1975). Because of the large magnitude difference between the components, accurate classification of the secondary is difficult although it is generally thought to be an A star. Ebbighausen and Struve (1956) detected the Mg II λ4481 line of the secondary on some Victoria plates. As a result of this detection, they suggested that the secondary is of type late B or early A. In addition to the Mg II λ4481 line, Grant (1959) also detected the Hα and Ca II K lines of the secondary. For the short-period components he determined the luminosity ratios at several wavelengths from the observed strengths of the Hα and Mg II lines relative to a set of A-type stars. Combining these luminosity ratios with a calibration of the equivalent width of the Ca K line in A stars, Grant determined a spectral type of A4 for the secondary. Plavec and Polidan (1976) classified the secondary as A1 III–IV from lines in the Ca II infrared triplet region. Olson (1968) determined a spectral type of A3–4 from spectrophotometry of selected lines in the blue spectral region.

We have attempted to determine the spectral type of the secondary and the magnitude difference of the close pair using the computer program of Parsons (1981). Inputs to the program are the assumed spectral type and luminosity classification of the two stars, the visual magnitude difference, and $E(B-V)$. From a table of intrinsic ultraviolet colors (see references in Parsons 1981) and the intrinsic *UBVRIJKLM* colors from Johnson (1966), a combined energy distribution is calculated with the input values. This calculated distribution is compared to the observed distribution after converting both to energy scale magnitudes using 3.64×10^{-9} ergs s^{-1} cm^{-2} Å^{-1} for $m(\lambda) = 0.00$.

The observed data consists of TD-1 fluxes from Thompson *et al.* (1978) and U, B, V, R, I, J, K, and L magnitudes from Johnson *et al.* (1966). For λ Tau the spectral classification of the primary was assumed to be B3 V and was held constant throughout the various solutions. The other initial parameters were A4 V, $\Delta V = 2.5$ mag (Grant 1959) and $E(B-V) = 0.04$ (Clements and Neff 1979). The last three parameters were changed by trial and error until a reasonable fit was obtained.

Table 6 lists the observed composite energy scale magnitudes for λ Tau and representative computed values. Unfortunately the secondary is a minor contributor to the observed flux at all wavelengths, even in the infrared. Inspection of Table 6 shows that variation of its spectral type from A2 V to A8 V has no appreciable effect on the magnitudes up to and including *R* and only a small effect on the *I*, *J*, *K*, and *L* magnitudes. Keeping in mind that the infrared energy distribution is influenced not only by the secondary spectral type but also by the exact values assumed for the temperature of the primary, $E(B-V)$, and ΔV, then the results in Table 6 indicate that the sensitivity of the observed energy distribution to secondary spectral type is not enough to put extensive constraints on the secondary's spectral type. The magnitude difference is, however, reasonably well determined, with $\Delta V = 2.3 \pm 0.2$ (est. error) mag. This is in excellent agreement with Grant's value of 2.45 mag.

Our spectra, which cover 105 Å centered at 4510 Å, show Mg II, Ti II, and Fe II lines of the secondary, but there is no sign of neutral lines, particularly of iron. For this wavelength region the magnitude difference from the energy distribution analysis is $\Delta B = 2.6$ or a luminosity ratio of about 11 to 1, while the photometric determinations of this ratio are even larger. The line depths of the broadened Fe II and Ti II lines are about 1.5% while that of Mg II is about 4%. In the same wavelength region we have obtained Reticon spectra of Vega, spectral type A0 V, and several sharp lined A2 V stars. From an examination of the line depths and equivalent widths of the Fe II, Ti II, and Mg II lines in these stars, a spectral type as early as A0 for the secondary can be ruled out since the lines would be too shallow to be detectable. Although all these lines are stronger in the A2 stars, they are still probably too weak to be detected as secondary features in λ Tau. For a spectral type as late as A8, the Fe I lines in this region are nearly as strong as the Fe II lines. Since we do not detect such neutral lines, this rules out such a late spectral type. Thus, the mid-A spectral type assigned to the secondary by Grant (1959) and later by Olson (1968) is consistent with our observations.

VII. DYNAMICAL EFFECTS OF THE THIRD STAR

The presence of the third star in the λ Tau system causes variations in the motion of the close pair. In addition to the velocity variations discussed in § IV, it also causes periodic variations in the eccentricity, in periastron passage (apsidal motion), and of the planes of the two motions (nodal precession). As noted by Mazeh and Shaham (1976), the last three effects are difficult to detect due to the long period of the variations, usually at least several hundred years, and/or the small size of the variation.

The λ Tau system with a period ratio slightly greater than 8:1 is one of the few systems for which such periods as apsidal motion and nodal precession are rather short. For λ Tau the period of nodal precession is expected to be 7–8 years (Söderhjelm 1975; Mazeh and Shaham 1976). This nodal motion will produce variations in the semiamplitudes of the two orbits, which may be detected spectroscopically, and variations in the eclipse depths, which may be detected photometrically.

