Publications of the Astronomical Society of the Pacific, **115**:49–58, 2003 January

The Masses of the B Stars in the High Galactic Latitude Eclipsing Binary IT Librae[1]

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Received 2002 August 28; accepted 2002 October 2

ABSTRACT. A number of blue stars that appear to be similar to Population I B stars in the star-forming regions of the Galactic disk are found more than 1 kpc from the Galactic plane. Uncertainties about the true distances and masses of these high-latitude B stars have fueled a debate as to their origin and evolutionary status. The eclipsing binary IT Lib is composed of two B stars, is approximately 1 kpc above the Galactic plane, and is moving back toward the plane. Observations of the light and velocity curves presented here lead to the conclusion that the B stars in this system are massive young main-sequence stars. While there are several possible explanations, it appears most plausible that the IT Lib system formed in the disk about 30 million years ago and was ejected on a trajectory taking it to its present position.

1. BACKGROUND

Faint blue stars at high Galactic latitude were first detected in a survey conducted by Humason & Zwicky (1947). Soon after, Bidelman (1948) brought attention to a number of high-velocity stars of early spectral type. The faint apparent magnitudes (sizable distances) and high velocities led to the conclusion that these objects, which appear at low spectroscopic dispersions to be Population I stars, were a part of the Galactic halo. A debate has raged since about the origin and characteristics of these high Galactic latitude B stars. Uncertainty about the masses or true distances of these stars has left the door open to many different scenarios. The discovery that IT Lib is an eclipsing binary (Kazarovets et al. 1999) raises to three the number of known eclipsing binaries at least 1 kpc above the Galactic plane whose components are B-type stars. The other two are V Tuc (Wood 1958) and DO Peg (Hoffmeister 1935). IT Lib is the brightest of the three and has light-curve and radial velocity data gathered for it. As a result, IT Lib presents us with an excellent opportunity to directly measure the masses of a pair of high Galactic latitude B stars.

Photometric variability was first noted in IT Lib (HD 138503) by Strohmeier (1967). Hill (1970) noted variability on the order of 0.2 mag. Houk & Smith-Moore (1988) classified the spectra of IT Lib (HD 138503) as B2/B3 (IV)(n) with a note that the lines appeared "somewhat filled in." Later observations by the *Hipparcos* satellite confirmed IT Lib's (HIP 76161) photometric variability. The 74th naming list of the Information Bulletin of Variable Stars (IBVS; Kazarovets et al. 1999) assigned the designation IT Lib and classified it as a possible eclipsing binary.

Analysis of the *Hipparcos* photometry annex data yielded an ephemeris with the parameters $P = 2.2674600$ days, $T_0 = \mathrm{JD}\ 2{,}448{,}500.76777$ (Turon et al. 1997). Unfortunately, there was a beat pattern between the period of IT Lib and the duty cycle of the *Hipparcos* satellite, so substantial gaps were left in the phase coverage from phase 0.30 to 0.58 and phase 0.63 to 0.75. The *Hipparcos* data show a strong primary eclipse, but the secondary eclipse falls in the gap of observations.

2. NEW SPECTRAL DATA

High-resolution spectra were taken of IT Lib with the Sandiford Echelle Spectrograph (McCarthy et al. 1993) on the McDonald Observatory 82 inch Struve reflector in 1999 March, 2001 February, and 2002 May. A summary of the observations is given in Table 1. The spectra were reduced and extracted using IRAF[2] and analyzed using the ASP software package developed by R. E. Luck.

H I lines, He I lines, and the Mg II 4481 line all have profiles with two well-defined minima over most of the observed period (see Fig. 1 for an example). The broadening due to rotation of the individual components is on the order of 100–150 km s^{-1}, so the lines from each component never completely separate from each other. This blending probably accounts for the line peculiarities noted by Houk & Smith-Moore (1988). As modeled in § 4, the primary component is 3–4 times as bright as the secondary in the bandpass of these spectroscopic obser-

[1] Based on observations made at the 2.1 m Otto Struve Telescope of McDonald Observatory operated by the University of Texas at Austin and also at the 2.1 m telescope at Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

[2] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1
SUMMARY OF SPECTROSCOPIC OBSERVATIONS

Observation Date (UT)	Julian Date	Spectral Coverage (Å)	S/N
1999 Mar 28	2,451,265.941	4120–4640	60
1999 Mar 31	2,451,268.949	4120–4640	65
2001 Feb 6	2,451,946.999	5590–6930	100
2001 Feb 9	2,451,950.005	5590–6930	60
2001 Feb 10	2,451,951.014	5590–6930	100
2002 May 22	2,452,416.764	4850–5630	50
2002 May 25	2,452,419.750	4850–5630	100

TABLE 2
HELIOCENTRIC RADIAL VELOCITY MEASUREMENTS

		COMPONENT VELOCITY (km s^{-1})	
JULIAN DATE	PHASE	A	B
2,452,416.764	0.04	−111.8	
2,451,950.005	0.19	−170.1	182.6
2,452,419.750	0.36	−135.6	155.0
2,451,265.941	0.50	−58.7	
2,451,951.014	0.63	55.6	−260.8
2,451,268.949	0.83	49.5	−280.1
2,451,946.999	0.86	42.3	−217.0

vations, so its spectral lines dominate the composite spectra. An assortment of N II, O II, Al III, Si III, and Fe III lines could be identified at the radial velocity of the primary component, but no lines other than H I, He I, or Mg II 4481 could be positively identified and attributed to the secondary.

The minima of the He I line profiles were used to measure the radial velocity of each component. At some phases, the center of the contribution from the secondary could not be measured because of blending, so only the radial velocity of the primary was measured at those phases. Table 2 summarizes the radial velocity measurements made from the observations, and Figure 2 shows them plotted by phase using the Turon et al. (1997) parameters.

