

# Contact Binary Stars in Survey Data

A *thesis submitted in partial fulfillment of the requirements of a degree of Bachelor of Arts in Physics at Pomona College*



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## **Abstract**

## Acknowledgments

To Mom and Dad

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# 1 Introduction - Contact Binaries at the Intersection

*Q: Why are contact binaries interesting (and important)?*

The contact binary star is placed at the intersection of some of the largest questions in modern astronomy.

transients - large explosions that briefly outshine a galaxy's worth of stars. Our own sun, in their cycles of magnetic activity. habitability - could planets exist around such systems? Would massive flares render life impossible? gravitational waves - massive contact binaries consisting of O and B Type main sequence stars. the structure of the galaxy - how we can use them as standard candles.

The contact binary also stands at the intersection of “old” and “new” observational techniques.

As we shall see, the first contact binary was discovered in a survey.

We roughly can split observational science into two modes:

1. Survey Mode: Look out and see what there is to see.
2. Target Mode: Observe very specific set of objects in a way tailored to learn about known phenomena.

In the 20th century, the science of astronomy was “data poor”. The limiting factor of discovery was observations from large telescopes of the day. The possession of data enabled the science. If a scientist had new, proprietary data, science would come out of it.

At the turn of the 21st century (enabled by advances in data storage, processing and robotics, and as a direct result of Moore’s law) observational astronomical science began to shift modes.

Old telescopes were being remodeled, old gears, motors and lenses were being replaced with robotic systems, enabling their autonomous operation. New telescopes were being constructed with the express purpose of deeply surveying the sky - with minimal human intervention. No longer inhibited by human operators, telescopes could image the sky continuously - dawn to dusk. Data poured from these telescopes like water from a firehose. The new images filled massive stacks of servers: for the first time, astronomers were “data rich”.

The monstrous stream of data had to be filtered. Scientists interested in new discoveries had to find the proverbial needle in the haystack. The most productive scientist was no longer the scientist with the best data, it became the scientist with the best techniques for filtering, stacking, folding, combining, or otherwise analyzing the data. Astronomers started shifting back to “Survey Mode”.

Asteroids were discovered by the thousands. The rate of supernova discovery accelerated from one every few years to *one every night*. The number of known eclipsing binaries ballooned from just over a thousand, to tens of thousands. The number of galaxies with known

distances lept from BLANK to BLANK. This progress is accelerating: within the decade, at least three major sky surveys of unprecedented depth and cadence will come online.

In the 21st century, we can study thousands of contact binary systems at once.

\*present tense\*

In §2 I provide a brief history of the discovery of the first contact binary star, and outline major leaps of understanding in the field. In §3, I discuss the types of observations that can be used to learn about contact systems. In §4, I explain the ways that astronomers are able to use measurements to physically characterize contact systems.

I then present original research that I have undertaken with Dr. Tom Prince, Dr. Ashish Mahabal, Dr. Eric Bellm, and Dr. Andrew Drake at the California Institute of Technology. In §6, we discuss how light-curve characteristics vary as a function of temperature. In §7, we present the results of the search for variability in contact binary luminosity on decadal time scales. In §8, we present the results of a search for flares on contact binary stars in survey data. Each section is prefaced with a list of driving questions (*Q:*), which are questions that the reader will find answered in that section.

What I hope this thesis is: 1. An introduction to the field of 2. People have developed techniques for studying the sky when astronomy was data-poor: how can we adapt these techniques to be useful in data-rich astronomy. 3. A roadmap for a promising summer student to use when continuing this work, either at Caltech or Pomona.

## 2 The Contact Binary Star

### 2.1 Discovery

*Q: How was the first contact binary star discovered?*

To understand the history of the study of contact binaries, we must start at the source: the advent of a precise way of measuring the brightness of a celestial object.

In 1861, J.K.F. Zöllner, developed the first practical photometer. In , the image of a real star as focused by a 5" objective lens was compared with the light of an artificial star, produced by a bunsen-like gas burner, in the same field of view [Staubermann, 2000]. The brightness of this artificial star could be adjusted by changing the relative orientation of two prisms, until it matched that of the real star. By recording the relative angle of the prisms when the brightness of the artificial and real star were equal, a photometric measurement could be obtained. In the 1860s, Zöllner supplied 22 photometers to the great observatories throughout the western world. One of these photometers arrived at the Potsdam Observatory , 15 miles southwest of Berlin's city center [Krisciunas, 2001].

Karl Hermann Gustav Müller , and Paul Friedrich Ferdinand Kempf collaborated on ob-

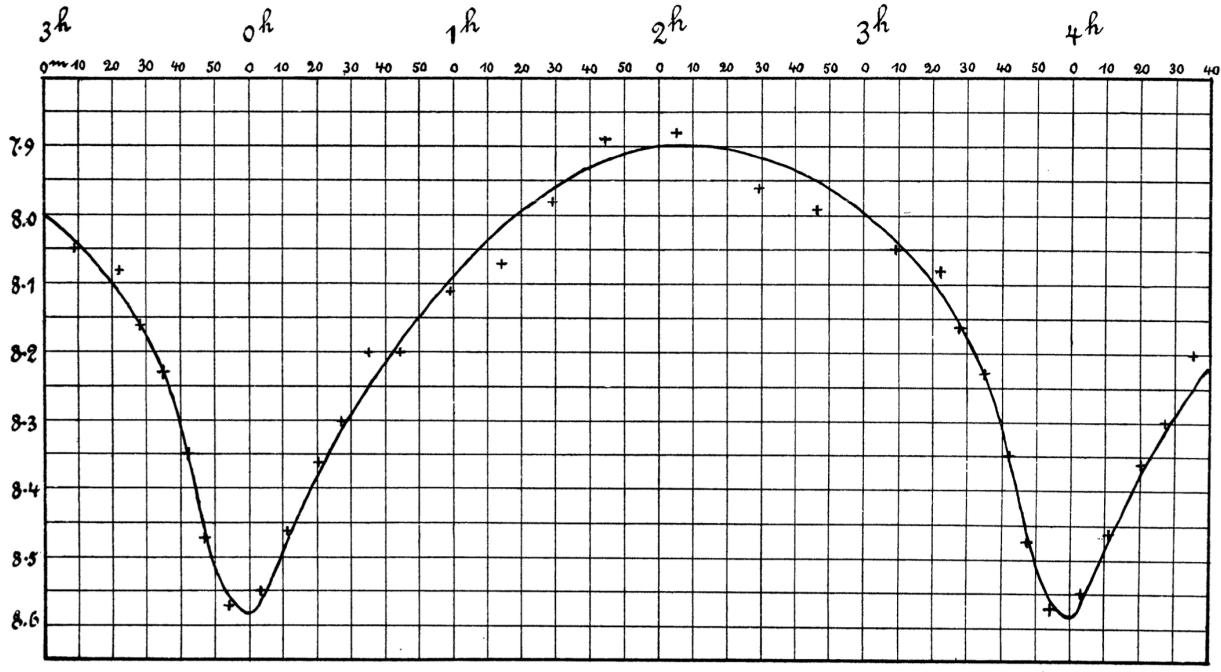
servations for the Potsdam *Photometrische Durchmusterung des Nördlichen Himmels* (Photometric Catalogue of the Northern Heavens), one of the three great photometric catalogues of the late nineteenth century [Bolt et al., 2007]. When it was finished, it contained the brightnesses and colors of roughly 14,000 stars down to visual magnitude 7.5 - a monumental undertaking.

While Kempf and Müller were making the initial observations for Part III of their *Durchmusterung*, they discovered that two measurements of an otherwise inconspicuous star (the first made in 1899, the second made in 1901) differed by an amount that was greater than was expected. In their survey, each star that showed the potential for variability was observed at a later date to verify the nature of variability.

At the Potsdam Observatory on January 14th, 1903, the sun set at 4:20pm. An hour and a half later, (at 5:56pm) Kempf and Müller began constructing a complete light-curve of  $BD + 56^{\circ}.1400$ , which would later be named W Ursae Majoris. They observed until 10:30PM. Follow-up observations three nights later allowed for the construction of the first light-curve of a contact binary star (Figure 2).



Figure 1: Fig. 4 from Staubermann [2000], showing a modern reproduction of a Zöllner photometer. Note the tube: the refractor telescope.



LIGHT-CURVE OF B. D. + 56°1400.

Figure 2: The first light-curve of a contact binary star. Note that the solid curve is interpolated by eye and drawn carefully in pen. Figure 1 from Müller and Kempf [1903].

The shape of the light-curve was unlike anything that Müller and Kempf had seen before, and they struggle to think of a physical system that can produce such a light curve, rejecting many hypotheses (LIST EXISTING HYPOTHESES), before speculating:

*“We may finally consider the hypothesis that the light-variation is produced by two celestial bodies almost equal in size and luminosity whose surfaces are at a slight distance from each other, and which at times almost centrally occult each other in their revolution... On this hypothesis we have only one difficulty, and the not inconsiderable one, as to whether such a system is mechanically possible and can remain stable for any length of time.”*

This is the beginning. In this thesis, written 114 years the initial discovery, we will journey to the forefront of contact binary research.

