A CONTACT BINARY SYSTEM IN THE KEPLER FIELD

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ABSTRACT

A CONTACT BINARY SYSTEM IN THE KEPLER FIELD

In this thesis, we carried out the light curve solutions of a contact binary system KIC (Kepler Input Catalog) 7821450 observed by Kepler. Kepler is a spaced-based mission that provides sufficient data about the systems that observed. Observations of the system were gained for 7 times during the 17 quarter. The temperatures of the components differ around 5155K. A detailed study of light curve of the system provides us the ratio of the temperatures and radii of the system. All the minima times of the system KIC 7821450 determined by using parabolic fit method. In this study we will use Phoebe program to analyse the light curve of the system.

ÖZET

KEPLER ALANINDA DEĞEN BİR ÇİFT SİSTEM

Bu tezde, Kepler teleskobu tarafından gözlemlenmiş değen bir çift yıldız olan KIC 7821450 yıldızının ışık eğrisi analizi yapılmıştır. Sistemin ışık değişimi değen bir çift yıldız olduğunu göstermiştir. KIC 7821450 sistemi de 5155 K civarında iki yıldızdan oluşan bir sistemdir. Sistemin detaylı ışık eğrisi analizi yapılarak bu sıcaklık ve kütle oranları tespit edilmesi mümkündür. Sistemin 17 quarter boyunca 7 defa gözlemleri elde edilmiştir. Bu çalışmada değen sistem olan KIC 7821450 sisteminin tüm minimum zamanlar parabolik fit yöntemi ile okundu. Işık eğrisi analizi için Phobe programı kullanılacaktır.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Evolution of Stars

The life of a star is defined as a contraction of unstable gas cloud. When the contraction takes place, the gravitational energy is released and turned into thermal energy. Initially, the gas is not dense that it radiates freely and the temperature cannot get high. As the contraction continues the temperature starts to rise and so does the internal density. The process takes place on the dynamical timescale in which the gas on the surface falls freely inward to the center. This leads to rise in the temperature and also density. At this stage, the containing hydrogen is in molecular phase. When the temperature becomes high enough to dissociate hydrogen atoms, the hydrogen and then the helium will be ionized. In the beginning, the gas was cool to resist gravitational energy, but now it is enough to generate pressure opposite to gravitational pull.

The contraction stops when the hydrogen and helium are totally ionized. The star is then in equilibrium which is called a protostar. The following evolutionary stages take place in the thermal timescale.

The opacity of the star is high at temperature in which it reached equilibrium. This high opacity prevents the radiation of gas and so the core is fully convective.

The evolution of the star will continue along Hayashi track that determines the position of the convective stars in the Hertzsprung-Russell (HR) diagram. Along the Hayashi track in the HR diagram (Figure 1.1) the radius of the star decreases steadily, but the luminosity decreases more rapidly. The temperature of the center continues to rise and the opacity drops. Hence, the energy begins to be transported by radiation and the star becomes radiative. The temperature is then so high that the nuclear reactions take place and luminosity increases .

The stars in the pre-main sequence phase are rare and hard to be detected. Because they are generally prevented by the remnant gas and dust cloud.

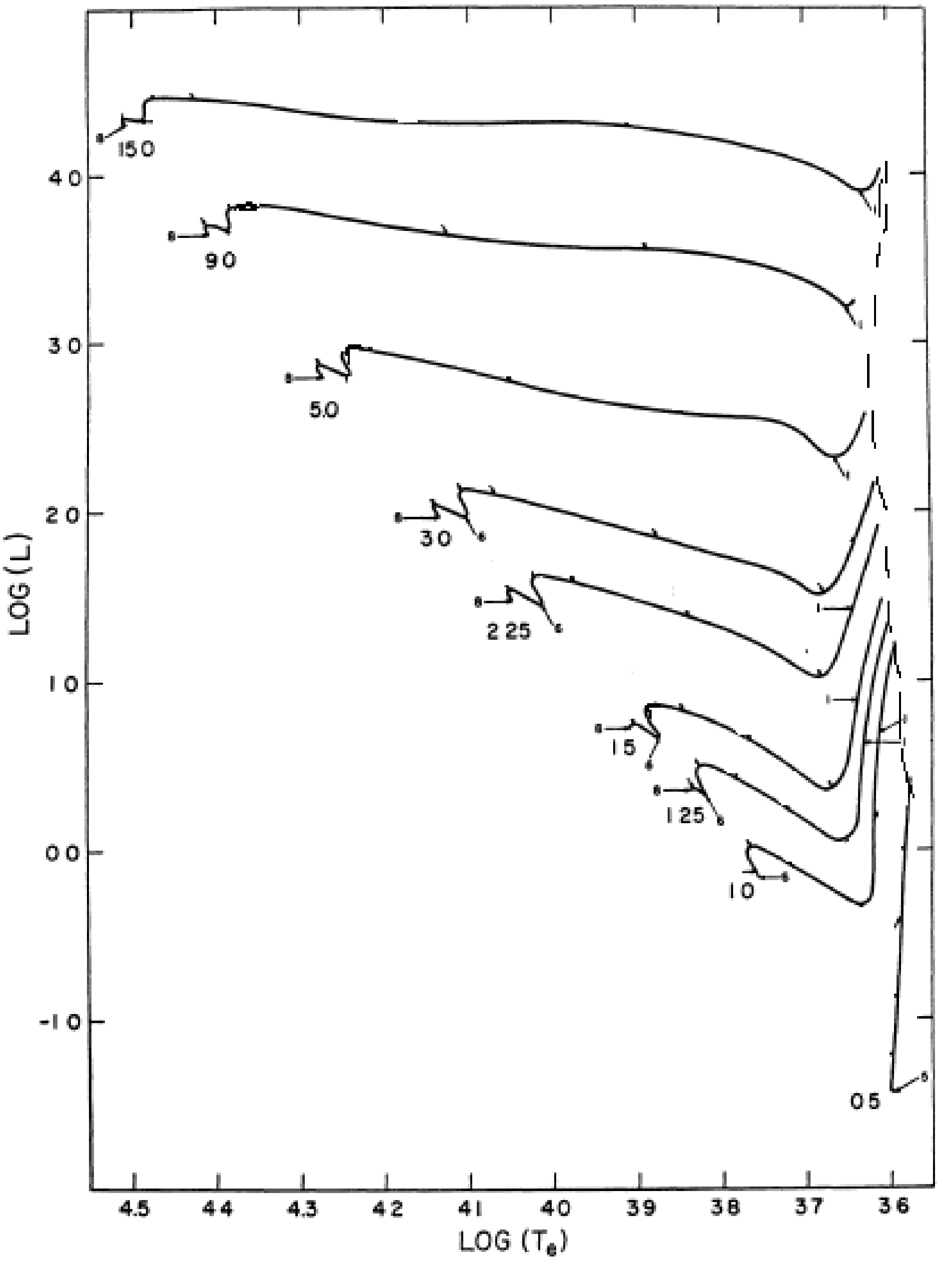

Figure 1.1. Paths in the H-R diagram of star contracting to the main sequence. [1]

1.1.1. The Main Sequence Phase

The main sequence phase is the evolutionary stage of a star where the star produce its energy from hydrogen burning in the core. This phase takes place in the nuclear timescale in which a star radiates all energy by burning hydrogen into helium. This is the longest stage of the evolution of a star and differs according to the masses of the stars. the massive stars radiate their energy so quickly that they spend less time in the main sequence phase. However, the low mass stars have longer main sequence lifetime. For example, the nuclear timescale of the Sun is 10^{10} years, but it is 2 million years for a star with mass $30M_{\odot}$ [2].