For the analysis in § 4, the individual weights of each radial velocity measure are set equal to each other. The measurements of the radial velocity of the secondary are somewhat more uncertain than those of the primary's velocity because the lines of the secondary are significantly weaker and often partially blended with the lines of the primary. The relative weighting of the two velocity curves is accounted for in the curve-dependent weights assigned to each data set as discussed in § 4.

3. NEW PHOTOMETRIC DATA

The photometric data for IT Lib from the *Hipparcos* Catalog Epoch Photometry Annex has substantial gaps in phase space. An effort was made to obtain more photometric observations of IT Lib at the unobserved phases in order to verify that the system does have a secondary eclipse and to provide more

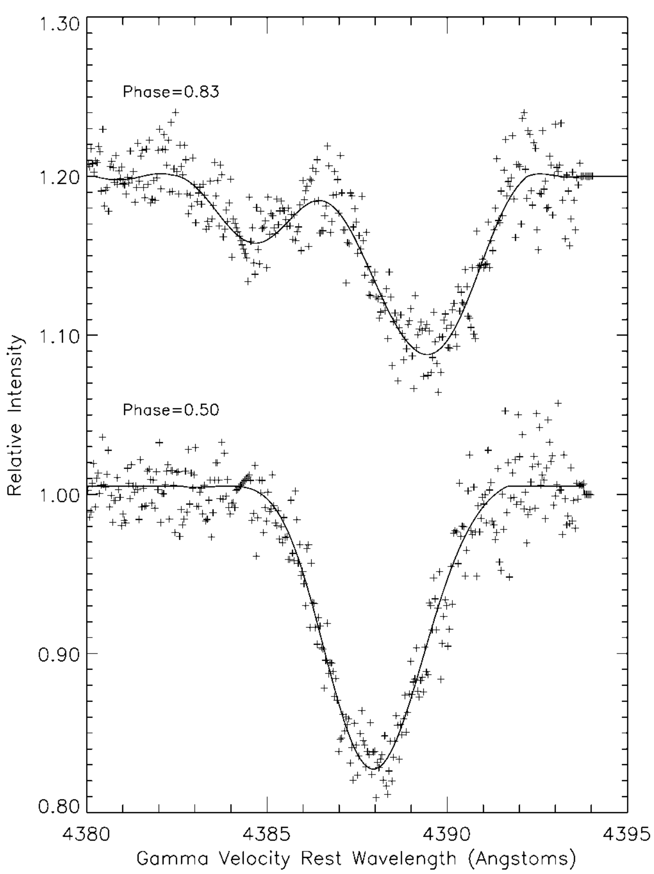

FIG. 1.—Spectral plot of the He I 4487.9 line at phases 0.83 (*top*) and 0.50 (*bottom*). Wavelengths are in the rest frame for the center of mass of IT Lib. The crosses are observed relative flux, and the plotted lines are the FFT to the data.

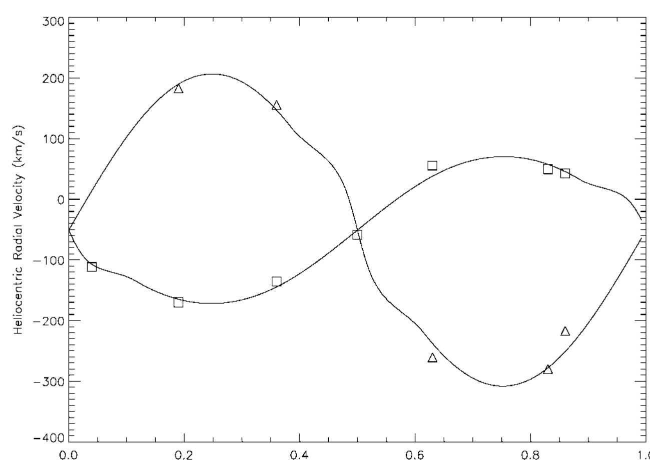

FIG. 2.—Plot of the observed radial velocities of the primary (*squares*) and secondary (*triangles*) components corrected to the heliocentric rest frame vs. phase. The curves are the predicted line-center velocities from the best-fit model to the IT Lib system. The symbols are about the size of the estimated errors.