## 2.2 Physical Characteristics

*Q: What are contact binaries made of? How do contact binaries generate their luminosity? Why are contact binaries shaped like peanuts? How are eclipsing binaries classified? How common are contact binaries compared to all main-sequence stars? How do contact binaries*

*form? How do contact binaries evolve over their lifetime? What is the ultimate fate of a contact binary? What do we know about the most massive contact binaries? What are some interesting magnetic phenomena that occur on contact binaries?*

In this section, we will work to gain a physical understanding of contact binary systems.

Contact binary stars are made up of two main-sequence stars. In §2.2.1 we will understand what main-sequence stars are like on the inside, how energy is generated in the cores of main-sequence stars, and how this energy is transported to the surface.

Once we have got a firm grasp of the properties of main-sequence stars, we will bring two of them together to form a contact binary. In §2.2.3, we learn that we must change the potential that the stellar matter exists in from the point potential to the Roche potential. Also, the components of contact binary stars can transfer mass and energy, from one to the other. We must take this into account when building our model.

In §??, we will learn how common contact binary stars are compared to single main-sequence stars. We will also learn how common they are in the Milky Way galaxy.

In §??, we will learn how contact binaries are formed. We will be introduced to the concepts of angular momentum loss (AML), and Kozai-Lidov cycles.

In §??, we will learn how contact binaries evolve during their lifetimes. We will see how this evolution can drive changes in the observable properties of contact binary systems.

[p.76, Webbink, 2003] excellent review of remaining problems in contact binary study.

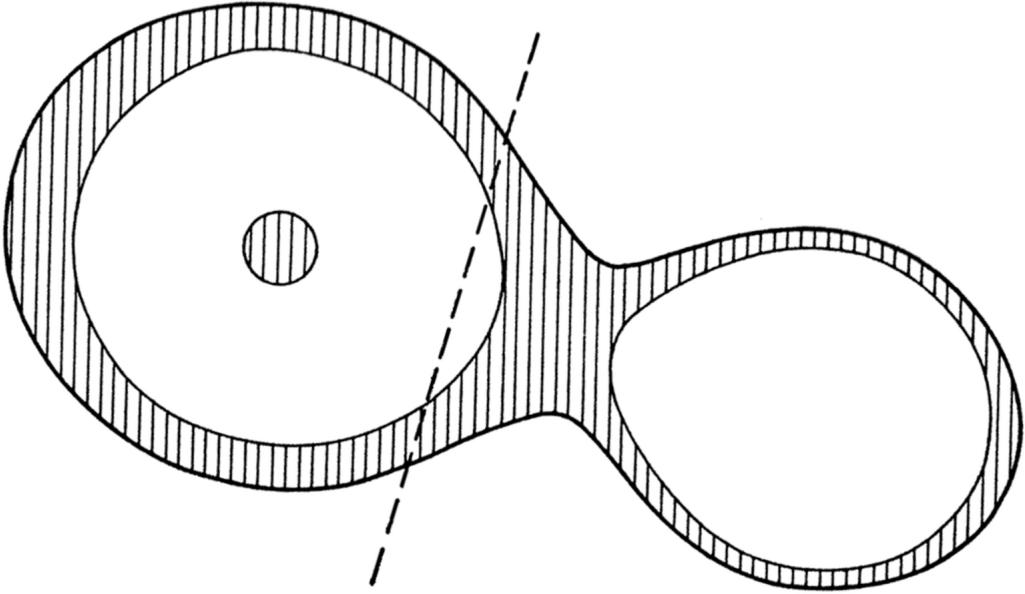
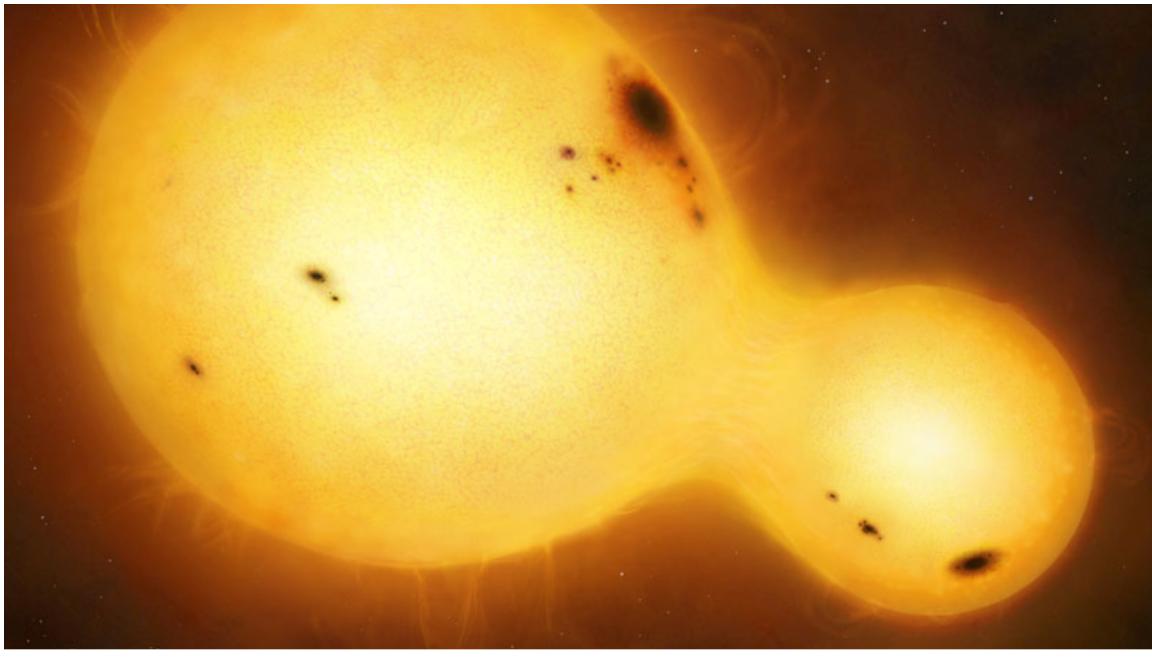


Figure 3: Model for a contact binary system. The hatched areas denote convection zones, and the vertical dashed line is the axis of rotation. Figure 1 from Lucy [1968a].

### 2.2.1 The Main-Sequence Star

Carroll and Ostlie [2006]

In order to understand the internal structure of contact binaries, we must first understand the structure of their two components: main-sequence stars. The most familiar example of a main sequence star is our Sun. When a star

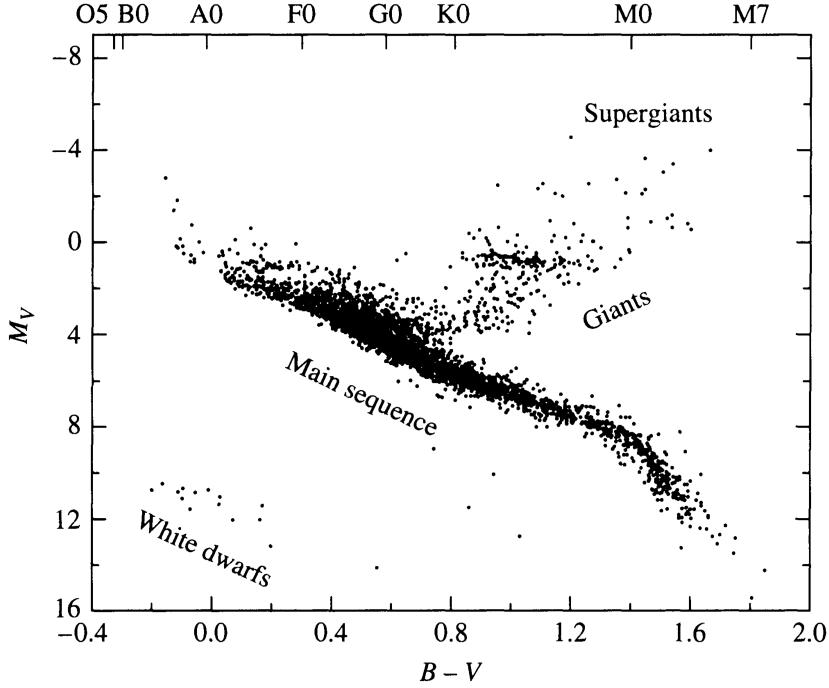


Figure 4: An observer’s Hertsprung-Russel (H-R) diagram. The data are from the Hipparcos catalog. Figure 8.13 from Carroll and Ostlie [2006].

Astronomers have an excellent understanding of the observables (like mass, luminosity, or temperature) of main-sequence stars. Models of main-sequence stars that rely on basic time-independent equations of stellar structure have been successful.