The massive stars are placed on the upper part of the main sequence in the Hertzsprung-Russell (H-R) diagram. The temperature of their centre are too high that they produce vast quantities of energy by burning hydrogen into helium by CNO cycle. Their core is convective that the energy is no longer transferred by radiation. The energy is transferred by material motion. Outside the convective core, the energy is carried by radiation and no nuclear reactions occur and this region is called *radiative envelope*.

The lower main sequence stars are less massive stars that energy is produced by proton-proton reaction. The temperature is not so high then, the core never becomes convective and remains radiative. Thus, the energy is carried by radiation. In the outer parts of the stars, the opacity is high due to the low temperature. Here, the radiation can no longer takes place that it becomes convective. The hydrogen is consumed in the core so rapidly that the amount of hydrogen in the core decreases. The structure of the upper main sequence stars and the lower main sequence stars are opposite. In the upper main sequence stars the core is convective and the envelope is radiative. The lower main sequence stars, on the other hand have radiative core and convective envelope.

The star will move upward direction through the main sequence in the H-R diagram (Figure1.2) when the hydrogen amount decreases. The star becomes hotter and brighter with a small change in radius. When the hydrogen in the core comes to end, the star will take a path to the right. Finally, it has a pure helium core with a hydrogen shell.

The stars with masses between $0.08M_{\odot}$ and $0.26M_{\odot}$ evolve slowly upward in main sequence. They have enough hydrogen to produce required energy. After the hydrogen comes to the end, there will be a pure helium core. Finally, the hydrogen is exhausted and they become a white dwarf.

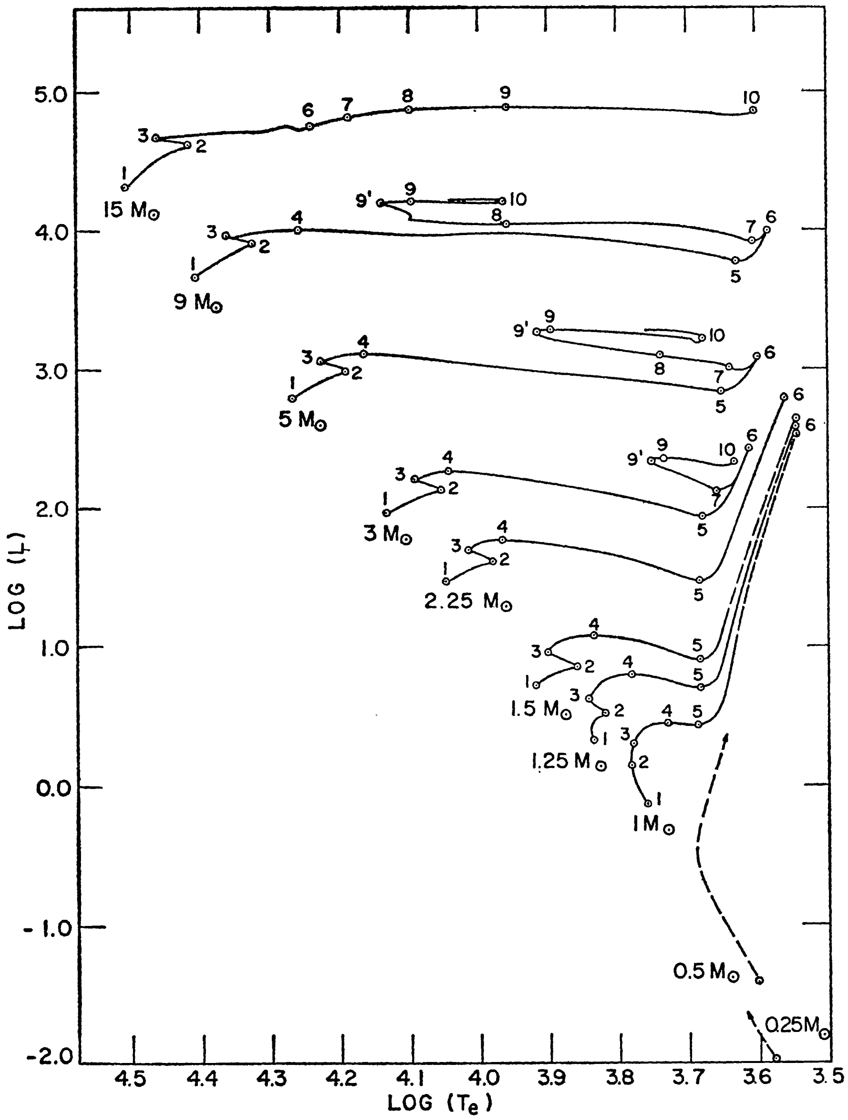

Figure 1.2. The evolutionary path of the different mass stars in the H-R diagram. [3]

1.1.2. The Giant Phase

The giant phase starts when the star exhausted its whole hydrogen by burning into the helium. Now the star has a helium core with hydrogen envelope. The helium concentration of the core corresponds to increase in the mass of the star. The increase in mass leads the expansion of the envelope. Because of this, star moves horizontally right in the HR diagram. However, it cannot pass the Hayashi track and move upward along the Hayashi track through higher luminosities. Then the star becomes a *red giant*.

As the mass increases in low-mass stars where M$\leq$ $0.23M_\odot$, then the density becomes so high that the star becomes degenerate and the central temperature continues to rise. If the mass of the star is high enough to have about 100 million degrees central temperature, the energy will be produced by burning helium into the carbon in the triple alpha chain. This helium burning causes sudden rise in the temperature of the core. After the degeneracy of the core is removed, the core begins to expand violently. A few seconds after the helium burning, the explosion occurs which is called *helium flash*. Thus, the star is positioned a new stage where helium is burning to carbon in nondegenerate core.

The following evolutionary stage after helium burning depends on the mass of the star. Because the mass determines how the temperature can become high and the degeneracy of the star as the heavier fuels are ignited. If the star used its helium in the core, the helium in the shell will still be burned. The star will move toward the lower temperature but higher luminosity in the HR diagram which is called the asymptotic giant phase.

The asymptotic giant phase comes to end when the radiation pressure has forced to remove of the outer layer and the remaining is a planetary nebula. In low or intermediate mass stars, the central temperature never gets so high in which the carbon cannot be burned, and they become carbon-oxygen white dwarf.

In massive stars with mass about $10M_\odot$, there may be oxygen or carbon flash that is similar to helium flash in low-mass stars but more powerful one. This leads the star to have a supernova explosion or may be cause the destruction of the star.

In more massive stars which have mass M $\geq 15M_\odot$, the core is convective and the carbon is burning into oxygen and silicon in sequence. This burning process goes on to an iron core. If the fuel is exhausted in the core, the nuclear reactions continue in the shells. After the explosion of the outer layer, the remaining core contracts as a black hole or a neutron star.