TABLE 3
NEW PHOTOMETRIC OBSERVATIONS USED IN THE ANALYSIS

Phase	Julian Date	Filter	Δ Mag[a]
0.137	2,452,348.958	*B*	0.114 ± 0.027
0.138	2,452,348.960	*B*	0.120 ± 0.045
0.139	2,452,348.963	*B*	0.114 ± 0.023
0.140	2,452,348.965	*B*	0.062 ± 0.024
0.141	2,452,348.966	*B*	0.086 ± 0.041
0.143	2,452,348.971	*B*	0.041 ± 0.009
0.143	2,452,348.973	*B*	0.026 ± 0.024
0.157	2,452,349.003	*B*	0.017 ± 0.016
0.158	2,452,349.005	*B*	−0.015 ± 0.034
0.158	2,452,349.006	*B*	−0.008 ± 0.030
0.159	2,452,349.008	*B*	0.006 ± 0.032
0.160	2,452,349.009	*B*	0.014 ± 0.029
0.161	2,452,349.012	*B*	−0.011 ± 0.049
0.161	2,452,349.013	*B*	0.018 ± 0.054
0.162	2,452,349.015	*B*	0.016 ± 0.031
0.163	2,452,349.016	*B*	0.019 ± 0.036
0.222	2,452,471.593	*I*	0.016 ± 0.022
0.223	2,452,471.596	*I*	0.009 ± 0.021
0.226	2,452,471.603	*I*	−0.017 ± 0.042
0.232	2,452,471.617	*I*	−0.034 ± 0.050
0.327	2,452,444.622	*R*	−0.001 ± 0.041
0.330	2,452,444.629	*R*	0.021 ± 0.043
0.331	2,452,444.632	*I*	0.003 ± 0.022
0.332	2,452,444.634	*R*	0.012 ± 0.034
0.334	2,452,444.637	*I*	0.011 ± 0.022
0.334	2,452,444.639	*R*	0.007 ± 0.032
0.336	2,452,444.642	*I*	0.034 ± 0.015
0.336	2,452,444.644	*R*	0.033 ± 0.028
0.338	2,452,444.647	*I*	0.014 ± 0.013
0.339	2,452,444.648	*R*	0.048 ± 0.028
0.340	2,452,444.652	*I*	0.012 ± 0.023
0.341	2,452,444.653	*R*	0.025 ± 0.021
0.342	2,452,444.657	*I*	0.021 ± 0.021
0.347	2,452,444.667	*I*	0.026 ± 0.047
0.349	2,452,444.671	*I*	0.035 ± 0.050
0.459	2,452,442.653	*I*	0.231 ± 0.023
0.459	2,452,442.655	*R*	0.216 ± 0.040
0.461	2,452,442.658	*I*	0.235 ± 0.023
0.462	2,452,442.660	*R*	0.221 ± 0.033
0.463	2,452,442.663	*I*	0.247 ± 0.015
0.464	2,452,442.665	*R*	0.234 ± 0.034
0.465	2,452,442.668	*I*	0.248 ± 0.026
0.466	2,452,442.670	*R*	0.238 ± 0.028
0.467	2,452,442.673	*I*	0.269 ± 0.028
0.468	2,452,442.675	*R*	0.296 ± 0.030
0.470	2,452,442.679	*I*	0.259 ± 0.029
0.472	2,452,442.684	*I*	0.251 ± 0.051

[a] The magnitude difference with respect to the magnitude of IT Lib in that filter at phase 0.25.

points for light-curve fitting in order to determine the properties of the system. Two sets of additional data were obtained. J. Feldmeier & J. C. Mihos (2002, private communication) obtained observations with the 2048 × 2048 Tektronix CCD (T2KA) with a Johnson *B* filter on the Kitt Peak 2.1 m. Those observations were reduced using sky flats and the nonlinearity correction of Mochejska et al. (2001). The bulk of the CCD observations were obtained using the 1024 × 1024 FLICam

TABLE 4
PHOTOMETRIC REFERENCE STARS

Star	R.A. Offset (arcmin)	Decl. Offset (arcmin)	Red Magnitude
0600-18258994	−3.54	2.38	12.4
0600-18267326	−1.24	1.63	12.7
0600-18266249	0.41	2.75	14.0
0600-18259671	−3.17	1.55	14.1
0600-18262147	−1.77	0.34	14.1
0600-18262375	−1.66	−1.53	13.8
0600-18274971	4.92	−3.13	11.8
0600-18271754	3.23	0.35	13.3
0600-18261506	−2.14	−2.91	14.1
0600-18287726	−4.23	-5.00	12.4
IT Lib	0.00	0.00	9.0

NOTE.—Positions and magnitudes are from Monet et al. 1998.

(SIA-003 AB SITe back-illuminated CCD) using Cousins *R* and *I* filters on the Warner and Swasey Observatory, Nassau Station 36 inch reflector. Table 3 gives a summary of the observations.

The data were reduced in IRAF and aperture photometry was done with the IRAF procedure QPHOT. The apertures for QPHOT were set to approximately 3 σ, the FWHM of the stellar profiles. Table 4 identifies the reference stars. All the reference stars are between 3 and 5 mag fainter than the target. There are no brighter reference stars in the fields of view ($10'.4 \times 10'.4$ for the 2.1 m data and $5' \times 5'$ for the 36 inch data). As a result, uncertainty in the background turned out to be the largest contributing factor to the photometry errors.

The simple average of the scaled relative magnitudes with respect to each reference star is taken to be the measured relative magnitude of IT Lib for each individual image. The σ is taken as the random error of each individual measurement. The errors are higher for the measurements in Cousins *R* because the night sky is significantly brighter in that bandpass. Larger errors also occurred on nights where moonlight and/or clouds and humidity made significant contributions to the sky brightness. Only data with errors smaller than 50 mmag were used in the analysis (Fig. 3).

There was no need for absolute calibration of the photometry gathered. The Wilson (2001) code used to perform the analysis is capable of performing a simultaneous solution to multiple light curves in multiple filters/bandpasses. The relative magnitudes in each filter were converted to relative intensity normalized to phase 0.25 and inputted as four separated data sets (Johnson *B*, Cousins *R*, Cousins *I*, and *Hipparcos V*) along with the appropriate effective wavelength data for each filter. Individual data points were weighted by the inverse square of their error.

4. ANALYSIS OF ORBITS AND MASSES OF COMPONENTS

The parameters of the IT Lib system were derived from the radial velocity and photometric data using the program of