The time-independent equations of stellar structure are a set of relationships between the properties of main sequence stars. They tell how pressure ( $P$ ), enclosed mass ( $M_r$ ), enclosed luminosity ( $L_r$ ), and temperature ( $T$ ) change as a function of radius  $r$ . You will notice that that all of the following equations are actually derivatives. When we supply the appropriate boundary condition (eg. “the temperature  $T$  at 1 solar radius is 5800K”), the equations allow for the complete solution

$$\frac{dP}{dr} = -G \frac{M_r \rho}{r^2} \quad (2.1)$$

$$\frac{dM_r}{dr} = 4\pi r^2 \rho \quad (2.2)$$

$$\frac{dL_r}{dr} = 4\pi r^2 \rho \epsilon \quad (2.3)$$

$$\frac{dT}{dr} = -\frac{3}{4ac} \frac{\bar{\kappa} \rho}{T^3} \frac{L_r}{4\pi r^2} \quad (2.4)$$

In the equations of stellar structure, there is a hidden assumption. These time-independent equations of stellar structure assume that the stellar matter exists in the potential of a point mass  $M_r$ .

$$\Psi_{\text{point}} = \frac{GM}{r} \quad (2.5)$$

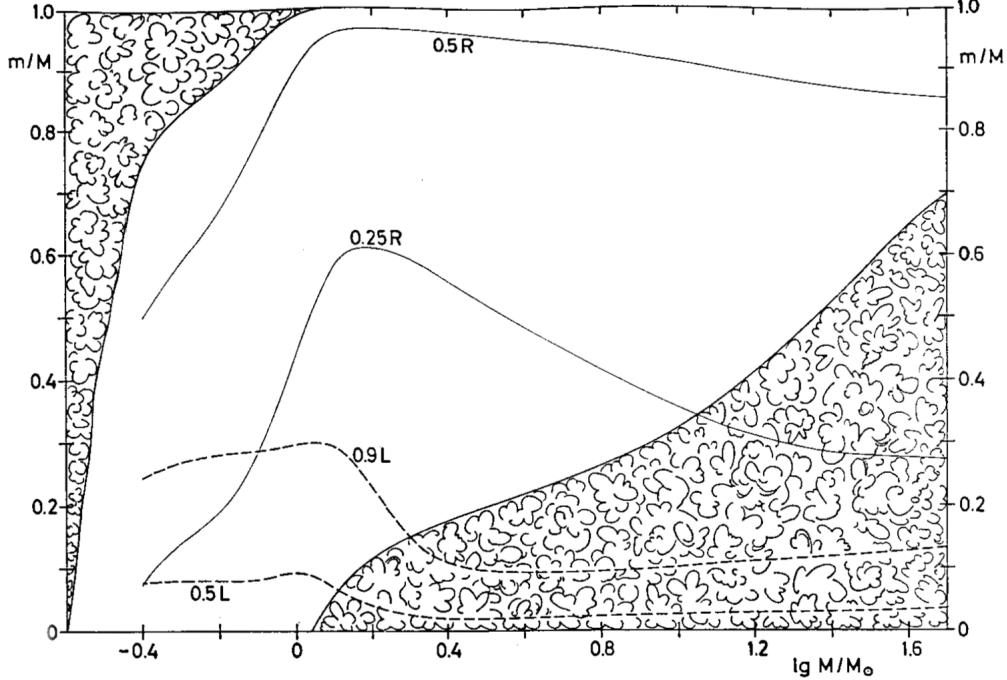


Figure 5: The mass values  $m$  from centre to surface are plotted against the stellar mass  $M$  for zero-age main-sequence models. “Cloudy” areas indicate the extent of the convective zones inside the models. Two solid lines give the  $m$  values at which  $r$  is  $1/4$  and  $1/2$  of the total radius  $R$ . The dashed lines show the mass elements inside which  $50\%$  and  $90\%$  of the total luminosity  $L$  are produced. Figure 22.7 from (pp. 212) of Kippenhahn et al. [1990].

Energy is generated at the core of low mass main sequence stars via the Proton-Proton Chain, or *pp chain*. The pp chain has three branches, each producing helium out of Hydrogen (H), Helium (He) and Beryllium (Be).

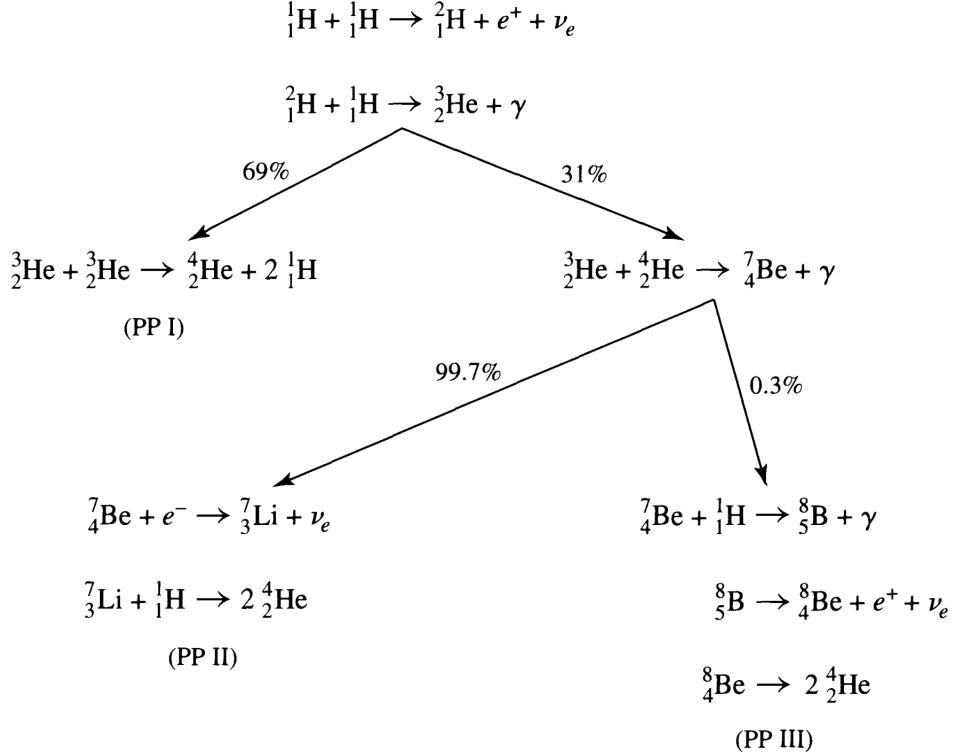


Figure 6: A diagram of pp chain reactions. Percentages by the arrows indicate the branching ratios, revealing that the PP I and PP II chains occur much more frequently than the PP III chain. Figure 10.8 from Carroll and Ostlie [2006].

The energy produced by all three branches of the pp chain can be represented:

$$\epsilon_{pp} = 0.241 \rho X^2 f_{pp} \psi_{pp} C_{pp} T_6^{-2/3} e^{-33.80 T_6^{-1/3}} \text{ W kg}^{-1} \quad (2.6)$$

Where  $T_6 \equiv T/10^6$  K. When we expand Equation 2.6 in a power law about the solar core temperature of  $T_{\odot, \text{core}} = 1.5 \times 10^7$  K, we see that the resulting power law has a  $T^4$  dependence near  $T_{\odot, \text{core}}$ :

$$\epsilon_{pp} \approx \epsilon'_{0,pp} \rho X^2 f_{pp} \psi_{pp} C_{pp} T_6^4 \quad (2.7)$$

### 2.2.2 The Criterion for Stellar Convection

In our study of contact binary stars, we will find it useful to derive the conditions necessary for stellar convection to occur. We follow closely the analysis presented in Carroll and Ostlie [2006].

The two primary methods of energy transport in main-sequence stars are convection, and radiation. In radiation, the stellar material is in hydrostatic equilibrium, and energy

is transported through it via electromagnetic waves. If conditions are such that radiation cannot transport energy away from the core efficiently enough, the stellar material itself will have to move to transport this energy, disrupting hydrostatic equilibrium. We call this disruption convection.

In their derivation, Carroll and Ostlie envision a bubble of gas with its own temperature, pressure, and density in a surrounding gas medium.

Absolute magnitudes and luminosities [Rucinski and Duerbeck, 1997] [Rucinski, 2006]

The classical Roche model allows eclipsing binaries to be separated into morphological types [Terrell, 2001].

### 2.2.3 The Roche Potential

#### The Roche Potential

The Roche model assumes: synchronous rotation, circular orbits, two point masses, in the rotating frame [Kopal, 1959] :

Mochnacki [1984]:

“In Cartesian coordinates, with the origin at the center of mass of the primary, the  $x$ -axis aligned with the centers of mass, and the  $z$ -axis parallel to the rotation axis, the potential at a point  $(x,y,z)$  co-rotating with binary system is given by: ”

$$\Psi(x, y, z) = -\frac{G(M_1 + M_2)}{2a} C \quad (2.8)$$

where

$$C(x, y, z) = \frac{2}{1+q} \frac{1}{(x^2 + y^2 + z^2)^{\frac{1}{2}}} + \frac{2q}{1+q} \frac{1}{1+q[1+q[(x-1)^2 + y^2 + z^2]^{\frac{1}{2}}]} + (x - \frac{q}{1+q})^2 + y^2 \quad (2.9)$$

$q = \frac{m_2}{m_1}$ ,  $(x, y, z)$  are in units of  $a$ , the separation between the two point masses.

The Roche potential has points where  $\nabla\Psi = 0$ , called Lagrange Points (see Figure ??).

