

# Binary Systems

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The observation of STF 1169 AB and STF 42 were completed through observation request to the LCO. 4 filters were applied, and images were taken with 1 second of exposure time each, yielding a total of 15 seconds of data for each filter. The binary systems observed are chosen among a list of possible candidates filtered under the condition that the separation is greater than 3 arcsec, with primary and secondary magnitude being in the range between 7 to 10, and that they have known orbits. Such a research project was inspired by Gates et al.'s previous attempt on observing WDS 13472-6235 [1], deriving the idea to use similar magnitude of the parameters  $\theta$ ,  $\rho$ ,  $m_1$ ,  $m_2$  among the chosen candidates as well as the idea to acquire similar parameters. Possible theoretical calculations of orbital trajectories and improvements can be done upon yielding experimental data of  $\rho$  and  $\theta$ .

## I. INTRODUCTION

### A. History of binary star

The first ever visual binary star was discovered soon after the first telescope was built. J.B. Riccioli made the first discovery of a binary system in around 1650, roughly when I. Newton was 7 years old. Soon after comes Wilhelm Herschel, who was the owner of the then largest telescope in the world. He aimed to examine the speculation of "smaller suns revolving round larger suns", which was proposed and predicted by C. Mayer, and I. Newton respectively in their own time. Herschel then set out to "examine every star in the heavens", which is the motivation that fuels astronomy research even to these days. His aim was to examine the differential parallaxes since he did not believe in binary stars being physical systems. In 1782, he published his first catalogue consisting of 269 binary stars, followed by 434 additional binary stars in 1784 with the assistance of his sister Caroline as he continued his observation. Later in 1803, Herschel yielded experimental results that was the first observational evidence in agreement with "the universality of Newton's law of gravitational attraction". These results are worthwhile to study since the observations are made with a telescope mounted on a stand with only 2 degrees of freedom, or to be more mathematically formal, the telescope is only adjustable in  $\theta$  and  $\phi$  in spherical coordinate. Some other important experimental results were also published in 1797 as a revision in regards to relative positions having shifted that are not due to differential parallaxes. [2]

Another important figure other than Herschel was Friedrich Georg Wilhelm von Struve. Born in April 15, 1793, he was an astronomer and geodesist from the Struve family. He fled to Imperial Russia during the French occupation of Germany, where he began the study of astronomy and pursued his passion for astronomy around 1808. Joseph Fraunhofer gifted

Struve a nine-inch telescope, also known as "the Great Refractor" for its equatorial mounting drive that can eliminate drift of stars due to rotation of the earth. Such a gift motivated Struve to discover most of the new stars, even though most of the binary stars have been discovered by Herschel. He also used "the Great Refractor" to make measurements of angular separation and position angle for 2,714 double stars.[3] the STF convention of binary star documentation is also rightfully titled STF, which stands for "STruve Friedrich". One of the discoveries by Struve includes STF 42 AB, a binary system that we are currently studying.

### B. What is a binary star?

Binary stars are worthwhile to study because fundamentally, a binary system can compose of two or more stars, and that the binary system of star A and star B, having an orbit around one another due to gravitational coupling, can also orbit around a larger system. Most observable binary stars consist of triple or higher number of bodies. For any binary systems with more than 2 bodies, the center of mass of the other orbiting stars is used as the reduced mass of the secondary star. Different types of binary stars are: Visual Binaries, Spectroscopic Binaries, Eclipsing Binaries, Astrometric Binaries, "Exotic" Binaries.[4] More importantly, visual and spectroscopic binary stars are of research interests because they can offer fundamental information about the stellar masses, which can be used to extrapolate other fundamental information.

Our current research is focused on visual binaries, as we will use Las Cumbres Observatory to continue our observation.

STF 1169AB is a binary star system located in a constellation called Camelopardalis, STF 42 is a binary system located in a constellation called Andromeda.