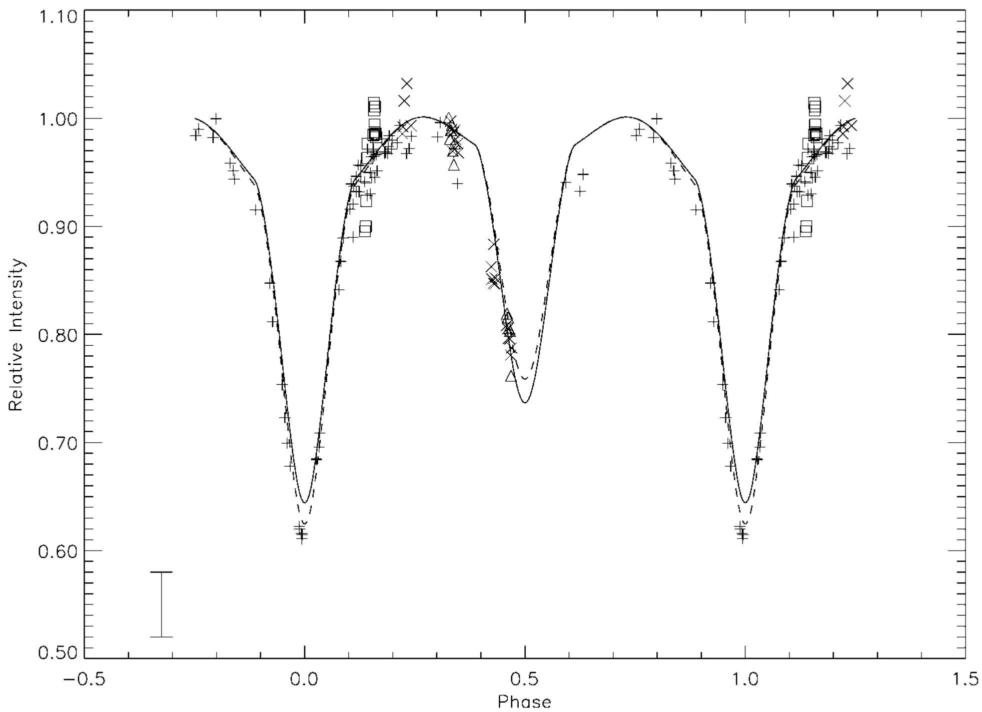

FIG. 3.—Plot of the photometric observations used to determine the best-fit parameters for the IT Lib system including *Hipparcos* Photometry Annex data (Turon et al. 1997) (*pluses*), data provided by J. Feldmeier & J. C. Mihos (2002, private communication) (*squares*), and data obtained on the Nassau 36 inch reflector in Cousins *R* (*triangles*) and Cousins *I* (*crosses*). The solid curve is the modeled light curve in Cousins *I* (deepest in the secondary eclipse). The dashed curve is the modeled light curve in Johnson *V* (deepest in the primary eclipse). At lower left is an error bar representative of the average error ± 0.03.

Wilson (2001). Wilson (2001) uses the model of Wilson & Devinney (1971) with some modifications. The following assumptions are used: synchronous rotation of the components, the components radiate as blackbodies, an orbital period of 2.267460 days and a zero epoch of JD 2,448,500.76777 (Turon et al. 1997), and the luminosity of the secondary component is computed as a function of temperature and surface area of that component. The logarithmic limb-darkening law was used. Limb-darkening coefficients used in the models are taken from the tables of Van Hamme (1993) for stars of the appropriate mass and temperature. The gravity brightening and reflective albedo coefficients used are the ones suggested by Wilson (2001) for hot stars with radiative envelopes. While the temperature of the secondary component is allowed to float, the temperature of the primary component is held constant at 22,000 K, which is consistent with the observed colors of the system and the mass of the primary component.

TABLE 5
CURVE-DEPENDENT WEIGHTS

Curve	Weight[a] (σ_c)
Hipparcos V light curve	0.0023
Johnson *B* light curve	0.0057
Cousins *R* light curve	0.0056
Cousins *I* light curve	0.0017
A component RV curve (km s^{-1})	5.85[b]
B component RV curve (km s^{-1})	11.93[b]

[a] For the light curves in units of normalize light at phase 0.25.

[b] The values used in the analysis were 1/10 these values. See text for explanation.

Curve-dependent weights were applied in order to compensate for the differences in precision between the light and velocity data sets. The Wilson (2001) code allows the weighting of curves by the standard deviation of the curve (σ_c). The method of Kallrath & Milone (1999) using the differences between pairs of consecutive points in phase space was used for calculating the value of σ_c for each light curve. In the case of the radial velocity curves, the values were not spaced close enough to evaluate differences between consecutive points in phase space, so the truncated FFT method (Kallrath & Milone 1999) was used instead by simulating the velocity curve to first order with a sine function. The curve-dependent weights calculated from this method are listed in Table 5.

The σ_c for each velocity curve, when normalized to the curve amplitude, is roughly 20 times larger than the σ_c of each of the light curves, which translates to a relative weight in the total solution on the order of 400 times smaller than the light-curve weights. Some parameters have no dependence on the light curves (such as the semimajor axis and Γ velocity). Full simultaneous solutions of both light and velocity data together calculated errors for these parameters on the order of 50%–60% of the parameter values. Solutions performed using only the velocity data produced parameters with almost the same values but with errors that were 2–4 times smaller than those obtained in the full simultaneous solution. This led to the conclusion that the weights of the velocity curves were probably understated relative to the light curves. It seems reasonable that the velocity data sets should have lower curve weights since they have significantly fewer data points. However, the velocity data are more evenly distributed in phase space than any of the light curves.

In order to rectify the difference between the errors in the full solution and the solution using only the velocity data, the calculated σ_c values for the velocity curves were divided by a factor of 10. This change gave the velocity curves roughly the same but still less weight than each of the light curves. When these curve weights were applied to the full simultaneous solution, none of the derived parameter values were significantly different from those obtained using the unaltered curve weights. However, using the altered curve weights did reduce the errors of the velocity-dependent parameters to essentially the same error values given by the solution to the velocity data alone. These corrected σ_c values were used in the analysis to obtain the best-fit parameters.