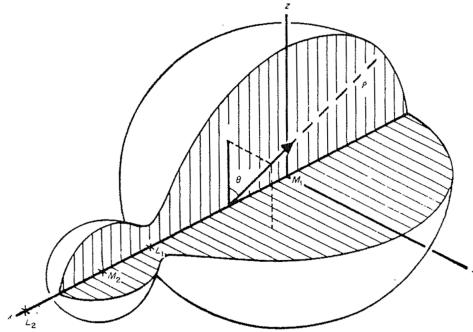


Figure 7: The coordinate system used in equations 2.8 and 2.9 to describe the potential  $\Psi$  of a contact binary system. Figure 1 from Mochnacki and Doughty [1972]

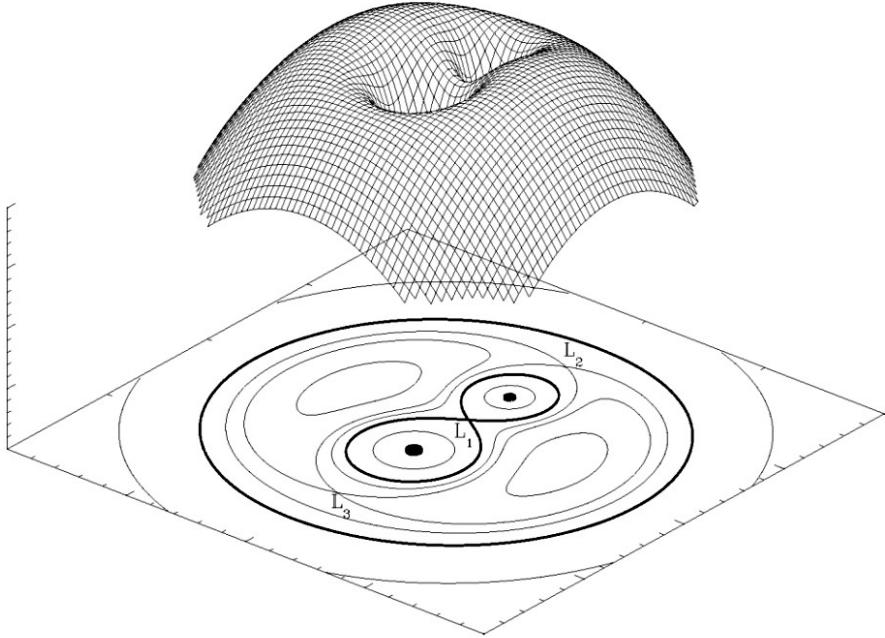


Figure 8: A composite 3D and contour plot of the Roche potential. The Roche lobe is the dark equipotential curve shaped like the  $\infty$  symbol. Three out of the five Lagrange points are labelled  $L_1, L_2, L_3$ . [Sluys, 2006]

Now that we understand the shape of the Roche potential, we can learn how the Roche potential is used to classify eclipsing binary stars, in a scheme primarily developed by the work of Kopal [1959]. In Figure 9, we see three types of eclipsing binaries. In Detached systems, the photosphere of each component is well within the Roche lobe (the equipotential curve shaped like  $\infty$ ). In a Semi-detached configuration, the photosphere of one component fills the Roche lobe, while the photosphere of the other component remains well within the Roche lobe. In Overcontact systems, both components overfill the Roche lobe, and a bridge of stellar material connects the two components, covering the  $L_1$  point [Terrell, 2001].

An important note on the semantics of binary star classification. Kuiper [1941]

The origin of the term overcontact [Wilson, 2001]

For an excellent review, see: [Kallrath and Milone, 2009]

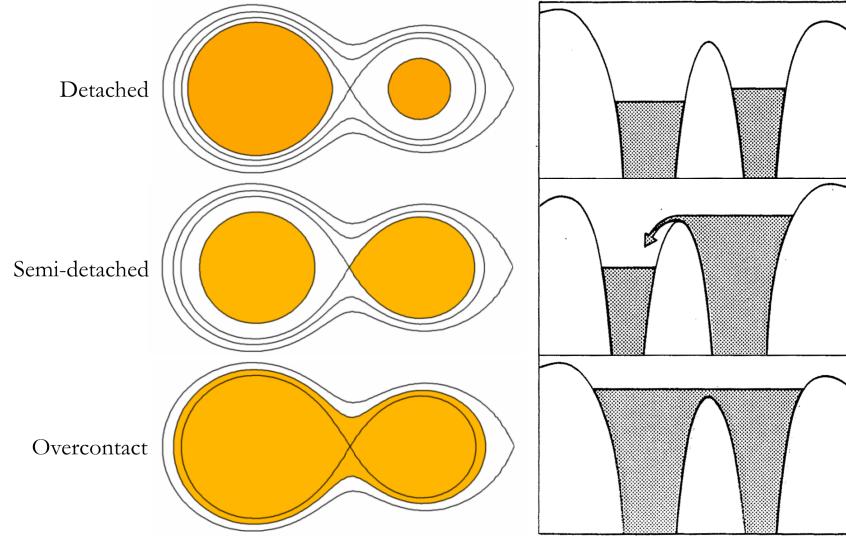


Figure 9: Types of eclipsing binary systems based on Roche geometry. Figures 2,3, and 4 from Terrell [2001], and Figure 1.4 from Pringle and Wade [1985]

#### 2.2.4 Thermal Equilibrium Models

Thermal Equilibrium Models

$$\nabla P = -\rho \nabla \Psi \quad (2.10)$$

$$\nabla \rho = \frac{dP(\Psi)}{d\Psi} = \rho(\Psi) \quad (2.11)$$

If we assume a homogenous composition on equipotential surfaces, then all state variables (pressure, density, temperature) are functions of  $\Psi$  alone. In order to achieve hydrostatic equilibrium, energy must be exchanged between the two components of the contact binary.

We can construct two model main sequence stars, with masses  $M_1$  and  $M_2$ . Main sequence stars will obey main-sequence scaling relationships, which are well defined laws the describe how stellar radii, density, and temperature vary with stellar mass [Kippenhahn et al., 1990]. The mass - radius relationship is particularly important when constructing contact models.

$$\left( \frac{R}{R_\odot} \right) = \left( \frac{M}{M_\odot} \right)^\alpha \quad (2.12)$$

$$\left( \frac{R_1}{R_2} \right) = \left( \frac{M_1}{M_2} \right)^{0.46} \quad (2.13)$$

Because of the mass - luminosity relationship of main sequence stars, there is a mass ratio - luminosity ratio relationship for the components of contact binaries:

$$\left(\frac{L_1}{L_2}\right) = \left(\frac{M_1}{M_2}\right)^{0.9} \quad (2.14)$$

In order for the binaries to be in contact, their photospheres must touch physically. This allows us to introduce the contact criterion, in which the separation between the centers of the components are equal to the sum of the two radii:

$$a = R_1 + R_2 \quad (2.15)$$

We can relate the combined masses of the two stars to their periods using the generalized form of Kepler's Third Law:

$$P^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3 \quad (2.16)$$

Advection is a transport mechanism of a substance, or property (e.g. temperature, density) by a fluid due to the fluid's bulk motion.

### 2.2.5 Common-Envelope Evolution

Common-Envelope Evolution

Common-envelope Evolution, (CEE) [Ivanova et al., 2013]

## 2.3 Frequency and Density

[Rucinski, 1998a] Studies using OGLE data on the galactic bulge (Baade's Window) indicates that the frequency of contact binaries relative to main sequence stars (or spatial frequency) is approximately  $\frac{1}{130} = 0.7\%$ , in the absolute magnitude range of  $2.5 < M_v < 7.5$ . A later study using ASAS data shows that the spatial frequency is 0.2% in the solar neighborhood [Rucinski, 2006] in the absolute magnitude range of  $3.5 < M_v < 5.5$ .

A catalog of 1022 contact binary systems in ROTSE - 1 data placed the space density of contact binaries at  $1.7 \pm 10^{-5} \text{ pc}^{-3}$

Contact binaries are the most frequently observed type of eclipsing binary star, because their eclipses can be detected at a wide range of orbital inclinations. In recent searches for eclipsing binary stars in survey data [Drake et al., 2014b] contact binary stars comprised 50% of the new variable stars discovered.

## 2.4 Mechanisms of Formation

Formed in Contact. Lucy [1968b] was incorrect in assuming that contact systems exist at Zero Age Main Sequence (ZAMS).

[Yıldız and Doğan, 2013]

[Li et al., 2007]

Initially Detached, but then inspiral Angular Momentum Loss through stellar winds.  
Angular Momentum Loss through tertiary components. [Lohr et al., 2015]

A study by ? has established a lower limit on the number of triple systems

## 2.5 Evolution in the Contact State

Thermal Relaxation Oscillations [Wang, 1994]. May cause orbital period changes observed in Qian [2001].