Söderhjelm (1975) examined the existing photometry which at most shows only a slight change in the eclipse depth. From the observed constancy of eclipse depth he concluded that the long- and short-period orbits are coplanar to within about 7°. Mazeh and Shaham (1976) examined the spectroscopic observations for variations of the long- and short-period semiamplitudes. They suggested that the angle between the planes of the two orbits might be as large as 30° and that over the 7–8 year period of the associated precession the inclination of the short-period orbit varies from 90° to 60°. The observable consequence of such a variation would be that over a few years the depth of primary eclipse would change from about 1.2 mag to about 0.1 mag; i.e., in this latter situation the eclipse would be so shallow that λ Tau would hardly be recognizable as an eclipsing binary! There is no evidence whatsoever for such gross changes in the photometric behavior of λ Tau. The actual depth of primary eclipse is 0.43 mag in *B*; and the four photoelectric determinations of this depth, which were made between 1916 and 1954 and are summarized

TABLE 6

OBSERVED AND COMPUTED ENERGY SCALE MAGNITUDES FOR λ TAURI

	EFFECTIVE WAVELENGTH (Å)											
	1565	1965	2365	2740	*U* 3600	*B* 4400	*V* 5500	*R* 7000	*I* 9000	*J* 12,500	*K* 22,000	*L* 34,000
Observed energy (mag)	0.85	1.38	1.78	2.27	2.55	2.63	3.41	4.31	5.22	6.31	8.65	10.30
B3 V + A2 V, $\Delta V = 2.3$	0.86	1.38	1.78	2.25	2.56	2.63	3.41	4.28	5.23	6.30	8.75	10.45
B3 V + A4 V, $\Delta V = 2.3$	0.86	1.38	1.78	2.26	2.57	2.64	3.41	4.28	5.21	6.28	8.72	10.42
B3 V + A6 V, $\Delta V = 2.3$	0.86	1.38	1.78	2.26	2.57	2.64	3.41	4.27	5.20	6.26	8.69	10.38
B3 V + A8 V, $\Delta V = 2.4$	0.85	1.38	1.77	2.25	2.56	2.64	3.41	4.27	5.19	6.25	8.66	10.35

NOTE.—All magnitudes computed with $E(B-V) = 0.06$.

in Table 3 of Söderhjelm (1975), do not depart from this by more than 0.02 mag. If, for the sake of argument, it is accepted that the depth of primary eclipse ranges from ~1.2 mag to ~0.1 mag, then the fact that the four observed depths are so close to each other has to be put down to sheer chance. This chance is about 1/20,000, which is so small as to argue against any large-scale variation of the eclipse depth. In fact even this remote chance can be excluded by visual observations because "a 10 year series of visual estimates by Nijland (1932) does not show any evidence for a variable minimum depth," as Söderhjelm (1975) points out.[4] Mazeh and Shaham's suggestion must be dismissed as a fantasy; they probably overinterpreted the spectroscopic data. A series of eclipse depth measurements by photoelectric photometry over the 7–8 year period of precession would be well worthwhile because—as Söderhjelm notes—there is evidence of a *small* variation of depth.

Both Söderhjelm (1982) and Mazeh and Shaham (1979) have also examined the effects of a third body on the eccentricity of the short-period orbit. Mazeh and Shaham concluded that a low-mass third star induces a long term, nearly periodic variation in the short-period eccentricity. Even for an eccentricity as small as 10^{-3} they found that the amplitude of the variation could be as large as 0.04 in some of their test cases. In a more general study Söderhjelm concluded that the amplitude of the variation of the short-period eccentricity is small if the relative inclination between the two orbits is less than 39°. For relative inclinations greater than this value, the amplitude can become very large. As a result of these studies, we have chosen to list both the nonzero and zero eccentricity orbital solutions in Table 4.

As mentioned earlier, the period ratio for λ Tau is slightly greater than 8:1 and, therefore, the separation ratio is about 4:1. These ratios are the smallest of any known close multiple system (Fekel 1981). At periastron in the long-period orbit it is periodically possible for the separation between the short-period secondary and the third star to be about 58 $R_\odot$, or only 2.72 times the separation of the short-period primary and secondary. Because of this small separation ratio, it is of interest to examine the stability of the system.

From numerical integrations of three-body point masses, Harrington (1972, 1975) determined two important parameters for stability. Stability depends on the ratio of the periastron distance of the long-period orbit to the semimajor axis of the short-period orbit, q/a, and also on the relative sense, either corotation or counterrotation, of orbital motion. He found that his numerical results could be reasonably approximated by the equation

$$q/a = [(q/a)_0/\log(1.5)] \log[1 + m_3/(m_1 + m_2)] .$$

The quantities m_1 and m_2 are the masses of the stars in the short-period orbit, m_3 is the mass of the star in the long-period orbit, and $(q/a)_0$ is the parameter limit for the equal-mass case and is equal to 3.5 for the case of corotation and 2.75 for counterrotation. If the observed value of q/a is greater than the limiting value from the above equation, the system is stable. In the case of λ Tau the mass of the third star is 0.7 $m_\odot$ and we find that $q/a = 0.7$ and 0.5 for corotation and counterrotation, respectively. The observed $q/a = 3.4$, a value substantially greater than these limits. Thus according to the criteria of Harrington (1975) the λ Tau system is stable by a surprisingly comfortable margin.

To put the 8:1 period ratio of λ Tau in the context of the solar system, one can imagine the Sun replaced by a binary and the Earth in the place of the third star. The period of this hypothetical binary would be 45 days, and the Earth's orbit would be stable. Insofar as dynamical stability is concerned, the percentage of binaries that have planetary systems may be larger than is commonly supposed.

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[4] The accuracy of visual estimates of eclipse depth can be judged from the early visual photometry of λ Tau. The estimates of depth of primary eclipse made by seven different observers between 1848 and 1913, as summarized by von Aretin (1913), range from 0.36 mag to 0.58 mag and have an average value of 0.45 mag. The average of the differences between these visual estimates and the depth of 0.44 mag in V as measured by photoelectric photometry (Grant 1959) is 0.08 mag; thus the accuracy of visual estimates of eclipse depth is about 0.1 mag.

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