The Wilson (2001) code uses a least-squares fit that is iterated to simultaneously solve the parameters of the system. The program was run in a mode reserved for detached binary systems. Table 6 lists the best fits to the parameters defining the IT Lib system. Figure 2 shows the fit to the radial velocity data, and Figure 3 shows the fit to the light curve. The eclipses in the system are partial, and the system is best modeled by stars of 9.8 ± 0.7 and 4.6 ± 0.3 $M_\odot$ separated by 17.6 ± 1.1 solar radii.

TABLE 6
PARAMETERS DERIVED FOR IT LIB SYSTEM

Parameter	Value
Semimajor axis ($R_\odot$)	17.6 ± 1.1
Γ velocity (km s^{-1})	-50.9 ± 7.0
Inclination (deg)	78.1 ± 3.5
Ω_1	3.11 ± 0.24
Ω_2	3.03 ± 0.16
T_2 (K)	13620 ± 2068
M_2/M_1	0.467 ± 0.044
Eccentricity	-0.0095 ± 0.0129
Mass ($M_\odot$):	
Component A	9.77 ± 0.65
Component B	4.57 ± 0.30
Mean radius ($R_\odot$):	
Component A	6.87
Component B	4.77
$M_{\rm bol}$:	
Component A	-5.20
Component B	-2.33
Mean log (g) (cgs):	
Component A	3.75
Component B	3.74

5. DISTANCE FROM PHOTOMETRY

The calculated masses of the components are consistent with main-sequence stars of spectral class B2 and B7. The primary component is about 3–4 times as bright as the secondary, so its spectra dominates the observed composite spectra.

The photometric distance to the system can be found knowing the relative brightness of the components and the absolute magnitude of the primary component. It is possible to find the distance from the absolute magnitude of the combined system, but this introduces additional uncertainties in the form of assumptions that would have to be made about the absolute properties of both the primary and secondary component. Since the light from the system is dominated by the primary, its absolute properties are better constrained. The relative brightness of the components is also well defined by the fit to the light curves. The absolute bolometric magnitude of the primary as calculated by the Wilson (2001) code is -5.20. The bolometric correction for a B2 V star is -2.35 (Cox 2000), which yields an absolute V magnitude of -2.85 for the A component.

The apparent V magnitude of the primary (V_1) can be obtained from the apparent magnitude of the combined system (V_c) and the fraction of light from the primary relative to the combined system (F):

$$V_1 = V_c + 2.5 \log_{10} (1 + F).$$

The calculation is carried out at maximum light in Johnson V (phase 0.271). The observed maximum apparent V magnitude of the combined system taken from Turon et al. (1997) is 9.09. The apparent magnitude comes from the maximum apparent magnitude of the system in the Tycho V filter, corrected to Johnson V by the method prescribed by Turon et al. (1997). The fraction of light from the primary relative to the combined system (F) is 0.7767 as calculated by the Wilson (2001) code. This yields an apparent V magnitude of 9.71 for the primary alone. The extinction factor (A_V) from Schlegel, Finkbeiner, & Davis (1998) is 0.702 [assuming $A_V/E(B-V) = 3.1$]. From the above quantities, a distance of 2.4 kpc is obtained, which places IT Lib 1.0 kpc above the Galactic plane.

There are many sources of error to consider, including the uncertainty in the physical parameters of the primary component, uncertainty in the extinction factor, and uncertainty in the relative brightness of the components. An error of a few tenths of a magnitude would translate into a 20%–30% error in distance. The true errors in this case are unknown, so a standard photometric distance error of 30% is assumed in the following analysis.

TABLE 7
ATOMIC LINE DATA

Atomic Species	λ_0 (Å)	E_0 (eV)	gf	EW (mÅ) Measured	EW (mÅ) Scaled	Abundance
N II	4227.750	21.5995	8.689E−01	29.1	35.6	7.89
N II	4241.800	23.2463	5.400E+00	26.9	32.9	7.46
O II	4351.260	25.6614	1.687E+01	40.8	50.0	8.27
O II	4416.975	23.4192	8.375E−01	93.1	114.0	8.79
O II	4596.177	25.6635	1.585E+00	73.8	90.4	8.89
Al III	4512.565	17.8083	2.624E+00	19.2	23.5	5.64
Al III	4529.189	17.8182	4.688E+00	68.3	83.7	6.16
Si III	4552.622	19.0163	1.959E+00	131.7	161.3	7.08
Si III	4567.840	19.0163	1.175E+00	118.3	144.9	7.15
Si III	4574.757	19.0163	3.926E−01	69.6	85.2	7.08
Fe III	4222.271	20.8704	1.800E+00	24.3	29.8	7.72
Fe III	4310.355	20.8688	1.519E+01	21.8	26.7	7.25

6. ANALYSIS OF AGE VERSUS KINEMATICS

Knowing the distance, the systemic radial velocity, and the proper motions allows one to compute the true space velocity of the system. Proper motions for this system are present in *Hipparcos* (Turon et al. 1997), the ACT2000 (Urban, Corbin, & Wycoff 1997), the Tycho-2 catalog (Høg et al. 2000), and the UCAC1 (Zacharias et al. 2000). These independent measures were averaged together by the method of Martin & Morrison (1998) to obtain a more accurate average proper motion of $\mu_\alpha = 1.82 \pm 0.67$ mas yr^{-1} and $\mu_\delta = -1.26 \pm 0.76$ mas yr^{-1}. The systemic radial velocity (-50.9 ± 7.0 km s^{-1}) was taken from the analysis of the radial velocity curves.

