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CALIBRATION OF STELLAR PARAMETERS OF 85 PEG SYSTEM

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ABSTRACT

We have investigated the evolutionary status of 85 Peg within the framework of standard evolutionary theory. 85 Peg has been known to be a visual and spectroscopic binary system in the solar neighborhood. In spite of the accurate information of the total mass ($\sim 1.5 M_{\odot}$) and the distance (~12pc) from the *HIPPARCOS* parallax, it has been undetermined an individual mass, therefore the evolved status of the system. Moreover, the coupled uncertainties of chemical composition and age, make matters worse in predicting an evolutionary status of the system. Nevertheless, we computed the various possible models for 85 Peg, and then calibrated stellar parameters by adjusting to the recent observational data. Our modelling computation has included recently updated input physics and stellar theory such as opacity, equation of state, and chemical diffusion. Through a statistical assessment, we have derived a confident parameter set as the best solution which minimized χ^2 within the observational error domain. Most of all, we found that 85 Peg is not a binary system but a triple system with an unseen companion 85 Peg B_b $\sim 0.16 M_{\odot}$. The aim of the present paper is (1) to provide a complete modelling of the stellar system based on the evolutionary theory, and (2) to constrain the physical dimensions such as mass, metallicity and age.

Keywords: stars, stellar evolution, stellar atmosphere, visual binaries, spectroscopic binaries, 85 Peg

1. INTRODUCTION

85 Peg (HD224930) is a bright visual and single-lined spectroscopic binary system. It is one of the most interesting binary systems because 85 Peg has been known to be metal-poor old population in the solar neighborhood. Since it was discovered by Burham (1879), there has been numerous studies on : orbital elements from astrometry (Söderhjelm 1999), physical parameters (Griffin 2004, Van't Veer 2005), stellar evolutionary status (Perrin et al. 1977, Fernandes et al. 2002), presence of an unseen tertiary (Hall 1948, Fernandes et al. 2002), and asteroseismic oscillation (D'Antona et al. 2005). Over more than a century, the dynamical data for 85 Peg has been collected. Recently, the determination of parallax has been improved by the the *HIPPARCOS* (Söderhjelm 1999). The main updated dynamical parameters are collected in Table 1.

Although 85 Peg has well-defined brightness ($M_V \sim 5.75$), distance ($\sim$ 12pc), orbital period ($\sim$ 26yr), and total mass ($m_{tot} \sim 1.49 M_{\odot}$) from the *HIPPARCOS* parallax, its small angular separation

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Table 1. Orbital elements and astrometric data of 85 Peg from the *HIPPARCOS* parallex. (Söderhjelm 1999, Griffin 2004). P is the orbital period, a the semi-major axis, i the inclination, e eccentricity, π parallax, γ the radial velocity, K_1 the half-amplitude of the radial velocity of the primary component, $a_1 \sin i$ the semi-major axis of the relative orbit, and M_{tot} the total mass of the system.

parameters	values
P (yr)	26.31 ± 0.01
a	$0''.83 \pm 0''.01$
i	$-49° \pm 1°$
e	0.38 ± 0.01
π (mas)	0.0796 ± 0.003
γ (km s^{-1})	-36.22 ± 0.03
K_1 (km s^{-1})	4.49 ± 0.05
a_1 sin$i$ (au)	3.68 ± 0.04
$M_{tot}/M_\odot$	1.49 ± 0.1

($a \sim 0.83$ arcsec) and magnitude difference ($\Delta M_V \sim 3.08$) make it difficult to determine the accurate individual mass of each component. Indeed, there has been a discrepancy between the mass ratios derived from photometry and spectroscopy with respectively. From the photometric magnitude differences, the reduced mass ($\mu = m_2/(m_1 + m_2)$) is determined $\mu \sim 0.38$, which means that the bright primary is more massive than the secondary. From spectroscopic analysis, however, it is confirmed to be $\mu \sim 0.48$ (Griffin 2004). It implies that the mass of the faint secondary is nearly equal to the primary component. For this mass ratio problem, one of the reasonable explanation is that 85 Peg is a triple system with a hidden mass, 85 Peg B_b.