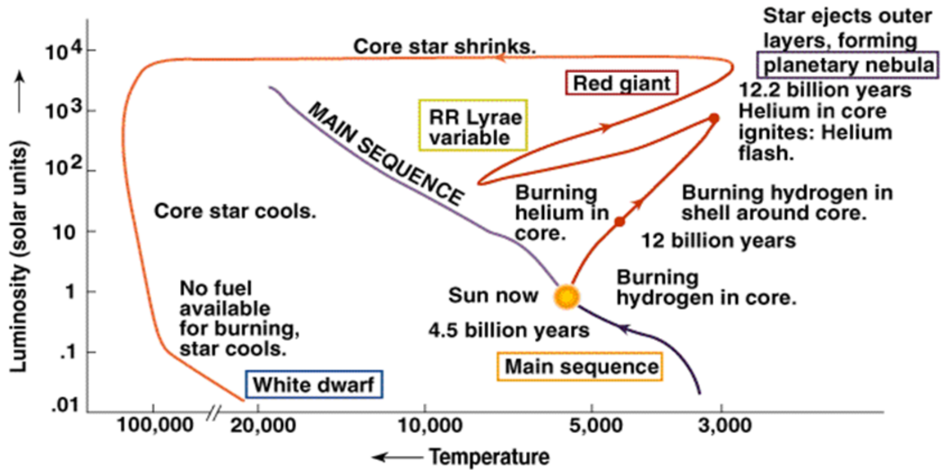

Figure 1.3. The evolutionary path of a low-mass star like our Sun in the H-R diagram. [4]

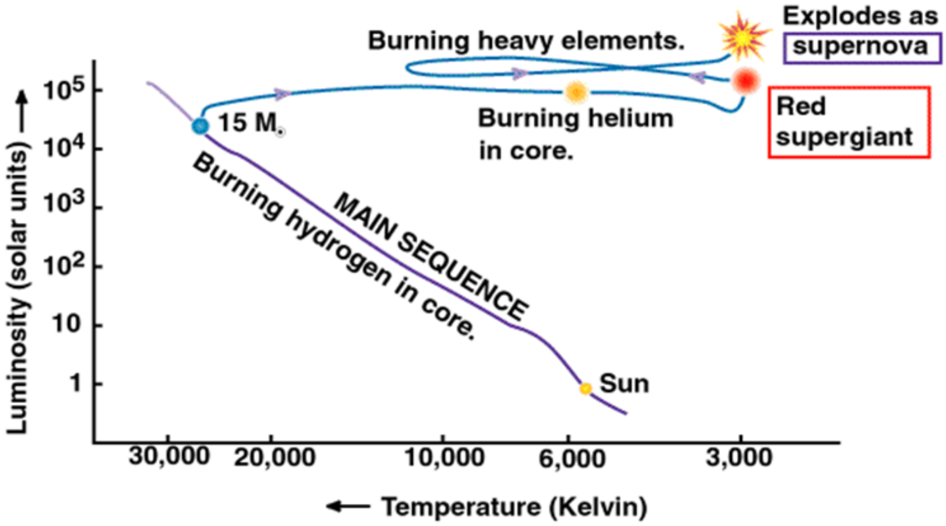

Figure 1.4. The evolutionary path of a high-mass star the H-R diagram. [4]

CHAPTER 2

BINARY STARS AND KEPLER MISSION

2.1. Binary Stars

Binary star is a system consisting of two stars that orbit around a common center of mass under the influence of their gravitational attraction. Most of the observed stars in the sky belong to a binary or a multiple system (i.e. a system with three o even more components). Among these stars the frequency of the observation is more than %50 for B-type and approximately %90 of F and G type stars [5, 6]. The prevalence of binary systems allows us to infer physical properties of the stars.

From the observable results of stars such as blackbody radiation, parallax, spectra *etc*. one can determine the surface temperature, luminosity and other physical parameters of them. The mass of a star, on the other hand, can be directly obtained by studying the gravitational interaction with other objects by using Kepler's 3rd Law. The initial mass of a star is the most important parameter that determines the fate of a star. Knowledge about the mass and other parameters provides important information about the structure and stellar evolution of stars. In addition, observing binary star systems astrophysicists can study single and binary star evolution and test modern stellar formation and evolution theories [7] .

Binaries can be classified into different groups [2, 7] according to their Roche geometries, determination methods and light curves. Based on their determination methods binary stars can be studied into five different sub-groups. In ***Apparent binaries*** the two stars appear to be close to each other while they are not gravitationally connected; hence these binaries are not *'real'* binary systems. One of the component in a binary system might be fainter than its component, which makes it difficult to detect. Sirius was an excellent example of this type of binary system that is called ***astrometric binary***. The variation in proper motion that could be explained by an unseen component in the system revealed that Sirius is not a single but a binary star system. Indeed the unseen component in the system, the Sirius B was discovered to be a white dwarf in 1915. Almost a century later, in 2005 by using the Hubble Space Telescope (HST) astrophysicists could determine the radius and the mass of the white dwarf Sirius B.

Figure 2.1. Hubble Space Telescope image of Sirus A and Sirius B. [8]

In ***visual binaries***, on the other hand, the duplicity of the star can be detected when the system is observed in a telescope. Components of the system orbit around the common center of mass with periods that can vary from one year to thousand years. After the faint companion of Sirius discovered in 1862, it is now classified as a visual binary. If the distance to the binary is known, then the orbital separation can be found which leads to determine the total mass of the binary.

If the duplicity of a star cannot be understood in a powerful telescope, but only from its spectrum, it is now a ***spectroscopic binary***. In spectroscopic binaries, the star is detected as a single star but the lines in the spectrum are shifting due to the Doppler affect resulting back-and-forth motion that can be explained if the star has component. Doppler shifts of one or both components can be measured; these systems are classified single-lined and double-lined spectroscopic binaries, respectively (Figure 2.4). In single-line spectroscopic binaries, one of the components is so faint that the spectroscopic properties cannot be detected. In double-line spectroscopic binaries, the luminosities of the components are nearly the same that we obtain two oppositely oscillating spectral lines. The mass ratio of the binaries can be calculated directly from the double-line spectroscopic binaries. The radial velocity of the star can be directly calculated from the Doppler formula and if we plot radial velocity as a function of time, we obtain the velocity curve. From the radial velocity curve the orbit of the star can be determined.

Another group of binary stars is ***eclipsing binary***. The orbital plane of the binary lies close to the line of sight then the components of the star are seen as they eclipse one-

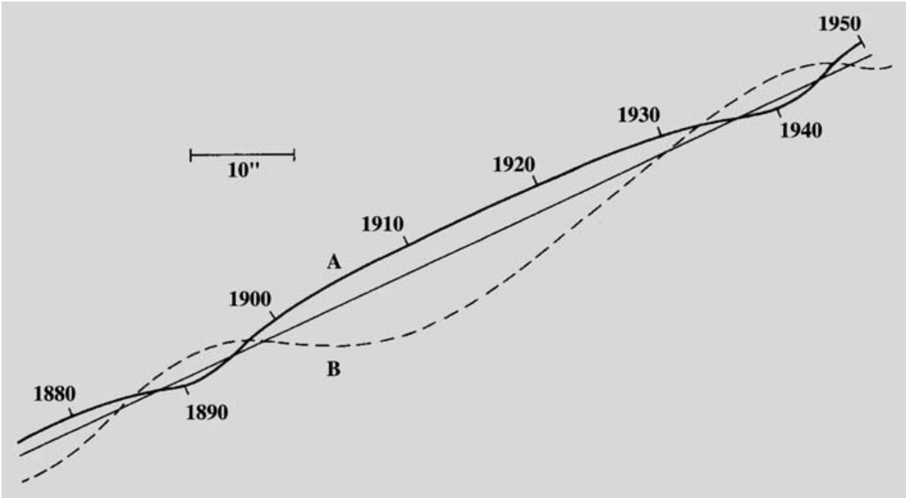

Figure 2.2. The apparent path of Sirius and its companion. [2]