## II. INSTRUMENTATION AND METHODS

### A. Choosing the appropriate candidates

#### 1. Background

One of the justifications of setting  $\rho \geq 3$  is that this is the requirement set by the Pulkovo program of observations and studies of visual binary systems, using a 26 inch refractor, specific to the photographic technique of theirs that differs from Spectrometry, Photometry and Speckle Interferometry. Note also that classical methods of determining orbits of these binary system is not applicable, due to their unusually large orbital period of at least 300 to 500 years. Such a large period is also justified due to their angular separation  $\rho \geq 3$ . The objective of their research is to provide basic kinematic and dynamical parameters of multiple stellar systems through the use of astrometric observation. Thus, the determination of their orbits, masses, and orbital orientations can be calculated, yielding appreciable relative motions. A.A. Kiselev and O.V.Kiyaeva have constructed a mathematical model in calculating the orbit called "the method of Apparent-Motion Parameters" (AMP), which can be applied to binary stars, provided the binary system also has information on trigonometric parallaxes and radial velocities relevant to position observations.[5]

$$r^3 = k^2 \frac{\rho \rho_c}{\mu^2} |\sin(\theta - \psi)| \quad (1)$$

$$k^2 = 4\pi^2 M_{AB} \quad (2)$$

In the above expression, we can clearly see that the orbital period has a dependence on a list of parameters:

$\rho$  — the angular separation from Primary Star to Secondary Star (arcsec)

$\theta$  — the position angle of the relative position (deg)

$\rho_c$  — the radius of curvature of the observed short arc of the orbit (arcsec)

$\psi$  — the position angle of the direction of relative motion (deg)

$\mu$  — the apparent relative velocity (arcsec/year)

Holding  $\rho_c$ ,  $\psi$ , and  $\mu$  constant, the above expression can yield a theoretical periodic trajectory of the binary system, and one will be left with  $\rho$  and  $\theta$  to go about their calculation of the orbital trajectory.[5][6] However, if the other three parameters are not specified, the calculation may have ambiguity, considering  $\mu$  is also a parameter that needs experimental data.

The parameter  $\mu$  above is another parameter to be measured experimentally, to yield common proper

motion, one can find  $\frac{\rho}{\mu}$ , which gives a "short-lived" approximation of the orbital period of 1000 to 3500 years.[7] ( $\mu$  changes over time)

AMP model is capable of calculating an orbital trajectory. However, it requires utilizing trigonometric parallaxes and some components of the radial velocities, meaning the two stars will have to be observed separately in order to yield the two parameters, either at a different time, or at another location far from the original location of observation.[8]

Other approaches to calculating the orbit are possible, but would be out of the scope of this immediate research. One worth mentioning briefly is the Thiele-Innes Method, a method complementary to AMP and offers invaluable insights for possible correction to AMP, which uses the eccentricity  $\sqrt{1 - e^2}$ , and a system of 2 equations for the respective positions  $x_i = AX_i + BY_i$  and  $y_i = FX_i + GY_i$  as its main parameters to go about a Least Square Method (LSM)  $\sum_j \frac{\partial x_c}{\partial p_j} \Delta p_j = y_{oi} - y_{ci}$  to minimize deviation  $\Delta p_j$ , which, without going into too much detail of what  $\Delta p_j$  is, is a dynamical element depending on other implicit variables. This is a method of extrapolation to numerically yield an orbit. Such an approach results in a nonlinear LSM solution if solved symbolically, and its solution to the orbit results in a 7-Dimensional Space, and many other unknown parameters remain unresolved.[8] The currently known theory does not appear to have the intention of providing a truly deterministic solution, and rather, they only aim to provide a forecast of the system's trajectory within the next 500 years to 1000 years, which may or may not be a great estimate considering most orbits require a period of over 1000 years, similar to the model of weather forecast.

One may claim that 5 parameters are manageable, but as I quote Enrico Fermi here, "I remember my friend Johnny von Neumann used to say, with four parameters I can fit an elephant, and with five I can make him wiggle his trunk." [9] While the theoretical construct provides valuable insights of the orbits of the binary systems, no one can be certain as to whether the above mathematical expressions are truly precise or not.

The motivation behind the study of binary system is that it offers valuable insights about galactic dynamics, evolution of stellar matter, hinting at possible exoplanets outside of the solar systems, offering hints at the origin and evolution of binary systems. This gives motivation and hints to another research for the calculation of habitable zones outside of the solar system. One must also keep in mind that theoretical models for short binaries cannot be applied to wide binaries since the estimation will give several tens of stellar mass, far off of its appropriate magnitude, which can be confirmed with mass-luminosity

relation. [10] Thus, corrections to the AMP method is necessary.

## 2. Principles

Once the candidates are chosen, each binary system is to be observed by applying 4 filters: Bessel B, Bessel V, SRSS r', SRSS i'. Every filter is used to take a total of 15 images with exposure time of 1 second each. Once the data is yielded, python scripts would then be used to process the images. One can also use AstroImageJ to process the images the same way.