The *UVW* space velocities were computed by the method of Eggen (1961). The *UVW* velocities were converted to V_π, V_θ, V_z assuming the solar motion of (V_π, V_θ, V_z) = (−9, 232, 7 km s^{-1}) for an object in close proximity to the Sun with (U, V, W) = (0, 0, 0) (Mihalas & Binney 1981). IT Lib's true space velocity was computed to be (V_π, V_θ, V_z) = (-1.6 ± 4.1, 207.0 ± 13.3, -35.9 ± 7.7 km s^{-1}). Errors are difficult to estimate for these velocities because the true error in the distance in unknown. For this analysis, the distance error is assumed to be 30% ($\pm$0.7 kpc), which is reasonable for a photometric distance. V_π are V_θ are consistent with a star within the rotating Galactic disk; V_z and the height above the plane lead to the conclusion that while components of IT Lib's velocity are disk-like, it has been somehow ejected out of the disk into the Galactic halo. Of particular interest is that IT Lib is moving back toward the plane of the Galaxy, presumably traveling on the downhill side of a ballistic trajectory.

The average main-sequence lifetime of a 10 $M_\odot$ star is about 22 million years (Iben 1967). The orbital integrator of Harding et al. (2001) was used to estimate the number of years that have elapsed since IT Lib was last in the Galactic plane ($Z = 0$). By integrating the orbit backward in time, it is found that it took 33 ± 4 million years for IT Lib to travel from $Z = 0$ to its present location. The maximum Z distance that IT Lib reaches from the disk on this trajectory is just over 1.1 kpc. We shall return to this apparent discrepancy after a discussion of the abundance analysis of the primary component.

7. CHEMICAL ABUNDANCE ANALYSIS

The spectrum used for the abundance analysis of IT Lib was taken at phase 0.829 (1999 March 31; see Table 1). According to the model of the system, at this phase both stars are unobscured, so the observed spectra is a straight blend of the light from both components. At this phase, the lines of the primary and secondary component are near maximum separation, making it easier to measure the contribution to the line from each individual component. Equivalent widths of 12 lines identified with the primary component were measured. Because both stars are unobscured at this phase, the continuum contribution from the secondary could easily be removed from the measured equivalent widths. The continuum contribution of the secondary component was removed from the measured equivalent widths by calculating the ratio between the continuum flux of the primary versus the total combined flux of the system (F) and applying this ratio to the equivalent width in this manner:

$$W' = W(1/F).$$

The value of F is calculated for the appropriate bandpass and phase using the Wilson (2001) code ($F = 0.816$ at phase 0.829); W is equivalent width measured from the composite spectra and W' is the rescaled equivalent width used in the abundance analysis.

There were no lines (other than the H I, He I, and Mg II 4481 lines) that could be positively identified and attributed to the secondary. This is not surprising because of a combination of the signal-to-noise ratio of the observation, the rotational broadening of the components, and the fact that the light from the primary component dominates the spectra.

The lines that were measured for the primary component are listed in Table 7 along with the atomic data for those lines.

TABLE 8
ATOMIC LINE DATA

T_{eff}	log (g)	v_{turb}	MEAN ABUNDANCES				
			N II	O II	Al III	Si III	Fe III
Model:							
22,000	4.00	10.0	7.74 ± 0.30	8.79 ± 0.35	5.96 ± 0.37	7.23 ± 0.04	7.58 ± 0.34
22,000	3.75	10.0	7.67 ± 0.30	8.65 ± 0.34	5.90 ± 0.36	7.10 ± 0.04	7.49 ± 0.34
22,000	3.50	10.0	7.63 ± 0.30	8.51 ± 0.32	5.86 ± 0.36	6.99 ± 0.04	7.40 ± 0.34
22,000	3.00	9.0	7.65 ± 0.30	8.32 ± 0.30	5.93 ± 0.36	6.89 ± 0.04	7.33 ± 0.34
26,000	4.00	9.0	7.71 ± 0.33	8.30 ± 0.29	6.11 ± 0.36	7.02 ± 0.04	7.43 ± 0.37
24,000	4.00	9.0	7.66 ± 0.31	8.48 ± 0.32	5.96 ± 0.37	7.06 ± 0.04	7.44 ± 0.35
20,000	4.00	10.0	7.98 ± 0.29	9.29 ± 0.37	6.16 ± 0.42	7.60 ± 0.05	7.87 ± 0.32
Average normal B star[a]			7.99 ± 0.33	8.57 ± 0.17	6.32 ± 0.33	7.36 ± 0.18	7.37 ± 0.22
Solar photosphere[b]			7.92 ± 0.06	8.83 ± 0.06	6.47 ± 0.07	7.55 ± 0.05	7.50 ± 0.05

[a] Martin 2003.
[b] Grevesse & Sauval 1998.

The computer program LINES (Sneden 1973; R. E. Luck 2001, private communication) was used to calculate LTE abundances from the equivalent widths for individual lines. The primary broadening mechanism in these stars is the quadratic stark effect, for which this version of LINES uses the method of Cowley (1971). ATLAS9 (Kurucz 1993) was used to build the stellar atmospheric models.

Because the primary is slightly distorted, the gravity varies by a small amount over the surface. The mean surface gravity for the primary component as calculated by the Wilson (2001) code is log (g) = 3.75. The effective temperature of a 9.8 $M_{\odot}$ star is approximately 22,000 K. The temperature/gravity relations of Napiwotzki, Schonberner, & Wenske (1993) obtain the following values for the Strömgren photometry published by Hauck & Mermilliod (1998): $T = 22{,}060$ K, log (g) = 3.62. This agrees well with the parameters obtained from the model of the system.

The microturbulence was determined using the lines of the 4550 Å Si III triplet. The relative gf values of the triplet are well known and the lines cover a range of equivalent widths, making this triplet ideal for determining microturbulence. The microturbulence is calculated from the triplet by finding the value at which each line in the triplet gives the same abundance value so that there is no trend in abundance with respect to equivalent width. The microturbulence found for each model used is listed in Table 8. These are rather typical values for a B star of this temperature under the assumption of LTE.