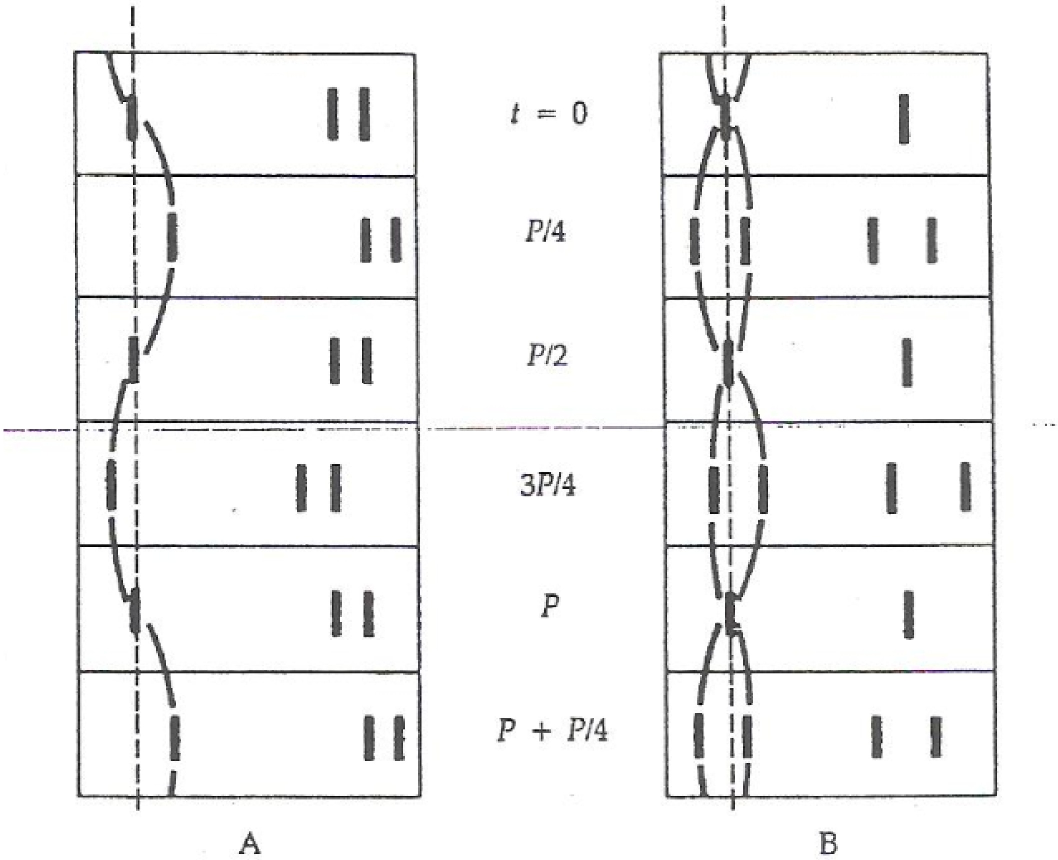

Figure 2.3. Spectra of spectroscopic binaries (A) A single-line system. (B) A double-line system. [9]

another. At the eclipse time one component passing over the other will cause a decrease (minimum) in light of the star behind. The variation in light as a function of time gives the light curve of the binary. If the hotter but smaller one (primary) is eclipsed by the fainter component (secondary), there will be a deep minimum in the light curve, otherwise, the minimum will be shallow. The study of the light curve with additional data provides a plenty of information about the mass, shape, luminosity of the star and the types of eclipsing binaries. There are three types of eclipsing binaries; Algol type, β Lyrae Type, and W Ursae Majoris.

2.1.1. Algol Type

In Algol stars, the total magnitude is nearly constant during the period. There are two different minima in the light curve one of them is deeper than the other. The shape of the minima exhibits if the eclipse is total or partial. In total eclipse, one component will be totally invisible during the period and the minimum is flat. In partial eclipse, the component will not be completely invisible which is seen as a smoothly decreasing light in the light curve. Thus, the shape of the minima gives information of the type of the eclipse which corresponds to the inclination of the orbit.

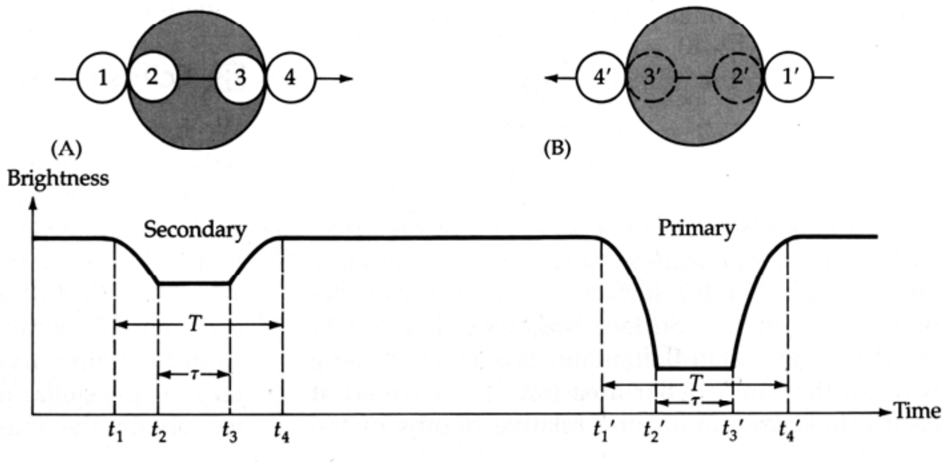

Figure 2.4. The total eclipse for circular orbits. The four numbered contact point define the duration of the eclipse. (A) The smaller star passes in front of the larger one. (B) The smaller star is behind the larger one. [9]

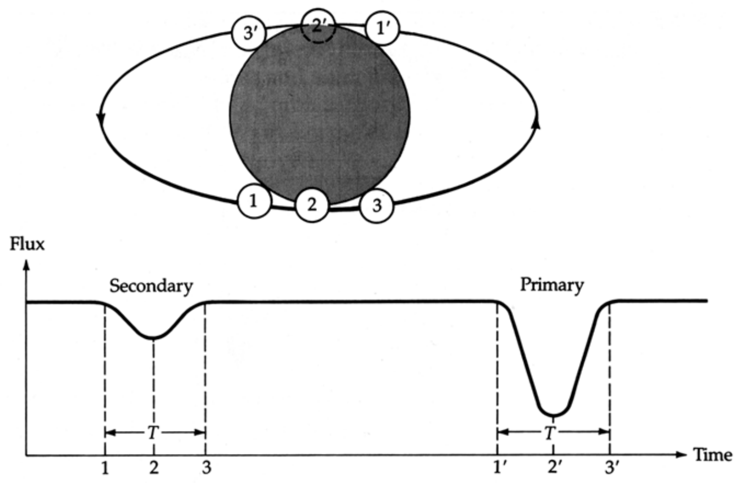

Figure 2.5. The partial eclipse. The smaller star is assumed to be the hotter. [9]

2.1.2. β Lyrae Type

If one of the stars fills its Roche Lobe and the gravitational pull causes the mass transfer from large component to the other across the inner Lagrange point then it is called semi-detached or β Lyrae . The total magnitude The results of the mass transfer are shown in the light curve.

2.1.3. W Ursae Majoris

In W Ursa Majoris type binaries, also called contact binary, the shapes of the minima are nearly the same that are wide and round. Both stars in this system fills their Roche Lobes.