The structure of contact binaries [Kähler, 2004]

Angular momentum and mass evolution [Gazeas and Stępień, 2008]

masses and angular momenta [Gazeas and Niarchos, 2006]

contact binaries occupy a very narrow range of parameter space [Gazeas, 2009]

Overall evolution [Stepien and Gazeas, 2008], 2016 review of close binary evolution [Tutukov and Cherepashchuk, 2016]

Short period limit [Rucinski, 2007] [Drake et al., 2014a] Lohr et al. [2012]

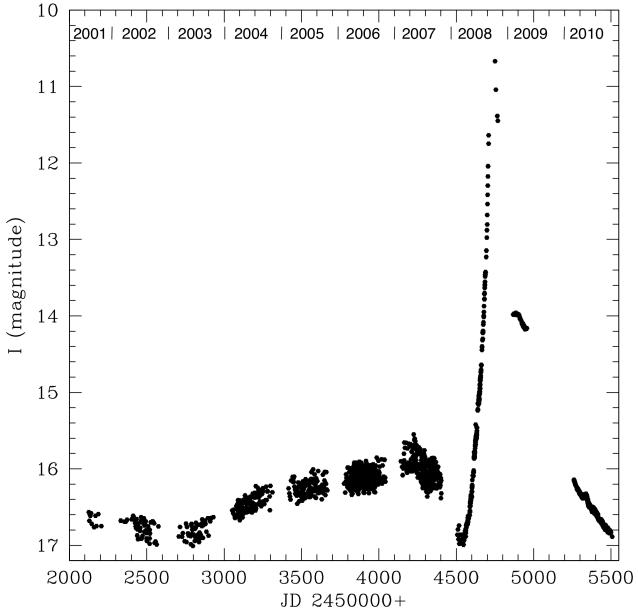
## 2.6 Evolution out of the Contact State

It is generally accepted that the contact state of binary evolution ends with the inspiral and merger of the two components. The merger event is where the contact system becomes dynamically unstable, and rapidly coalesces into a single, rapidly rotating star.

The tidal interaction between the two components of a contact binary star.

To understand when and why the contact state comes to an end, we must understand the range of conditions over which the contact state is stable.

Merger Tylenda et al. [2011].



**Fig. 1.** Light curve of V1309 Sco from the OGLE-III and OGLE-IV projects:  $I$  magnitude versus time of observations in Julian Dates. Time in years is marked on top of the figure. At maximum the object attained  $I \approx 6.8$ .

Figure 10: Light curve of V1309 Sco from the OGLE-III and OGLE-IV projects:  $I$  magnitude versus time of observations in Julian Dates. Time in years is marked on top of the figure. At maximum the object attained  $I \approx 6.8$ . Figure 1 from Tylenda et al. [2011]

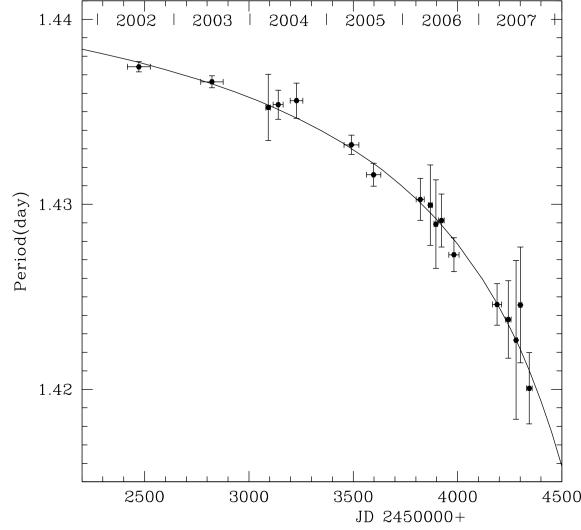


Figure 11: Figure 2 from Tylenda et al. [2011]

The contact binary in the OGLE merger had a period of approximately 1.4 days. Long-period contact binaries [Rucinski, 1998b]

Blue straggler Andronov et al. [2006]

stability of the contact configuration [Rasio, 1995]

One of the ways that a contact binary system can merge is called the Darwin instability.  
In a Darwin instability, the ...

In the early 1990s, large numbers of new contact binaries were discovered among blue stragglers, in open and globular clusters

[Kaluzny and Shara, 1988] no discovery in six open clusters.

In the globular cluster M71, four contact binaries discovered by Yan and Mateo [1994], placing a lower limit of 1.3% on the frequency of primordial binaries in M71 with initial orbital periods in the range of 2.5 to 5 days.

Short period eclipsing binaries have been found among blue stragglers in the globular cluster NGC5466 [Mateo et al., 1990].

Review of binaries in globular clusters [?]

modern work on six binaries in NGC188 [?]

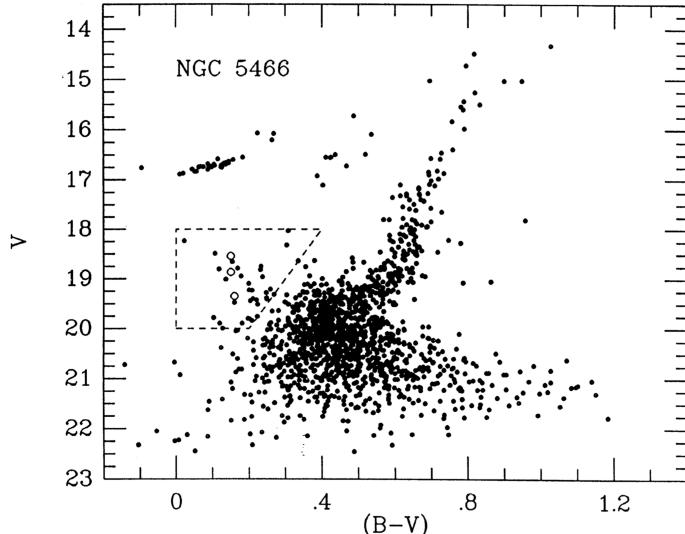


Figure 12: A color-magnitude diagram of globular cluster NGC 5466. The blue stragglers are defined to be all stars located within the region bounded by the dashed lines. The mean  $V$  magnitudes and  $(B - V)$  colors of the eclipsing binaries discovered by Mateo et al. [1990] are shown as open circles. Figure 1 from Mateo et al. [1990].

## 2.7 Early-Type Contact Binaries

TU Muscae [Penny et al., 2008]

MY Cam [Lorenzo et al., 2014]

UW CMa [Antokhina et al., 2011]

V382 Cygni [Popper, 1978]

Over forty have been found in the Small Magellanic Cloud [Hilditch et al., 2005]  
Massive contact binaries in M31 [Lee et al., 2014], [Vilardell et al., 2006]  
In modern survey data, we can observe individual eclipsing binary systems in nearby galaxies.

## 2.8 Magnetic Activity

In the solar atmosphere, the movement of plasma in the convective region creates magnetic fields, which in turn affect the motion of that same plasma. Contact binaries are rapidly rotating systems, with orbital periods of 0.2 to 0.8 days (compare this rate with the approximately 30 day solar rotational period)

Because late-type contact binaries have Common Convective Envelopes (or CCEs),

Some authors believe that the existence of the CCE buries the very strong surface magnetic field, which could prevent the production of flares [Qian et al., 2014].

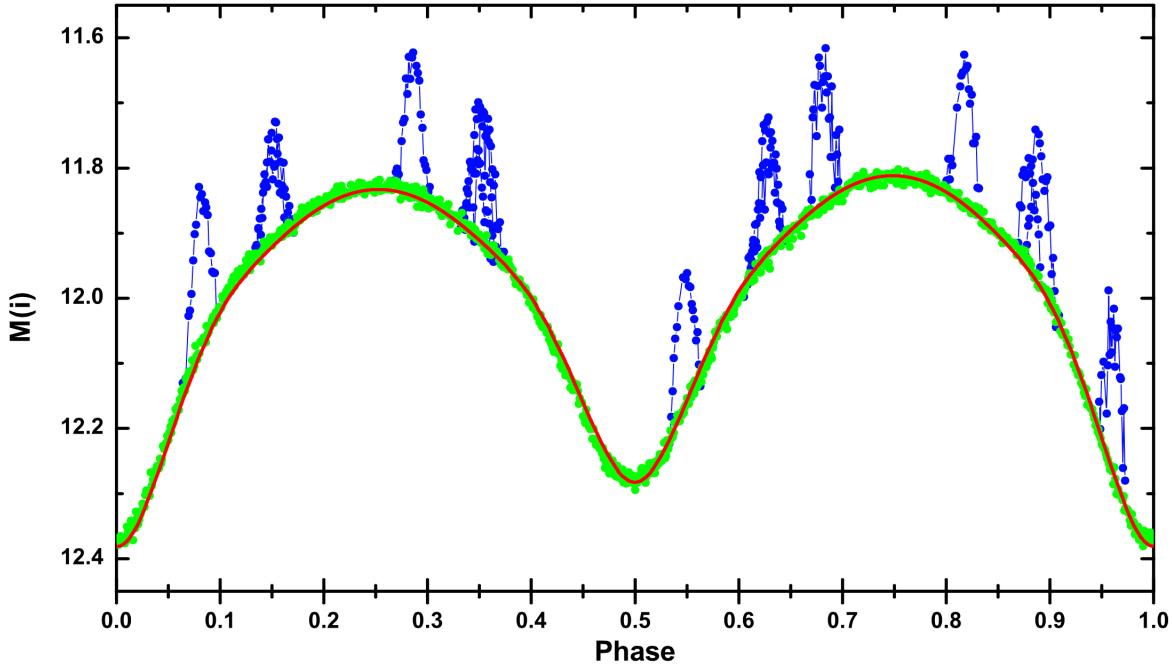


Figure 13: Fig. 15 from Qian et al. [2014]

[Balogh et al., 2015] book review of solar magnetic activity cycles.  
The applegate mechanism [Applegate, 1992] [Lanza, 2006]  
W UMa as X-ray sources [Stepien et al., 2001]  
Observational starspots and magnetic activity cycles. [Borkovits et al., 2005, Shengbang and Qingyao, 2000, Kaszás et al., 1998, Qian et al., 2007, Lee et al., 2004, Yang et al., 2012, Zhang and Zhang, 2004].