On the other hand, 85 Peg is an important object especially in chemical evolutionary history. In earlier studies on the solar neighborhood (Perrin et al. 1977), 85 Peg was known to have very low helium content. The determination of helium abundance is one of the most important problems in stellar evolution. Nevertheless, it is impossible to detect the helium abundance directly from stellar spectra. Therefore, it is inevitable to depend on theoretical modelling in order to describe the detailed interior structure and its evolved status. The purpose of present paper is to provide a consistent modelling of the stellar system based on the evolutionary theory and to constrain the physical characteristics such as mass, chemical composition and age. Most of all, the ultimate goal of this research is to obtain the starting model for three dimensional radiation-hydrodynamic convection simulation.

2. MODELLING

2.1 Opacity, Equation of State, and Mixture

We have computed stellar models by using the YREC stellar evolution code which was developed in Yale university. We have modified the YREC code for the relevant computation with recently updated input physics, such as opacities, equation of state, and mixture. We adopted OPAL Equation of state (updated in 2005), OPAL opacity (updated in 2001, Iglesias & Rogers 1996), and Alexander & Ferguson low temperature opacity table (updated in 2006, Alexander & Ferguson 1994, Ferguson et al. 2005). Indeed, two opacity sets are in a good agreement where these overlaps. The heavy elements composition of 85 Peg was assumed to be of the well-known solar scaled mixture with

Table 2. Spectrophotometric data of 85 Peg for reference coding (Van't Veer 2005, Griffin 2004).

Parameter	85 Peg A	85 Peg B
T_{eff}(K)	5600±50	4200±200
M_V	5.39±0.04	8.47±0.29
$L/L_\odot$	0.617±0.02	0.072±0.03
[M/H]	-0.7±0.1	
log$g$	4.6±0.1	

$(Z/X)_\odot \sim 0.02292$ (Grevesse & Sauval 1998). For the solar scaled mixture, the metallicity [M/H] was given by:

$$[\mathrm{M/H}] = \log[Z/X] - \log[Z/X]_\odot$$

In the case of metal-poor and late-type stars, because Fe I lines can be over-ionized by UV radiation, [Fe/H] values are underestimated. Therefore, non-LTE effect plays an important role in stellar atmosphere. We adopted NLTE correction $[\mathrm{Fe/H}]_{\mathrm{NLTE}} \sim [\mathrm{Fe/H}]_{\mathrm{LTE}} + 0.15$ dex for 85 Peg system (Thévenin & Idiart 1999). In our computation, convection was treated with the mixing length parameter according to Böhm-Vitense (1958). We considered mixing length parameter α_{MLT} as a free parameter. In our standard solar model, mixing length parameter is $\alpha_\odot \sim 1.83$ at age 4.55 Gyr.

2.2 Diffusion

We have fully considered chemical diffusion caused by gravitational settlement and thermal diffusion. Helium diffusion theory has been well established from solar atmosphere, and it has played an essential part of stellar astrophysics. Metal diffusion, however, has been somewhat controversial. In fact, diffusion process of heavy elements is still uncertain not only in the effect but also in the sign (Gratton, Sneden, & Carretta 2004). For a metal-poor low mass star having convective envelopes, a slight variation of heavy elements can change significantly its surface constituents during their MS life times. Therefore, we have considered metal diffusion as a standard prescription (Thoul, Bahcall, & Loeb 1994) as well as helium diffusion.