The classification of the eclipsing binaries depend their light curves. However, for a sufficient classification it is also necessary to look their Roche lobe geometry. According to their Roche geometry [11], they are grouped as *'detached'*, *'semi-detached'* and *'contact'* binaries. If neither of the components fill the Roche lobes then it is **detached**. When one of the components fills its Roche lobe and the gravitational attraction causes the mass transfer, the binary is called **semi-detached**. In **contact** binaries both stars fill their Roche lobe and they are in physical contact. The mass transfer may be carried out

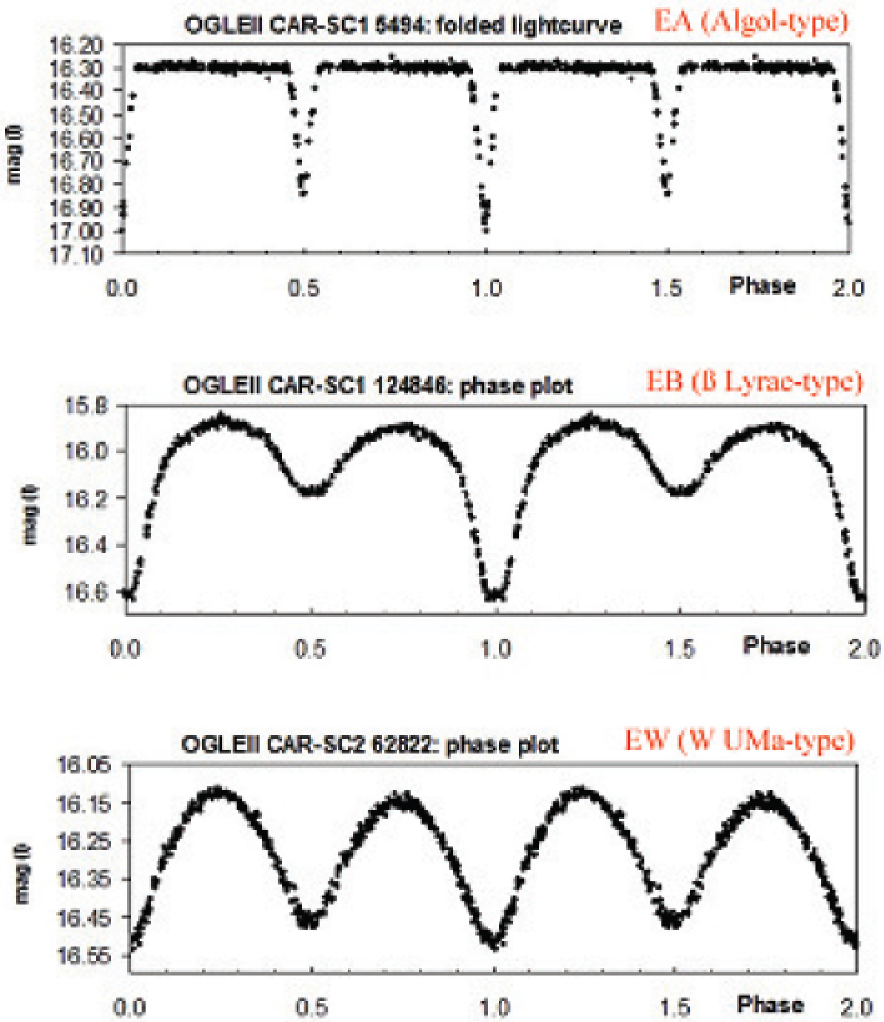

Figure 2.6. The representation of the light curves of the binaries of Algol, β Lyrae and W Ursae Majoris, respectively. [10]

through inner Lagrangian point L_1.

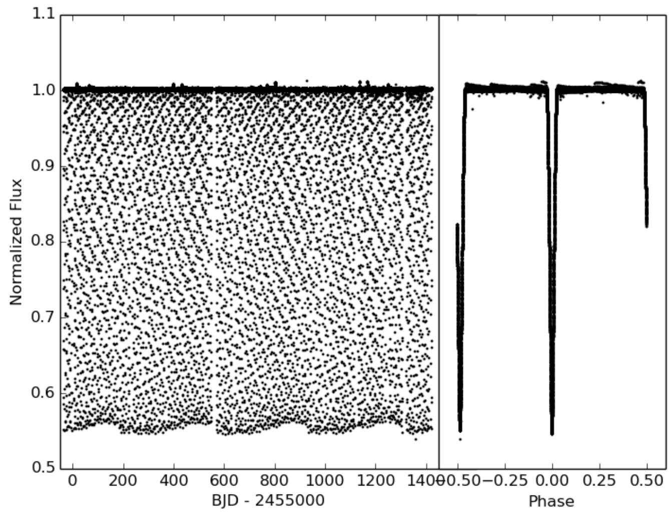

Figure 2.7. The light curve of detached binary system KIC 4445630. [12]

The contact binaries are grouped into two; low-temperature and high-temperature contact binaries. The low-temperature contact binaries (LTCB), also known as W UMa systems, have a convective envelope where the high-temperature contact binaries (HTCB) have a radiative envelope.

W Uma type binaries are classified into two subgroups of A-type and W-type. In A-type system the larger component is the hotter one although the smaller component is the hotter one [13]. The spectral types of the stars range from A to G in A-type and from F to K in W-type stars. The W-type binaries have shorter periods of 0.22 to 0.44 days [14]. A-types have smaller mass ratio values q than W-types have. The components of W Uma stars generally have equal surface temperature but in A-type the primary and in W-type the secondary are a bit more hotter [15].

2.2. Kepler Mission

Kepler Mission is a NASA's first space-based mission which is designed to detect frequencies of Earth-sized planets orbiting around the solar-like stars near or in the Habitable Zone (HZ). After the discovery of the first exoplanet in 1995 [16, 17] there are 1642 confirmed planets with 3787 unconfirmed Kepler planets this number increased to 5429

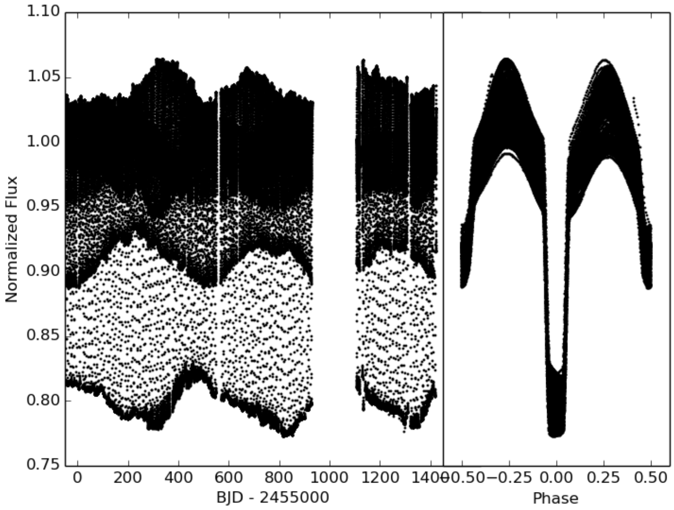

Figure 2.8. The light curve of semi-detached binary system KID 8868650. [12]