It is possible that starspots are responsible for the variation in brightness observed by CRTS. Doppler imaging techniques have confirmed the presence of large starspots on the surface of some contact binaries [Barnes et al., 2004].

Barnes et al. [2004] has used an Echelle spectrograph on the 3.9-meter Anglo-Australian Telescope to perform doppler imaging of the AE Phe system ( $P = 0.362$  d), revealing that the photosphere of the system is heavily spotted (Fig. 14).

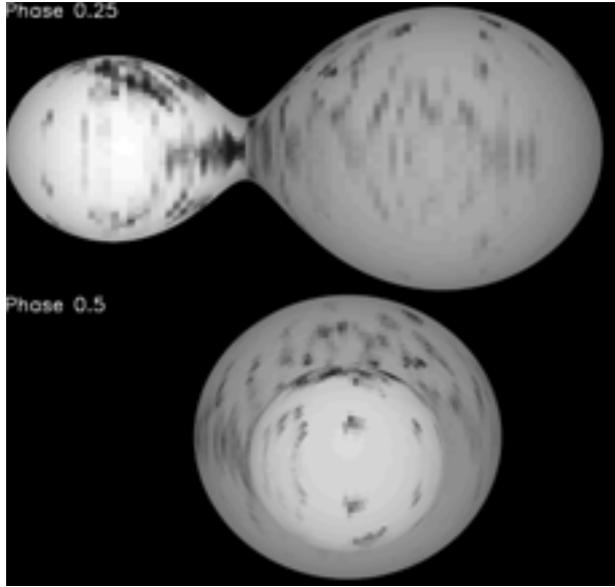


Figure 14: Fig. 5 from Barnes et al. [2004]

The evolution and migration of starspots on contact binaries has been tracked with doppler imaging [Hendry and Mochnacki, 2000] and more recently, in Kepler data [Tran et al., 2013, Balaji et al., 2015]. Starspots are magnetic phenomenon, and so their occurrence is related to the magnetic activity of their host star [Berdyugina, 2005].

## 2.9 Remaining Questions

## 3 Observations

*Q: What kind of observations can astronomers obtain from contact binary systems?*

Astronomy is unique as a science because all the information that can be obtained from an object in the sky comes to us as electromagnetic waves. Perhaps *THE* question in observational astronomy is: “What can we learn from these electromagnetic waves?”. The study of contact binary stars is no different. In this section, we will learn the ways that researchers study electromagnetic waves from contact binary stars.

### 3.1 Images of Contact Binaries

The oldest type of astronomical information is image data: “What do I see when I look through the telescope?”. To put this question in more formal language: “What is the distribution of the intensity of visible light as a function of position?”. When we look at the moon, for example, we can learn a lot about it: we might see some crater ”over here”, with a given size, shape, color, etc. We might see a dark lunar mare (or “sea”), “over there”, with another size, shape, color, etc. The moon is what we call a “resolved source”, meaning that features on it are distinguishable: we can separate “over here” from “over there”. In other words, the distance between “over here” and “over there” is larger than the resolution limit of our telescope.

Let’s see if we can reasonably obtain image data from a contact binary:

On a still, clear night at the Las Campanas observatory in Chile, Mike Long reports that the atmospheric resolution limit (or “seeing”) is 0.5 arcseconds. This is the best resolution that can be expected from a telescope on earth: Chile’s Atacama desert is known for some of the best seeing on earth.

$$0.5 \text{ arcseconds} * \frac{1}{3600} \frac{\text{arcseconds}}{\text{degrees}} = 1.4 \times 10^{-4} \text{ degrees} * \frac{\pi}{180} \frac{\text{radians}}{\text{degrees}} = 2.4 \times 10^{-6} \text{ radians} \quad (3.1)$$

In order to distinguish between the two components of a contact binary, the resolution limit of our telescope must be smaller than the distance between the centers of the two components.

For a contact binary star of solar type, this is about one solar radius:  $1R_{\odot} = 6.957 \times 10^5 \text{ km}$ . Let us place this hypothetical contact binary at the same distance as the nearest star, *Proxima Centauri*, which is 4.243 light years = 1.301 parsecs =  $4.014 \times 10^{13} \text{ km}$ .

To calculate the angle that a solar type-contact binary at the distance of *Proxima Centauri* would subtend, we will use the small angle approximation:

$$\sin(\theta) \approx \theta, \quad \cos(\theta) \approx 1 - \frac{\theta^2}{2}, \quad \tan(\theta) = \frac{\sin(\theta)}{\cos(\theta)} = \frac{\theta}{1 - \frac{\theta^2}{2}} \Rightarrow \tan(\theta) \approx \theta \quad (3.2)$$

If we set up a right triangle (as in Fig. 15), we see that the tangent of the angle  $\theta$  is equal to the radius of the sun divided by the distance to *Proxima Centauri*.

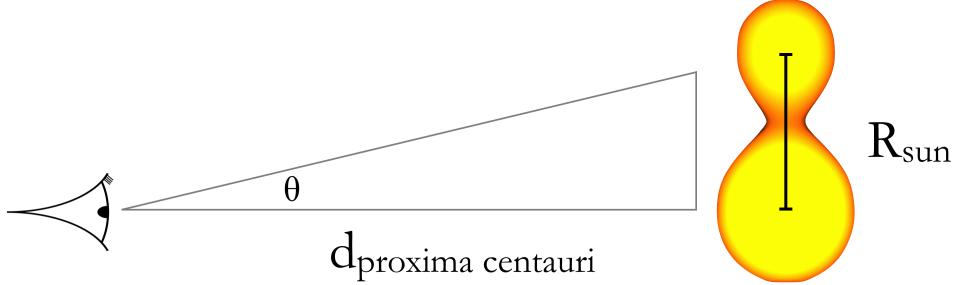


Figure 15: Calculating the angle  $\theta$  subtended by a solar-type contact binary at the distance of the nearest star.

$$\frac{R_{\text{sun}}}{d_{\text{proxima centauri}}} = \frac{6.957 \times 10^5 \text{ km}}{4.014 \times 10^{13} \text{ km}} = \tan(\theta) \approx \theta = 1.733 \times 10^{-8} \text{ radians} \quad (3.3)$$

When comparing the resolution necessary to distinguish the components of a contact binary to the best resolution possible on earth:

$$\frac{1.733 \times 10^{-8} \text{ radians}}{2.4 \times 10^{-6} \text{ radians}} \approx 0.01 \quad (3.4)$$

To summarize: we would need 100 times the resolving power achievable from the earth to obtain image data from a large contact binary at the distance of the nearest star. In actuality, the situation is worse. 44 Bootis is the nearest contact binary system to earth, at a distance of 13 parsecs (42 light years) it is 10 times further away than *Proxima Centauri* [?]. For this reason, we cannot obtain usable image data from contact binaries <sup>1</sup>.

### 3.2 Anatomy of a Contact Binary Light-Curve

*Q: Why does the flux received from a contact binary vary over time? Q: How was the light-curve used to determine what a contact binary was? Q: How can light-curve data be used to learn about contact binary systems?*

In images, contact binaries appear as an unresolved point source. At first glance, it may appear that astronomers are stuck: they cannot “see” the contact binary and so must remain uncertain about its characteristics. However, as Kempf and Müller learned in 1903, the amount of light received from a contact binary varies as a function of time. This function is called the light-curve:

---

<sup>1</sup>it is possible to achieve this resolution (as good as 0.0005") through long-baseline interferometry. Using the CHARA array on Mount Wilson, researchers have constructed a resolved image of the eclipsing binary system  $\beta$  *Lyrae* [?]. However, interferometric imaging is only possible for the brightest stars, so is not useful for contact binaries.

$$f(\text{Time}) = \text{Flux Received at Telescope} \quad (3.5)$$

A light curve is constructed from observations: by repeatedly measuring the brightness of a source over a certain time span, an astronomer can sample the light-curve and approximate its true shape.

Kempf and Müller knew that they could use the light-curve to learn about the shape of the contact binary system. First, they noted that the light-curve was periodic: after a certain amount of time, the trend in flux *exactly repeated* itself. Thus they knew that the process that was responsible for the variation in the flux was cyclical in nature.

They knew that the period of the light variation in W UMa was very stable (“The error of the period can hardly be more than 0.5s...”). They assumed that a rotational or orbital mechanism was responsible for the light variation. They thought that the presence of a large dark spot on a rapidly rotating single star, which was hypothesized to be “in an advanced stage of cooling”. However, W UMa was a white star, not a cool red star, leading Kempf and Müller to discredit this model. They also considered a single star in the shape of an ellipsoid - a large, however they calculated that this model did not describe the shape of the light-curve very well. In 1903, the eclipsing binary model was already proposed as a mechanism for the light-curves of certain stars (most notably Algol). To construct their model, they looked at existing eclipsing binary light curves and imagined what would happen if they brought the two stars close together. If they brought the two stars close enough together so that the stars were almost touching, there was always variation in the light-curve, just like they observed.