3. CALIBRATION OF STELLAR PARAMETERS

A stellar model can be constructed from a set of initial values, called modelling parameters $(m, Z/X, Y, \alpha_{MLT}, t)$, m is stellar mass, Z/X is metallicity, X is hydrogen mass fraction, Z is mass fraction of metal, Y is helium mass fraction, α_{MLT} is mixing length ratio as a parameter represent to convective efficiency, and t is age. Calibration of a stellar system is to determine the modelling parameters such that fundamental properties at its age satisfy observation. Generally, standard stellar evolutionary theories are based on single stars. For a widely separated binary system, the standard evolutionary theory can be applied separately. For 85 Peg, its separation and subdwarf status can guarantee independent evolution. If there is no interference, a binary system can be supposed reasonably to have the same age and the identical initial chemical composition. Therefore, for a binary system, the modelling parameter set composed to be

$$(m_A, m_B, Z/X, Y, \alpha_A, \alpha_B, t).$$

Table 3. Calibrated parameters and fundamental properties of 85 Peg as a triple system.

	85 Peg A	85 Peg B	85 Peg B_b
$M/M_\odot$	0.794±0.01	0.532±0.02	0.164±0.04
Age (Gyr)		8.4 ±0.5	
$(X_0, Z_0; Y_0)$		(0.7555, 0.0045 ; 0.24)	
X_s	0.803	0.774	0.750
Z_s	0.0037	0.0041	0.0045
α_{MLT}	1.4±0.2	1.25±0.4	1.8
T_{eff}(K)	5600	4200	3430
$L/L_\odot$	0.617	0.072	0.004
[M/H]	-0.70	-0.63	-0.58
log$g$	4.50	4.75	5.14

In determination of an evolutionary status, there are many-fold degeneracy between stellar parameters. As an example, we can establish various models that they have the same temperature and luminosity, that is, the same position in the H-R diagram. To alleviate this serious degeneracy, more physical quantities such as metallicity and surface gravity must be included as a function of modelling parameters. We adopted recent observational data (Van't Veer 2005) as reference coding (Table 2). We can write relation between modeling parameters and fundamental parameters:

$$A = A_{ref} + \frac{\Delta A}{\Delta m}\delta m + \frac{\Delta A}{\Delta X}\delta X + \frac{\Delta A}{\Delta Z}\delta Z + \frac{\Delta A}{\Delta \alpha}\delta \alpha$$

where A is fundamental stellar parameters such as luminosity L, effective temperature T_{eff}, metallicity [M/H], and surface gravity log$g$. A_{ref} denotes reference values for iteration. In order to evaluate our stellar models statistically in the observational error, we used the χ^2 minimization method introduced by Lastennet et al. (1999):

$$\chi^2 = \left(\frac{L - L_{obs}}{\sigma(L)}\right)^2 + \left(\frac{T_{eff} - T_{eff,obs}}{\sigma(T_{eff})}\right)^2 + \left(\frac{[\mathrm{M/H}] - [\mathrm{M/H}]_{obs}}{\sigma([\mathrm{M/H}])}\right)^2 + \left(\frac{\log g - \log g_{obs}}{\sigma(\log g)}\right)^2$$

According to Caloi et al. (1999), the age of high velocity star is statistically older than $\sim$ 7Gyr. Because 85 Peg have high velocity with respect to local standard of rest, we have considered $t \geq 7$ as the constraint for the age estimation. In earlier studies, Perrin et al. (1977) found that helium abundance of 85 Peg might be extremely deficient ($Y \sim 0.2$). Furthermore, Fernandes et al. (1998) did not find a main-sequence solution which have solar-like helium abundance. Therefore we have regarded the helium abundance as a free parameter with the constraint $Y \geq Y_p$, where Y_p is the primordial helium abundance.