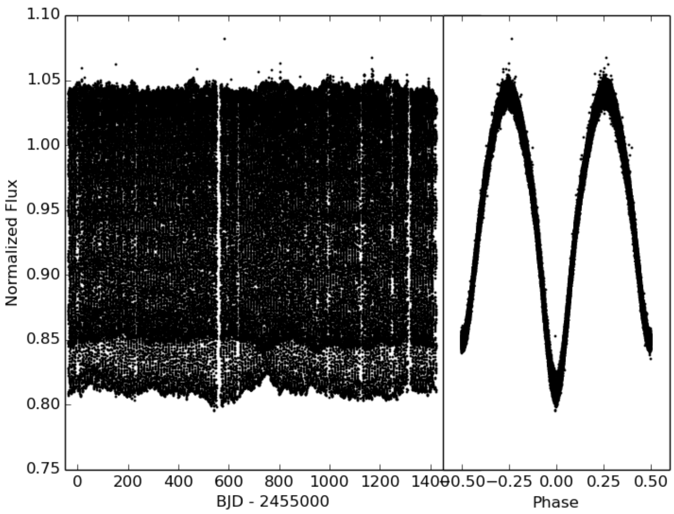

Figure 2.9. The light curve of contact binary system KIC 10447902. [12]

as of November 20, 2015 [18]. These planets are generally gas giants with orbital periods about a few years or less [17]. However, the main goal of the mission is to find habitable planets in the range of HZ where liquid water can exist with life-sustaining atmosphere [19].

A habitable planet satisfies the conditions of size from 0.8 to 2.2 R_E or, if assuming an Earth-like density, mass from 0.5 to 10 M_E . Planets cannot have enough surface gravity to retain an atmosphere if less massive than 0.5 M_E. If their masses are greater than 10 M_E, this time there will be gas giants [20]. Thus, the most suitable searching area for the habitable planet is the HZ.

The origin of the Kepler mission is a photometer designed by using the concept of a Schmidt telescope. The field of view (FOV) is more than one hundred square degree. It has a corrector with a 0.95m aperture. For a meaningful estimate of frequencies, more than 100,000 targets must be monitored. Hence, the FOV is located in the Cygnus constellation and looking along the Orion spiral arm which provides a wide variety of star field [16, 20–22].

The method using to detect terrestrial planets is transit method referred by Borucki and Summers (1984) [16, 23]. While a planet is crossing in front of its host star, it blocks the light of the star that causes variations in the stellar photometry as shape, depth and duration. The detailed study of the variations provides valid information about the characteristic feature of the planets and stars.

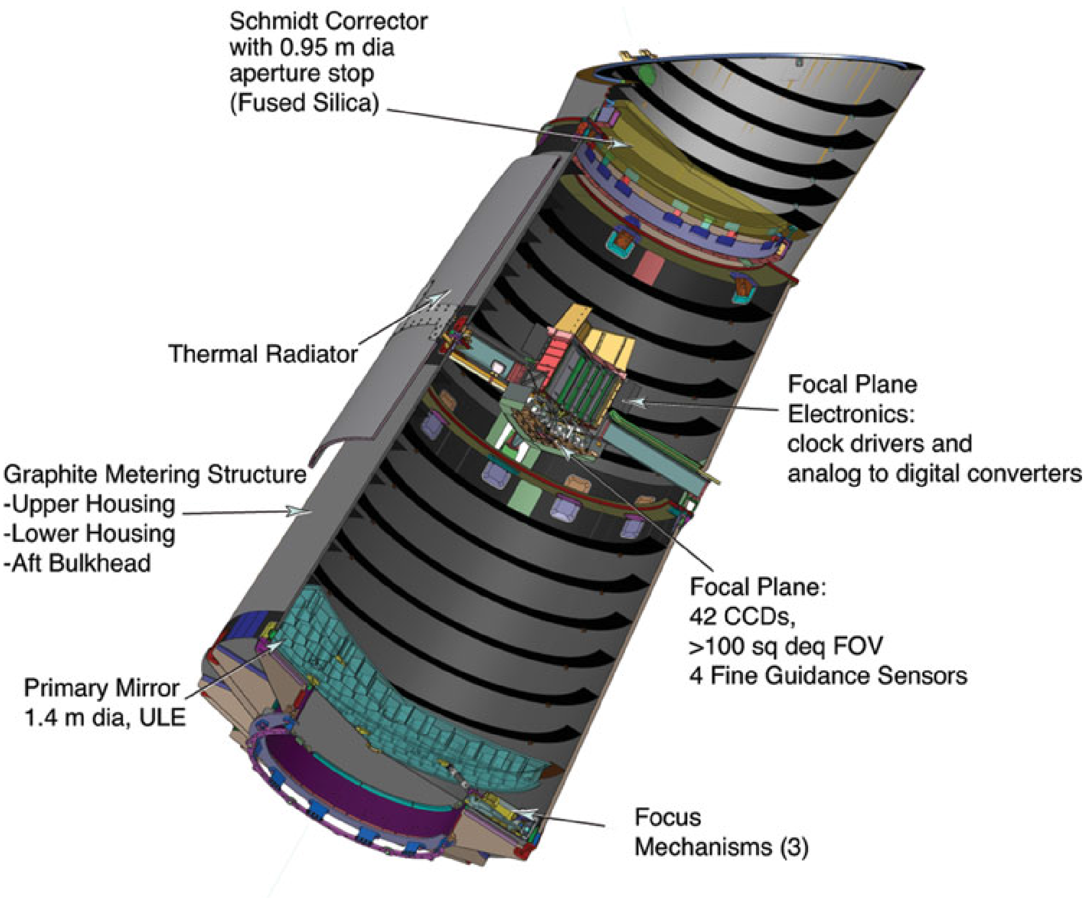

Figure 2.10. The structure of the Kepler Mission. [24]

CHAPTER 3

LIGHT CURVE ANALYSE OF THE SYSTEM KIC 7821450

3.1. New Kepler Observation

During the mission Kepler has precisely observed more than 150.000 stars in long-cadence. Among these stars nearly 2000 binaries were observed [12]. Kepler is a space-based mission and provide more accurate data rather than a ground-based telescopes. Thus, many problem in the stellar astrophysics such as stellar activity, extrasolar planets, etc. can be studied.

KIC 7821450 is a Kepler system. Observations of the system were gained for 7 times during the 17 quarter. During 1427 days, totally 35297 observation points were detected. The properties of the observation and the system are given in the Table 3.1 and Table 3.2, respectively. In Figure 3.1 the variation in flux of the system as a function of time is shown. In the figure, each quarter is demonstrated in different colors. The flux levels in Figure 3.1 also contain instrumental errors. Hence, each quarter must be normalized. The normalized data are shown in Figure 3.2.

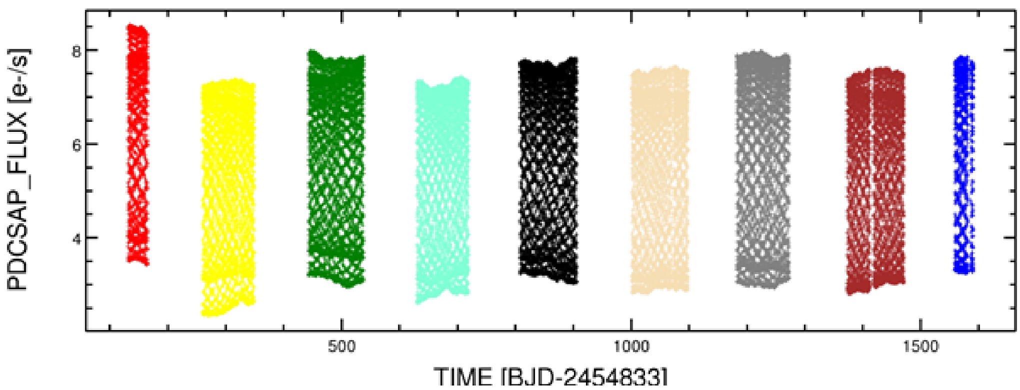

Figure 3.1. The raw data of KIC 7821450. The y-axis which is flux multiplied by 1000 and added 10000.