The results of the analysis over a range of temperatures and gravities are presented in Table 8. The favored model is 22,000 K, log (g) = 3.75. The results for individual lines in the favored model are listed in Table 7. The results using other models over a range of temperatures and gravities are presented to demonstrate how differences in the atmospheric models effect the abundances. For comparison, the solar abundance values (Grevesse & Sauval 1998) and the average abundance values for a sample of Population I B stars (Martin 2003) are given. The sample of Population I B stars are 12 stars situated in the Galactic plane covering the range of atmospheric parameters representative of B stars. The abundances in these stars were analyzed in the same manner as IT Lib. The abundances of the primary component are consistent with those for a normal Population I B star over the entire range of temperatures and gravities explored. N II and Al III are a bit depressed; however, when the errors in the analysis are considered, these anomalies are negligible.

8. DISCUSSION

8.1. Main-Sequence Lifetime versus Travel Time

The discrepancy between the main-sequence lifetime of the primary component (22 Myr) and the travel time back to the disk (33 Myr) may present a conundrum. Three possibilities exist to resolve the apparent conflict of facts: the travel time and main-sequence lifetime are not in conflict when all possible systematic errors are considered, the A component of the IT Lib system is somehow enjoying a prolonged main-sequence lifetime as a result of mass transfer or other method of rejuvenation, or the IT Lib system did not form in the Galactic disk.

The error budget for calculating the orbit of IT Lib does not allow for the possibility that IT Lib was in the Galactic plane 22 million years ago or less. Each component of the true space velocity is the sum of a term including the radial velocity and a term with a linear dependence on the distance to the star. The radial velocity term is well determined compared to the second term, which is perturbed by the error in the proper motion and multiplied by the uncertainty in the distance. Recall that the error in the distance is unknown, so in the Monte Carlo error simulation a distance error of 30% was assumed. A change in the distance would effect the U, V, and W velocities in a linear manner by −4.9, 1.6, and −9.2 km s^{-1} kpc^{-1}. If IT Lib is farther away, then it takes even longer for it to journey from the Galactic plane to its present location, so we are only concerned with the possibility that the distance has been overestimated. Because of the way that the velocity vector of IT Lib is oriented with respect to the plane of the sky, a large change in distance does not have a significant effect on the velocity vector of the star. If the distance to IT Lib is taken to be only 1 kpc, then it still takes about 28 million years to return to the Galactic plane. The likelihood is that there is not enough room in the error budget of the true velocity to put IT Lib in the plane any sooner than 28 million years ago.

The Galactic potential model and integrator used to calculate the trajectory of IT Lib are described in detail in Harding et al. (2001). This model contains disk, halo, bulge, and dark halo components, which are able to reproduce the observed motions of stars in both the disk and the halo under the most rigorous testing. The model assumes a smooth distribution of matter in the Galactic disk, which is a good approximation for our purposes since the gravitational influence of inhomogeneities in the disk becomes significant only within a few hundred parsecs of the Galactic plane. Stars on orbits that take them kiloparsecs out of the plane spend very little of their time that close, so for all intents and purposes the potential they experience is not significantly perturbed from the smooth approximation. It is reasonable to assume that this is a robust model that does not significantly contribute to the errors associated with the travel time back to the disk.

There is probably more uncertainty in the main-sequence lifetime of the primary component than in the travel time back to the disk. The main-sequence lifetime of a star is a simple relation between the luminosity of the star and the amount of hydrogen available to undergo fusion in the core. Mixing (by rotation, convection, or other means) can lengthen the main-sequence lifetime of a star by increasing the amount of hydrogen available for burning in the core. Modeling the evolution of massive stars becomes a complicated problem requiring the accounting of many processes, some of which are known only to an order of magnitude (Heger, Langer, & Woosley 2000). Talon et al. (1997) demonstrated that, for a model of a 9 $M_\odot$ star, the time to hydrogen depletion in the core can vary as much as 4 million years just by including or excluding convective overshooting from the model. Stellar rotation also influences mixing. Heger & Langer (2000) calculated that a 10 $M_\odot$ star rotating at 200 km s^{-1} has a main-sequence lifetime of 25 million years versus only 19 million years for the same model without rotation. In the IT Lib system, there is the additional consideration of the mixing effects that may be induced in one component through tidal interaction with the other component. It is difficult to estimate the effect of all these factors on the main-sequence lifetime of IT Lib A, but it seems reasonable to assume that the main-sequence lifetime falls in the range from 22 to 32 million years.

Taking all factors into account, it would be reasonable to say that IT Lib was formed in the Galactic disk just over 30 million years ago and that the primary component is still on the hydrogen-burning main sequence. When the uncertainty in the main-sequence lifetime of a 10 $M_\odot$ star in a close binary system is combined with uncertainty in the travel time back to the disk, this becomes a plausible explanation for IT Lib.

8.2. Ejection from the Disk and Rejuvenation through Mass Transfer

Hoogerwerf, de Bruijue, & de Zeeuw (2001) cite two mechanisms that are thought to produce a majority of runaway O- and B-type stars: the binary-supernova scenario (BSS) and the dynamical ejection scenario (DES). Stars ejected by the DES mechanism should not show any discrepancy between their actual and apparent ages. The problem remains of how one might eject a binary star system from the disk. While ejection scenarios may favor single stars, it still is possible, however unlikely it may be, that close binaries could also be ejected. IT Lib is a unique system and may well be one of those rare binaries that undergo DES ejection.