## 3. Python: Parsing and Filtering List

Given that Stelledoppie has more than 20,000 binary stars documented, many of which have intensity of light either being too high or too low, separation angle being too small, high airmass, processing is necessary to filter out stars that are not of interest. First, the candidate must have a known orbit, and must be main and physical double with (separation[= $\rho \geq 3$ ), and  $7 \leq m_1, m_2 \leq 10$ . These criteria are incorporated into the python script, so that after parsing and filtering the list with the criteria, the chosen candidates will be the appropriate candidates.

Another use of python script is to sort the two types of data: e00 and e91. "e00" is the raw data with no compression; "e91" is the data after compression. Only e91 data is necessary to process simply because compressed data is easier to work with than e00, which has lower resolution. After sorting them into their respective folder, each folder containing the image files is run through a nested if else if statement to be sorted into folders of their respective filters, having a  $\text{len}(\text{image}) = 15$  for all filter folders. At last, a total image sum for all images in each specific filter was yielded with a for loop over the 15 (2000+ x 1800+) arrays. Star coordinates in the image were also parsed and stored into a DataFrame.

## B. Python: Processing

The script provided by LA Sam Whitebook has a function defined previously called photometry, and in it contains another function called DAOSTarFinder imported from photutils.detection library, which finds the coordinates of the star in the image. Photometry is a function that returns 3 variables: time, positions, and aperture sums. There are also statistics computed using functions imported

from photutils and astropy libraries including the background noise and the mean background noise. These parameters are used in other parts of the script in order for the photometry function to work properly.

In picking out certain stars, the FWHM is incorporated to filter out unwanted stars since the galaxy is filled with stars in every corner possible. The definition of a full width half max (FWHM) is the length between the two halfway points of a Gaussian bell curve, which can be applied when analyzing the stars in the photo. For example, if the area of the star that appears on the image has a FWHM less than the threshold input radius/diameter, then the function DAOSTarFinder will not identify that bright dot as a star. Once the list of stars are identified, the list will be stored into a variable as a QTable, which will eventually be converted into a DataFrame for immediate ease of access.

Coordinates of the stars were stored into a variable as a QTable / DataFrame. One can convert the pixel coordinates into arcsec and degrees, but our group carried out the calculation using other astronomy softwares and excel due to insufficient time, and despite the conversion itself being a scalar, no one else in our group had enough understanding of how the python script works to know the conversion.

## C. Instruments

An astronomical telescope contains 2 converging lenses, one being the objective lens and the other being the eyepiece. Objective lens aims to converge light rays from spatial infinity into the focal point that overlaps with the eyepiece focal point. The eyepiece simply is there to form another compound lens system with the eye to flip the image from upside down to normal.

The above is worth addressing since our data uses a 0.4m Refractor Telescope whereas the Pulkovo's Observatory uses a 0.66m Refractor Telescope. While the results of the image may be minimal, possible discrepancy in data and precision between Pulkovo's and ours could be justified for this reason. For example, the magnification of image can be different, thus resulting in a slight numerical difference when calculating the  $\theta$  and  $\rho$ , and SNR, or the size of the star appearing on the image may also differ, not matching up with the scale of the image of another telescope, which should be of little relevance in our work, but important to note in the calculation when converting from pixels to arcsec or degrees.

### III. RESULTS

The mathematical expressions used to calculate  $\rho$  and  $\theta$  are found in Buccheim's article.[11] They are:

$$\rho = \sqrt{(\Delta\alpha \cos \delta_1)^2 + (\delta_2 - \delta_1)^2} \quad (3)$$

where, by small angle approximation,

$$\Delta\alpha \ll 1 \text{ and } |\delta_2 - \delta_1| \ll 1 \quad (4)$$

and

$$\theta = \tan^{-1}\left(\frac{\Delta\alpha \cos \delta_1}{\delta_2 - \delta_1}\right) \quad (5)$$

The data from each image is extracted and excel was used to process the data from each set of filter.