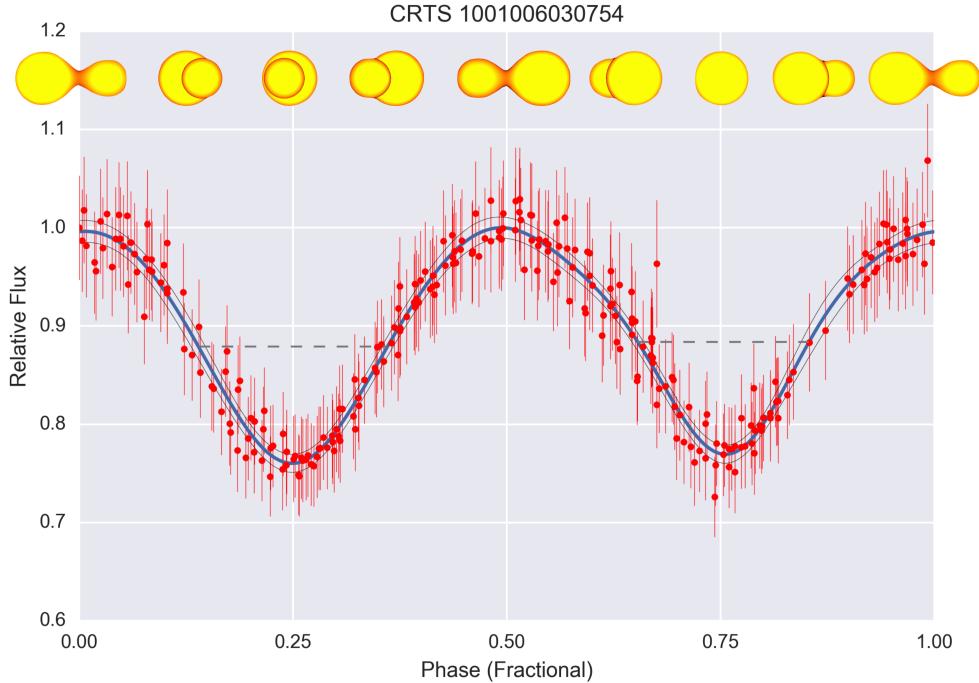


Figure 16: Light-curve is from CRTS data [Drake et al., 2014b]. Illustration of contact binary phase from an animation at: <http://cronodon.com/SpaceTech/BinaryStar.html>

The shape of a contact binary’s light-curve can tell us a lot about it. Indeed, the aim of much of the original work in this thesis is to determine how the shape of the contact binary light-curve correlates with physical parameters. I’ll now go through a few light-curve features

Not all contact binary light-curves look the same, so why is that?

### 3.2.1 Amplitude

### 3.2.2 Difference Between Eclipse Minima

### 3.2.3 Difference Between Out-of-Eclipse Maxima

### 3.2.4 Eclipse Width at Half-Minimum

## 3.3 Spectra

In this section, I describe some of the major sources of modern observations of contact binaries.

Since the late 1990s, photometric surveys that frequently observe large areas of the sky have come online. Through the careful classification of periodic variable sources in survey datasets, larger and larger samples of contact binary systems have been assembled, making

studies of contact binaries as a population possible. Previous surveys have compiled variable star catalogs which include many contact binary systems. Examples of such surveys are the All-Sky Automated Survey [ASAS, Pojmanski, 2000], Robotic Optical Transient Search Experiment [ROTSE, Akerlof et al., 2000], Trans-Atlantic Exoplanet Survey [TrES, Devor et al., 2008], Lincoln Near-Earth Asteroid Research program [LINEAR, Palaversa et al., 2013], and Catalina Real-Time Transient Survey [CRTS, Drake et al., 2014b]. Researchers have also selected pure samples of contact binary systems from large survey data sets for study. Researchers have previously used data from the Optical Gravitational Lensing Experiment [OGLE, Rucinski, 1996], Super Wide Angle Search for Planets [SuperWASP, Norton et al., 2011], and CRTS [Drake et al., 2014a] to construct pure contact binary samples for study. Lee [2015] have used this approach to study a pure sample detached eclipsing binaries from the CRTS variable catalog.



Figure 17: Images of the instruments used in six modern surveys. In the top left, SuperWASP [SuperWASP, Norton et al., 2011], ASAS [ASAS, Pojmanski, 2000], [ROTSE, Akerlof et al., 2000],

### 3.4 The Kepler Spacecraft

### 3.5 The Sloan Digital Sky Survey

York et al. [2000]

[Ivezić et al., 2007]

calibrations allow for stellar temperatures to be derived Fukugita et al. [2011]  
SEGUE is a program that collects stellar spectra.

### **3.6 The SuperWASP Survey**

follow-up on 1-meter telescopes in South Africa [Koen et al., 2016].  
more follow up [Darwish et al., 2016]

### **3.7 The LINEAR Survey**

### **3.8 The Catalina Surveys**

### **3.9 Other Surveys**

OGLE work has determined a criterion for overcontact based on Fourier coefficients [Rucinski, 1997]. [?]

Rucinski has used eclipse half-widths and Fourier components to estimate geometrical properties of the system:

[?]

the reliability of the mass-ratio determination from light-curve only data [Hambálek and Pribulla, 2013]

ROTSE study using fourier methods [Coker et al., 2013]

phenomenological study [?]

### 3.10 Future Surveys



Figure 18

## 4 Analysis Techniques

*Q: How do astronomers use their observations to learn about the physical characteristics of contact binary systems?*

Observational tests of theories of contact binaries Lucy and Wilson [1979]

### 4.1 Physical Light-Curve Modeling

The photometric light-curve of a contact binary is one of the easiest measurements to obtain.

The Wilson-Devinney Code

Fully automated approaches [Prsa et al., 2009] [Prsa et al., 2008]

recent advances in modeling code [Prša et al., 2013]

employing neural networks to find true binary parameters [Zeraatgari et al., 2015]

## 4.2 O-C Analysis

O-C Analysis is short for “observed minus computed”, referring to the fact that a measurement is the observed time of minimum light as compared to the computed time of minimum light.

1. A full light curve is obtained for the system in question.
2. Based on this light curve, the period is calculated, and an ephemeris is computed, listing all of the future times of minimum light.
3. Then, light curves are obtained at future epochs. The time of minimum light are compared to previous times of minimum light. The difference ( $O - C$ ) is plotted as a function of epoch.

On an O-C diagram, a linear change in period appears as a parabola.

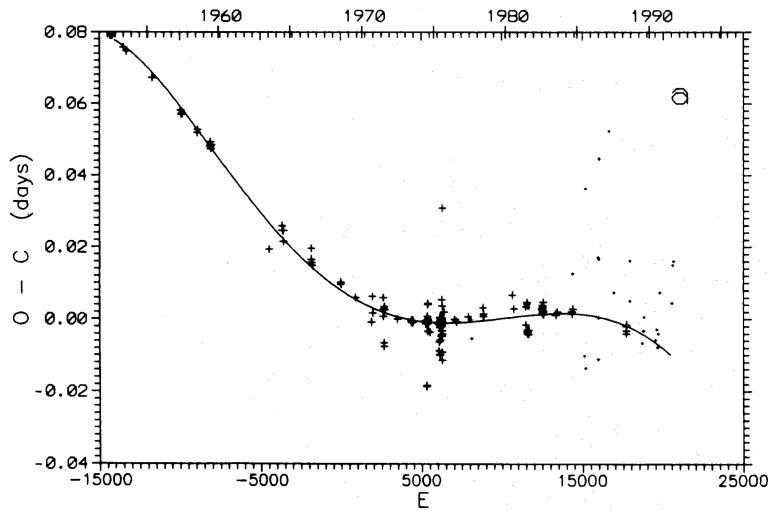


Figure 19: The O - C diagram of V566 Oph, fit by a least squares polynomial. Fig. 4a from Kalimeris et al. [1994]

On orbital period change [Kalimeris et al., 1994]

In contact systems, orbital period changes can generally be divided into (1) short-term variations, which happen on decadal (10 year) timescales, and (2) long-term variations, which happen on a thermal timescale.

Is O-C Analysis stable against the appearance and disappearance of starspots and photometric noise? [Kalimeris et al., 2002]

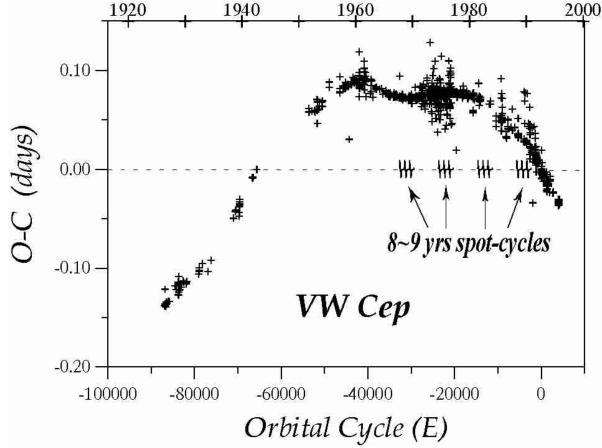


Figure 20: Fig. 7 from Kalimeris et al. [2002]

automated approach with SuperWASP [Lohr et al., 2015]

In data from surveys, the data may be too sparse to estimate times of minimum light from multiple epochs within the survey. A Lomb-Scargle (or LS) [Scargle, 1982] [Horne and Baliunas, 1986]

$$|\delta P| = (0.01728 \text{ s}) \times \left(\frac{N_0}{100}\right)^{-\frac{1}{2}} \times \left(\frac{T_{eff}}{5\text{yr}}\right)^{-1} \times \left(\frac{A/\sigma_N}{10}\right)^{-1} \times \left(\frac{P}{0.2\text{d}}\right)^2 \quad (4.1)$$

Qian [2001] has observed orbital period changes which indicate TRO.