Stars ejected from the disk by BSS once had a close companion, which exploded in a supernova. When the shell from the explosion passes the secondary, the system becomes unbound and the companion flies off with a velocity comparable to its original orbital velocity. Because mass transfer would occur in such a system prior to and as a result of the supernova explosion, the ejected companion is “rejuvenated.” Hoogerwerf et al. (2001) show by tracing BSS candidates back to their star cluster of origin that runaways produced by BSS are probably blue stragglers, appearing younger than they really are. If IT Lib were ejected by BSS, then it would have probably originated in a ternary system with the current components orbiting the more massive supernova progenitor at a distance greater than the distance between the remaining components. The mass transfer from the supernova progenitor to the remaining components could possibly explain the discrepancy between their main-sequence lifetimes and travel time back to the disk.

There is probably not any appreciable mass transfer occurring in the system now because the model shows that it is fully detached and there are no spectral emission features (particularly Hα) that could be associated with a mass stream or accretion disk. It is probable that a mass-transfer event large enough to influence the evolution of either component in the system would manifest itself as photospheric abundance anomalies. In order to move enough mass to have a significant impact, one would have to dredge deep enough to involve processed material in the mass transfer that would end up in the outer layers of the component receiving the transfer.

8.3. In Situ Halo Star Formation

Another possibility is that the IT Lib system did not form in the Galactic disk at all. The apex of the trajectory followed by IT Lib occurred 10 million years ago at a height of 1.1 kpc. Assuming that IT Lib formed in a high-velocity cloud (HVC) or intermediate-velocity cloud (IVC) at that time there would be no conflict between the main-sequence lifetime of the primary and the travel time from its position at birth to its current location. The motions of molecular clouds are influenced by magnetic and hydrodynamic forces that do not affect the motions of individual stars (Binney & Merrifield 1998). As a result, it seems possible to form a close binary pair and drop it out of a cloud on a trajectory toward the disk without invoking any binary star ejection mechanism.

Van Woerden (1993) and Christodoulou, Tohline, & Keenan (1997) report that the conditions thought to exist in HVCs are conducive to the formation of individual massive stars. Even though the conditions appear to exist in the HVCs for star formation to theoretically occur, no observational evidence of star formation in these clouds has been found (Willman et al. 2002; Ivenzic & Christodoulou 1997; Hambly et al. 1996[3]). Star formation apparently is occurring under what are thought to be similar environmental conditions in the H I bridge between the LMC and SMC (Christodoulou et al. 1997). Comerón et al. (2001) report signs of star formation occurring in the halo of the edge-on spiral galaxy NGC 253, which they conclude shows that it is possible for star formation to currently be occurring in the HVCs of the Milky Way. While the absence of evidence is not evidence of absence, it would be easier to accept the scenario of IT Lib forming in an HVC or IVC if there was other, more compelling, evidence. Because of uncertainties in the distances and trajectories of the IVCs and HVCs, it is not possible to determine if any known HVC or IVC clouds intersected the orbit of IT Lib at any time in the past.

8.4. Evidence from Abundances

The results of the abundance analysis could provide additional information that would favor one scenario over another. If IT Lib were rejuvenated and ejected in a BSS ejection, then it is expected that the elemental abundances observed in the photospheres of the components should be enhanced, particularly those abundances of helium and nitrogen (Hoogerwerf et al. 2001; Heger & Langer 2000). Likewise, if IT Lib had undergone mass transfer between components in its past, then the abundances might reflect this activity. If IT Lib were formed in an HVC or IVC, we would expect the abundances of the components to be compatible with those observed by Wakker (2001) for those clouds.

The analysis of the lines associated with the primary component of IT Lib show abundances that are in line with those expected for a Population I B star found in the Galactic disk. Nitrogen does not appear to be significantly enhanced, as would be expected in the BSS scenario. There are no other obvious abundance anomalies, as would be expected if processed material had been accreted onto the primary. Even if the atmospheric parameters of the primary are varied over a range of gravities and temperatures, the derived photospheric abundances are consistent with what would be expected for a "normal" Population I B star found in the Galactic disk. The abundances of the primary do not lend weight to any of the scenarios involving rejuvenation of the system through mass transfer, nor does IT Lib A appear to be markedly metal poor, as might be expected from a star formed in an HVC or IVC in the Galactic halo.

8.5. Conclusion

There does seem to be enough evidence to suggest that there is actually no discrepancy between the main-sequence lifetime of the primary and the travel time back to the disk. When accounting for possible errors, particularly those associated with the main-sequence lifetime of a massive star, it becomes evident that there is probably no discrepancy at all. It seems most likely that IT Lib is a pair of Population I B stars that were ejected from the star-forming regions of the Galactic disk by DES about 30 million years ago.

It is important to recognize that conclusions reached about the IT Lib system do not automatically apply to any other high Galactic latitude B stars. The careful analysis of full space velocities (radial velocities and proper motions) using a comprehensive model of the Galactic potential will help identify more Population I B stars that have been ejected from the disk. The reasons to study a sample of normal Population I B stars at large distances may not be obvious, when their nearby cousins are easier to study at high precision. Population I B stars that have been ejected from the disk have a lower limit set on their ages by the analysis of their trajectory, constraining their ages better than their disk-bound counterparts. As a result, these stars might be used to start to piece together an observational picture of the evolution of high-mass B stars on the main sequence. This would be of great benefit to those who model these stars and may help enhance our understanding of stellar energy generation and energy transport processes in general.

I wish to acknowledge R. Earle Luck for his continued assistance and support. I also wish to acknowledge John Feldmeier and Chris Mihos for their efforts obtaining photometric observations of IT Lib and John Feldmeier for useful conversations concerning this research and reducing the 2.1 m data. Finally, I want to thank the anonymous referee for the time and effort he/she gave to contribute many insightful comments and suggestions that had a positive impact on this paper. This work was supported in part by the Jason J. Nassau Scholarship Fund and the Townsend Fund.

[3] Also presented at ASP Conference 92.

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