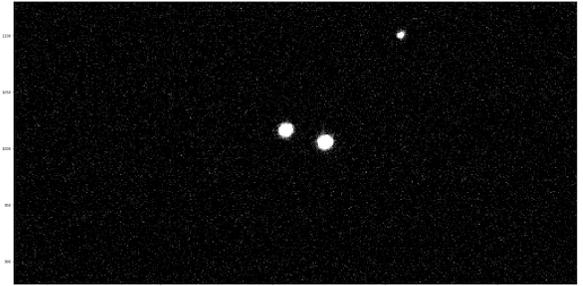
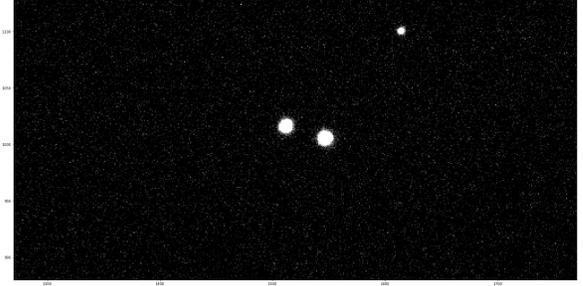
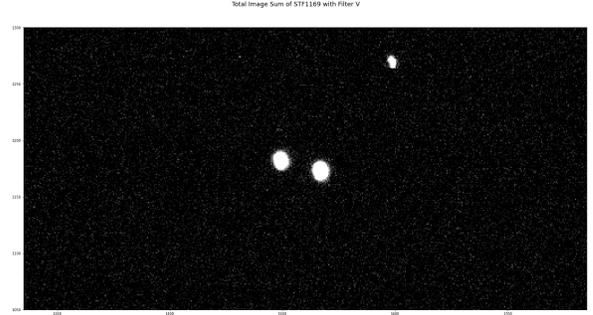
#### A. STF 1169 AB

Results for STF 1169 are as follows:

STF 1169 Averages		
Filter	$\rho$ (SEP) [arcsec]	$\theta$ (PA) [deg]
Bessel V	20.773	15.074
Bessel B	21.079	14.637
SDSS r'	20.862	15.717
SDSS i'	21.062	16.395
STDEV	0.1506	0.7672
STDError	0.0753	0.3836
Average	20.944	15.456
Data Comparison to Theory in 2022		
2009 Theory[5]	20.497	16.5
2022 Exp't	20.944	15.5

The data matches up and does not fall too far off from theoretical calculation. Images are attached at the very end of the paper. For separation, the standard deviation, and error are small, so the whole set of data appeared to be fairly consistent. On the other hand, the position angle seems to move around a lot, resulting in relatively large standard deviation and possibly slightly larger error.

See also:



The images are in the order of B,V,R,I, top to bottom. STF1169 Bessel B and V are taken with 0m4b aqawan, a 0.4m Refractor Telescope at Teide Observatory in Tenerife, Spain. STF1169 SDSS r' and i' are taken with 0m411, a 0.4m Refractor Telescope at McDonald Observatory in Fort Davis, Texas.

#### B. STF 42 AB

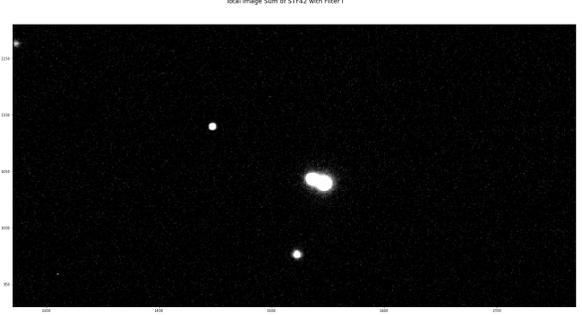
Results for STF 42 are as follows:

STF 42 Averages		
Filter	$\rho$ (SEP) [arcsec]	$\theta$ (PA) [deg]
Bessel V	6.2341	20.158
Bessel B	6.3257	21.641
SDSS r'	6.2656	19.960
SDSS i'	6.2214	19.864
STDEV	0.0465	0.8323
STDError	0.0232	0.4161
Average	6.2617	20.406
Data Comparison to Theory in 2022		
2009 Theory[5]	6.333	20.0
2019 Theory[10]	6.287	20.5
2022 Exp't	6.262	20.4

The data matches up with the theory prediction, with the newer orbit calculated in 2019 to be more accurate compared to the older orbit calculated in 2009. The deviation and error for  $\rho$  are relatively small, but deviation and error for  $\theta$  is greater. Note that the calculated orbit for 2019 has LSM method incorporated.[10] Images are attached at the very end of the paper.

Since our group had run into some difficulty parsing historical data from the WDS and Stelledoppie, we can only cite their graphs for discussion purposes. Historical Data as well as its orbit plotted on both 2009 orbit and 2019 orbit are locally indifferent, indicating a good sign of consistency. However, Once the trajectory is past a few hundred years, the trajectory drastically differ from one another.