### 4.3 Doppler Imaging

### 4.4 Fourier Analysis

## 5 Pause

Data from large All-Sky surveys is very different in nature compared data taken on a single night with a single telescope. Working with all-sky surveys presents huge advantages to working with traditional light-curve data, but it also has major drawbacks.

In “traditional” variable star observing, an observer slews the telescope to the target at the beginning of the night, and then takes a continuous sequence of images (from which she will make photometric measurements) at regularly spaced time intervals, until the star has rotated one full period, or until morning twilight. The observer can only look at one target at once, but the selected target is observed many times in one night.

In All-Sky surveys, the observing mode is different. All throughout the night, the telescope pans to a field taking a few images, and then rapidly moving on to the next field. A given source might only be observed one or two times in a given night. The survey operates

night after night, and after many years, it has amassed hundreds of observations of any point on the sky.

## 6 Light-curve Morphology

In our study, we aim to learn how contact binary light-curves vary as a function of photospheric temperature.

### 6.1 Light-curve Features

In order to understand how the light-curves change as a function of temperature, we must first figure out a way to describe a light-curve in a way that makes sense, both to humans and computers. In data science, this problem is called “feature selection” . Let’s consider what our light curve data actually is: a set of measurements of the flux of a contact binary. These measurements are taken at a certain time ( $t$ ), have a certain value, in our case a measurement of flux ( $f$ ), and this measured value has an associated error ( $e$ ). From CRTS, we obtain lots of these measurements. Our light curve looks like this:

Table 1: Format of Raw Data from CRTS

<b>time</b> ( $t$ )	<b>flux</b> ( $f$ )	<b>error</b> ( $e$ )
number	number	number
number	number	number
...	...	...

In the eight years between 2005 and 2013, CRTS observes a given source roughly 350 times. In other words, it reports about 350 timestamps ( $t$ ), 350 fluxes ( $f$ ), and 350 errors ( $e$ ) on those fluxes. So, the raw data comes to us as  $\approx 350 \times 3 = 1050$  individual numbers. These numbers are perfectly valid descriptors of the light-curve, but they are not easily understandable.

Thankfully, we can introduce some assumptions that will make the task of succinctly describing our light-curves easier. First, we assume that our light-curve is a *continuous function*. This means that there are not jumps or breaks in the true variation of light. The light-curve has a value at every point in phase, and is differentiable at every point in phase. Second, we assume that *the light-curve is periodic*: that the pattern of light variation will exactly repeat itself after some amount of time. In §7, we learn that this is not exactly true

for contact binaries when we observe them over many years. But for now, this assumption will serve us well.

Now, armed with our two new assumptions and light-curve data, we can construct a light-curve function. There are many ways to construct a continuous, periodic function from a set of data:

1. Polynomial Fit.

$$f(p) = \theta_0 + \theta_1 t + \theta_1 p^2 + \theta_2 p^3 + \dots (0 \leq p < 1)$$

$$f(p) = \sum_{i=0}^n \theta_i p^i (0 \leq p < 1) \quad (6.1)$$

2. Polynomial - Spline Fit.

$$f(p) = \dots \quad (6.2)$$

3. Fourier (Harmonic) Fit.

$$f(p) = \dots \quad (6.3)$$

There are many other forms that can be used to represent a continuous periodic function - but these are the most obvious choices. Each has advantages and disadvantages. For example, if the light-curve has large derivatives at some points in the phase (it has “sharp turns”), a polynomial spline fit may be the best choice.

We have elected to use the harmonic fit, because it has a history of use in the description of contact binary light-curves. It is easy to implement and can fit the data accurately.

Recall (as in Eqn. 3.5)

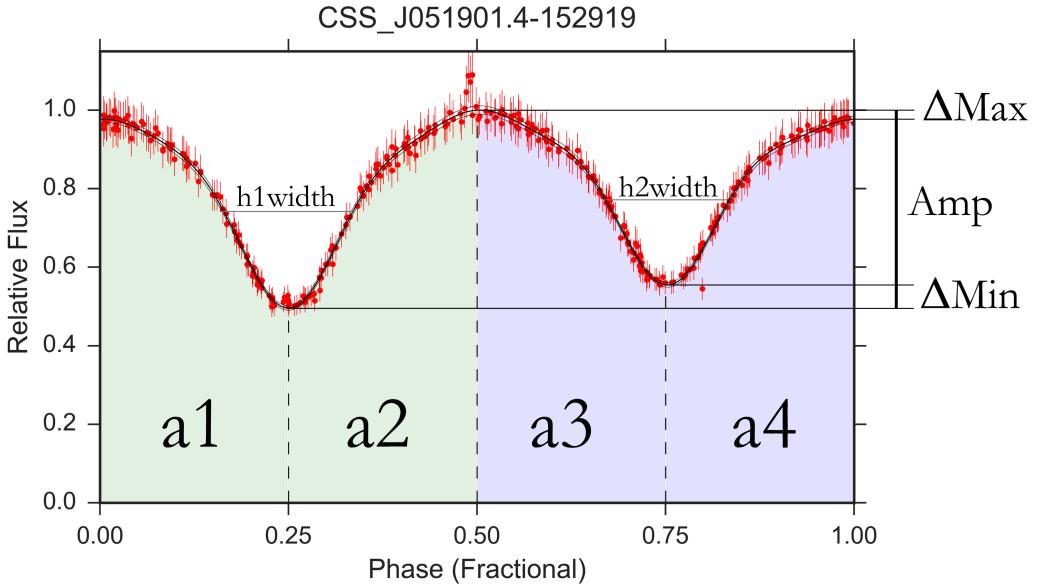


Figure 21

O'Connell [1951]

## 7 Luminosity Variation on a Decadal Timescale

In our study, we aim to learn how the luminosity of contact binary systems vary on decadal timescales. In §?? we talked about the light-curve as if it was one single function. In actuality, the shape of contact binary light-curves change over time (Eqn. ??).

$$f(\text{Phase}, \text{Time}) = \text{Flux Received at Telescope} \quad (7.1)$$

## 8 Detection of Flares

In our study, we aim to learn about the flaring frequency of contact binaries and to determine if flare characteristics vary as a function of photospheric temperature.

READ Walkowicz et al. 2011 and Shibayama et al. 2013.

Contact binaries are known X-ray sources [Chen et al., 2006]. Flare have been observed in X-ray bands using ROSAT [McGale et al., 1996]. EXOSAT has been used to observe a flare in X-ray and Microwave data on VW Cephei ( $P = 0.28$  days,  $T_1, T_2 = 5500\text{K}, 5000\text{K}$ ) [Vilhu et al., 1988]. Extreme UV observations have identified coronal characteristics [Brickhouse and Dupree, 1998]. Long time series observations of single m-dwarfs [Lacy et al., 1976]

During a continuous monitoring campaign in the winters of 2008 and 2010, Qian et al. [2014] observed a contact binary system CSTAR 038663 ( $P = 0.27$  days,  $T_1, T_2 = 4616\text{K}, 4352\text{K}$ ) for a total of 4167 hours (174 days) in the SDSS  $i$  band using the CSTAR telescope array in the Antarctic. In this time, Qian et al. [2014] discovered 15  $i$  band flares, revealing a flare rate of 0.0036 flares per hour. These 15 flares had durations ranging from 0.006 to 0.014 days (9 to 20 minutes), and amplitudes ranging from 0.14 - 0.27 magnitudes above the quiescent magnitude.

In 1049 close binaries observed by Kepler, Gao et al. [2016] have identified 234 “flare binaries”, on which a total of 6818 flares were detected. Kepler’s continuous monitoring capability and precise photometry make it extremely well suited to the detection of white-light flares [Walkowicz et al., 2011]. While CRTS does not match Kepler’s observing cadence, photometric precision, or ability to observe a given target continuously, it observes 33,000 square degrees a much larger area of the sky than Kepler does (100 square degrees) [Drake et al., 2009, Basri et al., 2005].

M-dwarfs have previously been searched for flares in Sloan Digital Sky Survey Stripe 82 data [Kowalski et al., 2009]. Our study will be similar to that of Kowalski et al. [2009], because we are also using survey observations of large regions of sky, as opposed to the continuous monitoring studies. Hilton et al. [2010] have discovered flares in the time resolved SDSS spectroscopic sample, using a Flare Line Index based on H $\alpha$  and H $\beta$  line strength.

In CRTS data, we monitor 9851 contact binaries. We aim to verify the relationships described in Gao et al. [2016], and focus on the contact binary subclass. We aim to place better constraints on the flare rate as a function of both orbital period and photospheric temperature. The dataset constitutes the equivalent of 40.6 years of monitoring continuous monitoring at an average cadence of one 30 second observation per 9 minutes.

## 9 Conclusion

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