4. DISCUSSION

We found the initial parameter set which minimized the observational error. With this initial values, the evolutionary status of 85 Peg must be subdwarf status at its age ($t \sim 8.4$ Gyr).

$$(m_A, m_B;\ X_0, Z_0, Y_0;\ \alpha_A, \alpha_B) \sim (0.8M_\odot, 0.53M_\odot;\ 0.7555, 0.0045, 0.24;\ 1.4, 1.25)$$

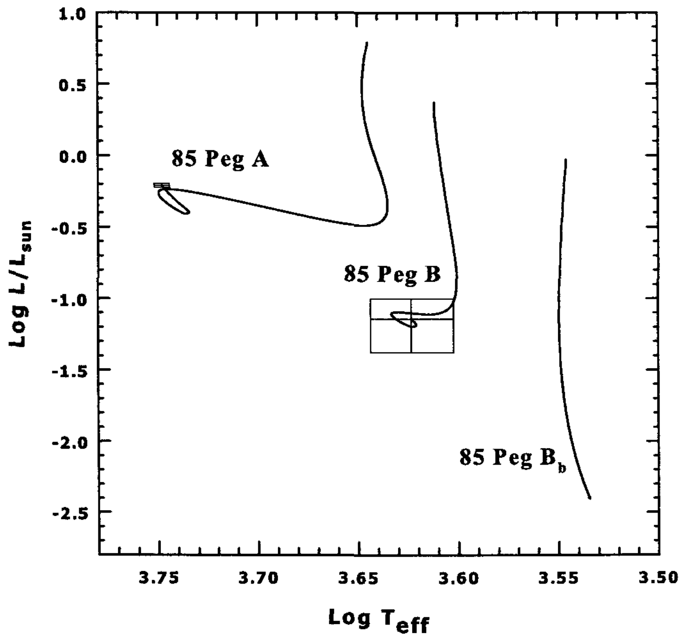

Figure 1. Theoretical evolutionary tracks of 85 Peg triple system in the H-R diagram. All tracks have been computed with the calibrated initial modeling parameters from stellar birth line to its age $t \sim 8.4$ Gyr. 85 Peg A is the primary, 85 Peg B is the secondary, and 85 Peg B_b is the undetected tertiary. Boxes delimit the observational error domains. One of the possible models for 85 Peg B_b was shown.

Table 3 shows the calibrated stellar parameters and fundamental properties of our best fit model. It is noticeable that 85 Peg has nearly primordial helium abundance $Y_0 \sim 0.24$. From its chemical composition and high space velocity, 85 Peg can be thought old population. In our calibration results, the surface gravity ($\log g \sim 4.5$) is subtly different from the *HIPPARCOS* data ($\log g \sim 4.6$). According to Nissen et al. (1997), surface gravities from *HIPPARCOS* were overestimated systematically. Disagreement of surface gravity seems to be a result from NLTE effects. Especially for low mass metal deficient stars, $\log g$ must be corrected with [Fe/H] (Thévenin & Idiart 1999).

Most of all, a difference between an estimated theoretical mass ($m_A \sim 0.8M_\odot, m_B \sim 0.53M_\odot$) and the total mass $m_{tot} \sim 1.5M_\odot$ reveals that there is a hidden mass of about $0.12 \sim 0.2M_\odot$. If this hidden mass is considered as a faint tertiary, mass ratio problem of the system can be explained at the same time. Figure 1 shows the evolutionary tracks in the H-R diagram for the primary, the secondary, and the undetected tertiary respectively. All tracks were computed from protostar to their theoretical age. In Figure 2, the detailed evolutionary tracks of each components are shown. The hypothesis that 85 Peg might be a triple system was suggested by Hall (1948). Recently, a series of studies (Fernandes et al. 2002, D'Antona et al. 2005) has predicted the presence of tertiary. Fundamental parameters of our model for 85 Peg B_b are listed in Table 3. Since low mass main-sequence stars have fully convective envelopes, we assumed that the mixing length ratio of 85 Peg B_b should be larger (~ 1.8) than that of the primary or the secondary. 85 Peg B_b may be an M type subdwarf with