See also:



The images are in the order of B,V,R,I, top to bottom. STF42 Bessel B and V are taken with 0m411, a 0.4m Refractor Telescope at McDonald Observatory in Fort Davis, Texas. STF1169 SDSS r' and i' are taken with 0m4b, a 0.4m Refractor Telescope at Haleakala Observatory in Maui, Hawaii.

#### IV. SIGNAL TO NOISE RATIO

The following expression was used, as adopted from lecture note:

$$\frac{S}{N} = \frac{FA_\epsilon\tau}{\sqrt{N_R^2 + \tau N_T}} \quad (6)$$

where

$$N_T = FA_\epsilon + i_{DC} + F_\beta A_\epsilon \Omega \quad (7)$$

and

$$A_\epsilon = A_\epsilon Q_\epsilon \quad (8)$$

One of the documentations included the numerical data for the value of flux for different filters.

SNR pass band	
Filter	Flux at $m = 0$ [Jy]
B	4260
V	3640
R	3080
I	2550

The other values in the calculation were  $N_R = 14e^-$ ;  $i_{DC} = 0.02e^-/s$ ;  $Q_\epsilon = 0.2$ ;  $F_\beta = 0.1\text{cps}/(\text{cm} \times \text{arcsec})^2$ ;  $\Omega = 9.571\text{arcsec}$ ;  $\epsilon = 0.5$ ;  $\tau = 1\text{s}$ ;  $A = 1200\text{cm}^2$ . The calculation for each set of filter with BVRI values from the SNR Pass band table plugged in is as follows:

SNR calculation result			
Star	Filter	F	SNR
1169	V	307.75	$1.916 \times 10^2$
1169	B	495.23	$2.434 \times 10^2$
1169	i	402.44	$2.193 \times 10^2$
1169	r	332.16	$1.991 \times 10^2$
42	V	210.96	$1.585 \times 10^2$
42	B	339.48	$2.013 \times 10^2$
42	i	275.87	$1.449 \times 10^2$
42	r	227.69	$1.647 \times 10^2$

One can see that the magnitude of the signal to noise ratio is  $10^2$ , hence showing good enough distinction between background noise and the star objects. Since the SNR is decent, finding the log of the total image sum array would be appropriate, and can reduce the saturated and pixelated texture of the image, and also eliminating most of the background stars.

## V. DISCUSSION

### A. Our Group's Data

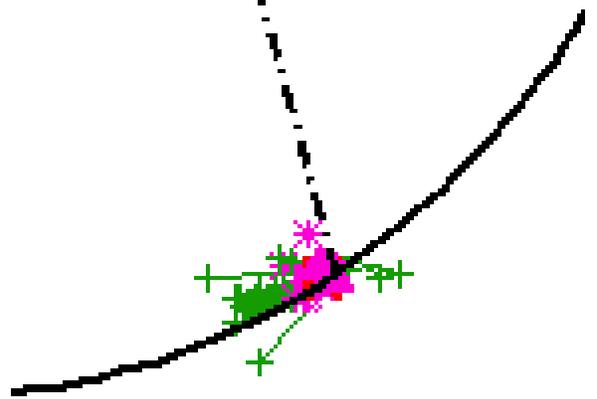
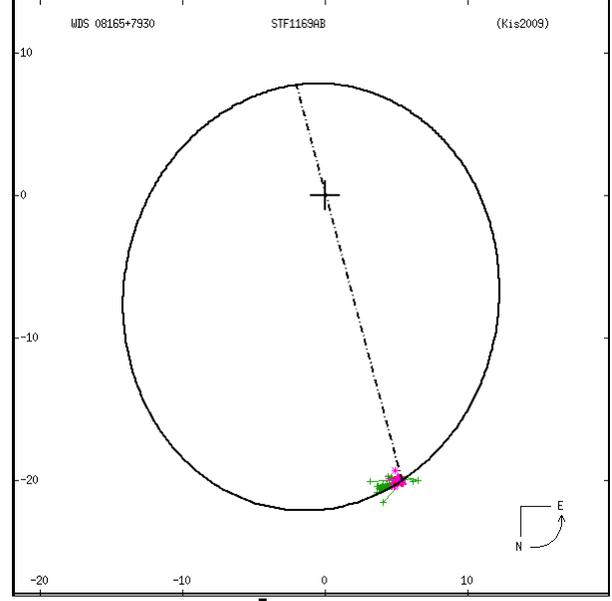
#### 1. Data

Our group's data for both STF 1169 and STF 42 did not deviate too far off from the theoretical calculation done in 2009 by Kisselev, Kiyaeva and Izmailov [5], with even less deviation with the calculation from the more recent calculation in 2019.[8] See table in Results.A/B. However, we were unable to properly compare our results with the historical data on a plot since we encountered software issues. One can see that  $\theta$  increases over the years. Initially, only Bessel B and V filters were used. Upon consulting with Dr. Lubin, SDSS r' and SDSS i' were also used afterwards.