Table 3.1. The long cadence observation journal of Kepler target KIC 7821450.

Quarter	Start Time	End Time	Points in LC
	Day	day	
1	131.5021254	164.9940155	1639
3	260.2146238	349.5058807	4370
5	443.4799874	538.1729102	4634
7	630.1649647	719.5584242	4375
9	808.5055925	905.9367166	4768
11	1001.198281	1098.335812	4754
13	1182.726568	1273.067012	4421
15	1373.478013	1471.14681	4780
17	1559.215741	1591.011606	1556

Table 3.2. The photometric properties of the system.

Parameter	Unit	Value
R.A.		19h 25m 52.28s
Dec.		43d 32m 59.35s
g mag	mag	15.588
r mag	mag	14.869
i mag	mag	14.658
z mag	mag	14.503
J mag	mag	13.433
H mag	mag	13.048
Ks mag	mag	12.933
Kepler	mag	14.937
E (B-V)	mag	0.127
Teff	Kelvin	5155
Surface Gravity	dex in cgs	4.292
Metallicity	dex	-0.133
Radius	Solar Radii	1.194

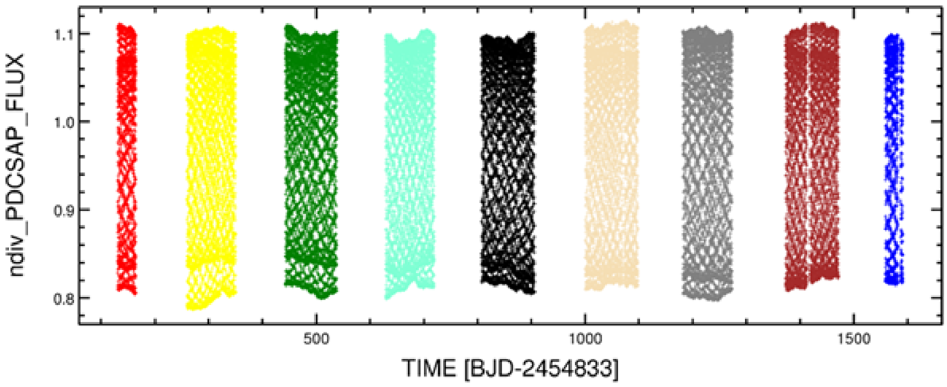

Figure 3.2. The normalized data of KIC 7821450

3.2. Light Curve of the System and Minima Times

Figure 3.2 indicates the flux chance as a function of time. If we handle only a small part of this figure, it will be clear that there are periodical variations (Figure 3.3). The period of the light variation is determined approximately 0.315 day from the Fourier analysis. This calculated period may be seen by the calculation of the times between two minima in Figure 3.3.

More detailed calculations can be done by obtaining the minima times in the light variations. Here, all minima times of the system were calculated (See Section 3.3). The linear ephemeris of a binary system was calculated in order to obtain starting epoch T_0 and the equation is given. The first term in the equation is the starting epoch of the primary minimum and the second term is the period of the binary. If we plot Figure 3.2 again by using the results of the Eq. 3.1, we obtain the light curve as shown in Figure 3.3.

$$BJD = 54964.68338(38) + 0.314762(1)XE \quad (3.1)$$

The components of the contact binaries have different masses but similar surface temperatures. KIC 7821450 is a contact binary system consisting of two stars with surface temperature of nearly 5155 K. It is possible to determine these temperature and mass ratios in detail by analysing the light curve of the system.The analysis of the light curve will be discussed in Section 3.4.

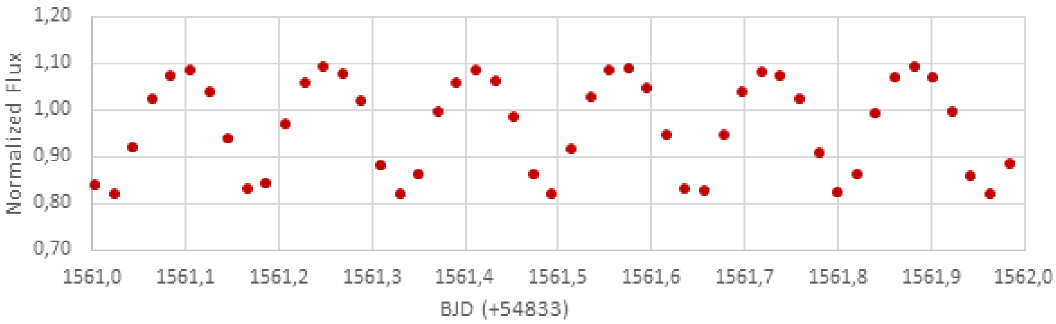

Figure 3.3. A part of light variation of the contact binary system of KIC 7821450 for one day.

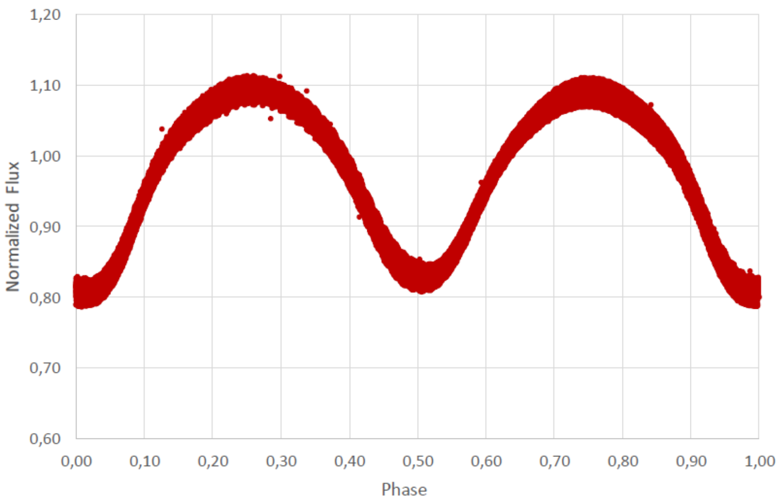

Figure 3.4. The light curve of the contact system of KIC 7821450

3.3. Eclipse Times for the System KIC 7821450

While the components of a binary are orbiting each other, it may display an eclipse depending on our viewpoint (Figure 2.4). The system which is studied in this research is also eclipsing. When the times in the middle of the eclipses that shown by the system are read and analysed, some physical phenomena may be suggested. If the orbital period of the system reveals variety, this will cause changes in the minima times. There are many factors causing changes in the orbit of the system such as mass transfer, existence of a third body, stellar activity, gravitational radiation may cause periodical change thus the angular momentum.

All of the minima times of contact binary system KIC 7821450 have been determined by using parabolic fit method. 4395 minima times were determined in total. Half of the minima times obtained is primary minimum and the other half is secondary minimum. All of the obtained minimum times have been analysed by accepting both mass transfer between the components and existence of a third body. For this, the formulation in Kalomeni et al. (2007) [25] was used. Graphics obtained for the periodical change of the system is shown in the Figure 3.5.