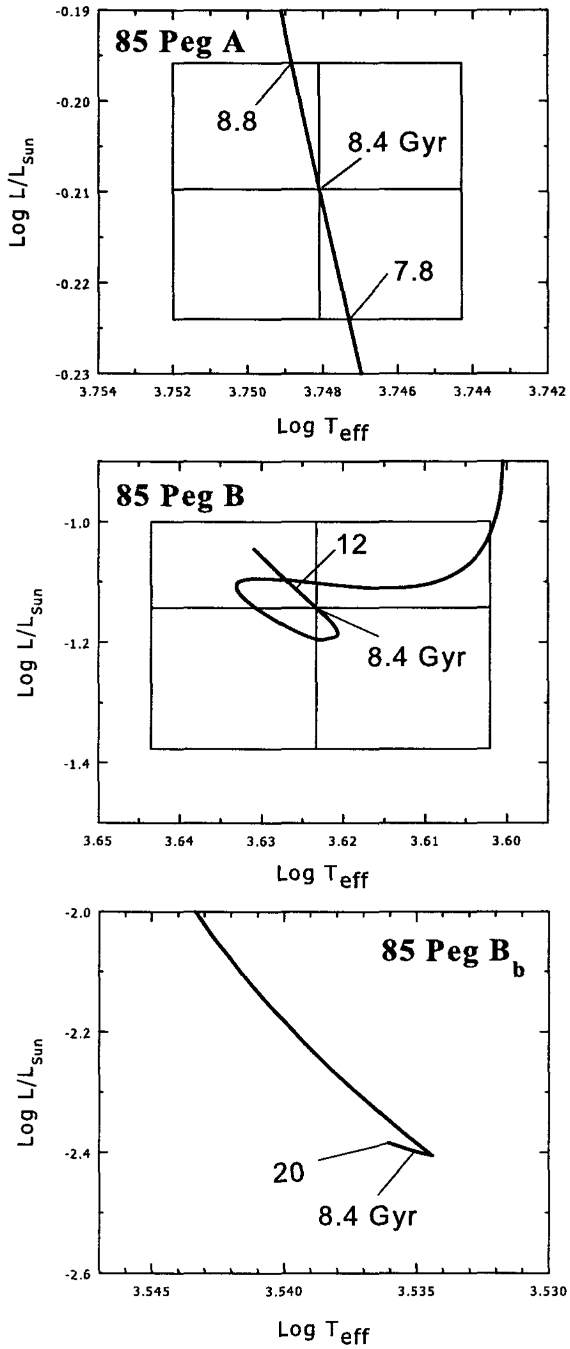

Figure 2. Detailed evolutionary status of an individual component of 85 Peg triple system. Evolutionary tracks of the primary (top), the secondary (middle), and an unseen tertiary (bottom) have been computed with the calibrated parameters.

the luminosity $\sim 0.004L_{\odot}$. Accordingly, 85 Peg B_b is expected not to contribute to the luminosity of the secondary component within the observational uncertainty.

Our mixing length ratio was determined to be somewhat lower value than expected. It seems that a lower α_{MLT} is due to its mixture. For a α-elements enhanced star, its evolution tracks is shifted to right in the H-R diagram. If 85 Peg has the α-elements enhanced mixture, it can be expected that higher α_{MLT} will compensate our fitting result. Moreover, the α-elements enhancement would not affect seriously to age, especially for low mass MS stars (Kim et al. 2002). The detailed abundance analysis will provide the clue of calibration of the mixing-length for low mass stars. From 2D hydrodynamical convection simulations, Ludwig et al. (1999) found that the mixing length ratio α_{MLT} of main-sequence stars decreases with an effective temperature, that is, with a mass. It is noteworthy that there is remarkable disagreement between results from stellar evolution codes and convection simulation. This discrepancy may be due to the variation of convective efficiency with depth and time. The 3D hydrodynamical simulation will provide more detailed information for a surface convection without a help of α_{MLT}.

The calibration of stellar parameters would provide deeper insight into physical processes in stellar systems. If the p-mode oscillation spectrum of 85 Peg is detected from the *MOST*asteroseismic observation, our work will contribute to interpretation of observational data. Moreover, as a metal-poor and helium-deficient old population in the solar neighborhood, 85 Peg must be a valuable tracer of the formation and the evolution of the Galaxy.

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