The primary and the secondary of the system selected under this project are given in Figure 3.5. As seen in the figure, the primary and the seconary minima exhibit changes in opposite periods. A sinusoidal or a parabolic change is not explicit in the system. It is estimated that the main factor causing the system to change is the effect of spot on the components. A similar study was presented by Rappaport et al. (2013) [26] for 39 Kepler system.

3.4. Light Curve Modelling

Armstrong et al. [27] gave the temperatures of the components of the binary system 5535K and 5419K, respectively. Likewise, same authors determined the temperatures of the components as 5416K and 5319K with different method. Both results show similar error levels. From this study it will be possible to obtain the ratio of the temperatures much more precisely from th light curve analysis. Phoebe [28] will be used for light curve analysis.

During the light curve analysis T_0, period P, inclination i, mass ratio q, temperature of the secondary T_2, potentials ($\Omega_1 = \Omega_2$), the relative stellar luminosity of the secondary

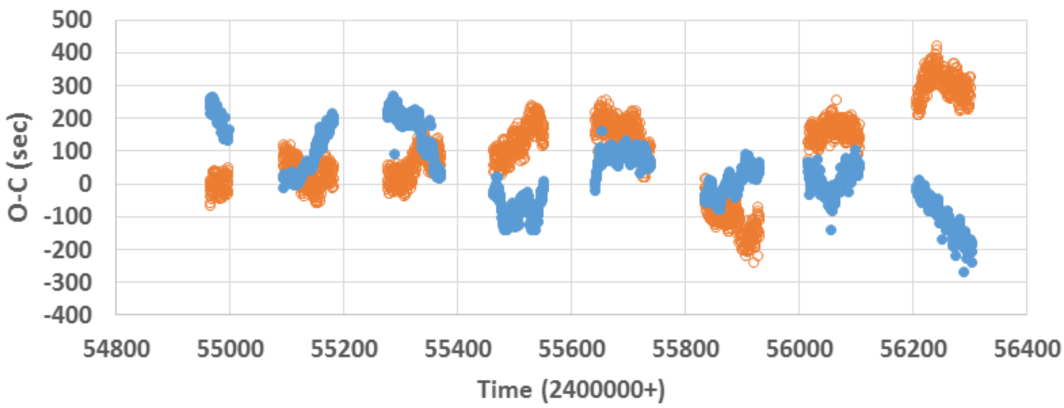

Figure 3.5. O-C variation of the system. Open circles and filled circles show minima times of primary and secondary, respectively.

were taken as free parameter. The temperature of the primary was taken from Armstrong et al. (2014) [27]. The parameters obtained as a result of light curve analysis are given in Table 2.3. *i* value of the binary system was obtained as 78.16 degree. When this value is combined with spectral observations to be conducted in the future, physical elements of the system can also be obtained. Synthetic light curve plotted by using elements obtained in Table 2.3 is shown in Figure 2.5. In this way all data gained from Kepler were used. Geometric appearance of the binary was drawn for period 0.25 and shown in Figure 3.6.

Table 3.3. The solutions of the system

Parametre	Birim	Parameters
i	(o)	78.16(2)
q (M2/M1)	-	0.1595(2)
T_1	K	5533
T_2	K	5133(66)
$\Omega_1=\Omega_2$	-	2.131(2)
L1/(L1+L2)	-	0.885
r_1	-	0.53990(2)
r_2	-	0.23453(6)

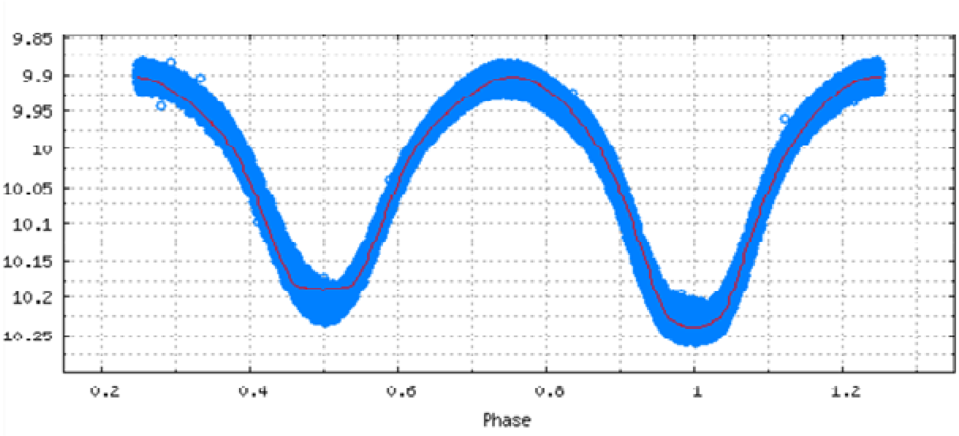

Figure 3.6. The light curve analysis of KIC 7821450 binary. The dots indicate observational data and the straight lines indicate synthetic curve.

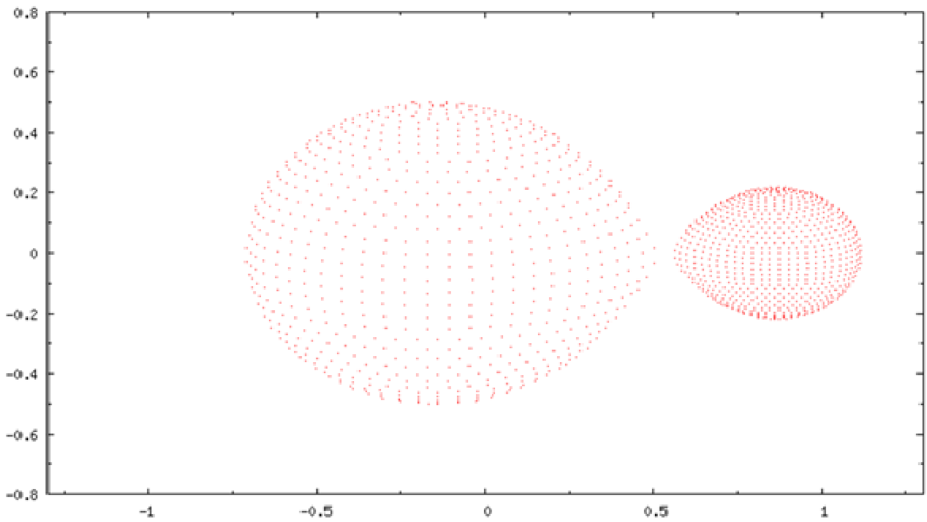

Figure 3.7. The geometric view of KIC 7821450 binary at phase 0.25

CHAPTER 4

CONCLUSION

In this thesis, we analysed the light curve of the system KIC 7821450. It was mentioned in the previous sections that KIC 7821450 is a contact binary system. The system was detected by Kepler mission and some obtained properties such as effective temperature of the system, period, BJD and *etc*. However, these are not adequate to understand the system. Here we aimed to gain more detailed information about the system.

First of all, we calculated all the minima times by using parabolic fit method by accepting both the existing of a third body and assuming mass transfer between the two bodies. Totally we obtained 4359 minima times and half of them are primary and the other half are secondary minimum. The O-C curve was obtained by using formulation from Kalomeni et al.2007. In the O-C curve, the primary and the secondary minima are in the opposite direction so it refers that this system does not contain a third body. Since the systems with a third body component have a sinusoidal O-C curves. The changes in the O-C curve might be due to the spots on the surfaces of the components.

After that we determined the unknown parameters of the systems by using a computer program PHOEBE. The results are shown in the Table 3.3 in Section 3.4.

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