See below for historical data for STF 1169.

STF 1169 Historical data		
Year	$\rho(\text{SEP})$ [arcsec]	$\theta$ (PA) [deg]
1832.35	20.74	10.1
1900.35	20.82	11.5
1930.19	20.913	12.8
1947.27	20.8	13.8
1962.227	20.692	14.962
2018.973	20.56	15.13
2022	20.94	15.5

Data above is yielded from WDS Catalog and our data is requested from LCO observatory.[12]



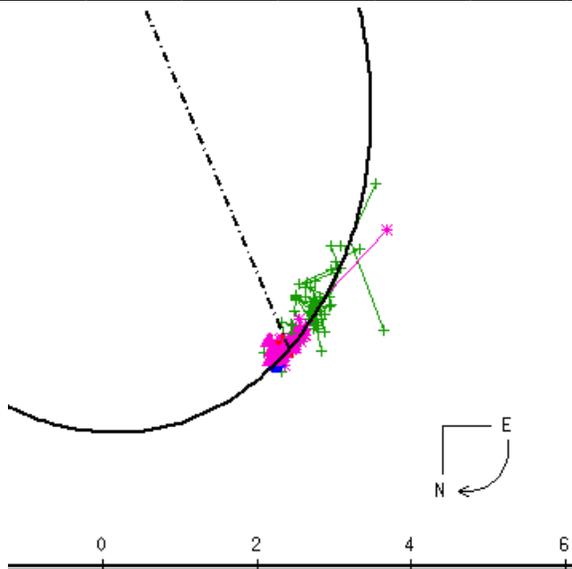
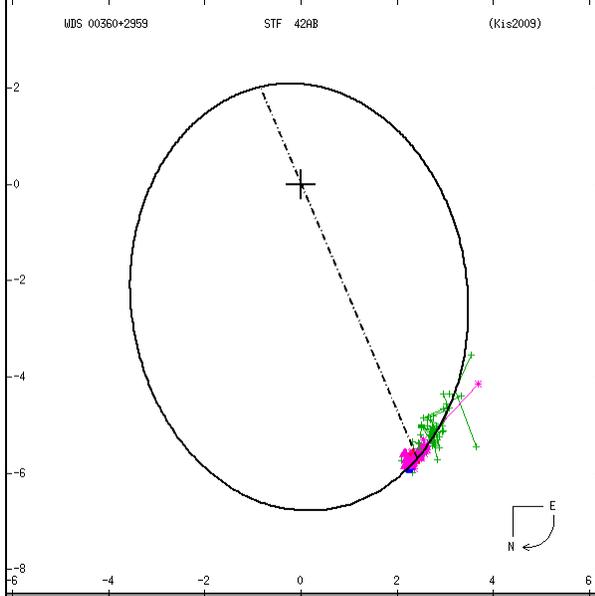
The above data are from VizieR Catalog and Kisselev et al.[5] Image at the top shows the orbit and the local data plotted. Image at the bottom shows the zoomed in area where the historical data are plotted. Our observed data correspond to the historical data, and numerically speaking they are in the same region.

Data of STF 1169 shows that the separation between two stars remain practically the same over the span of 190 years, with  $\theta$  steadily increasing, hinting that the secondary star is orbiting around primary star and that the secondary star is moving away from its primary star.

See below for historical data for STF 42:

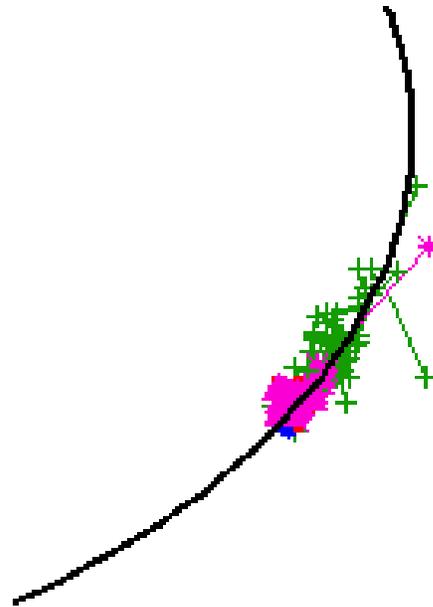
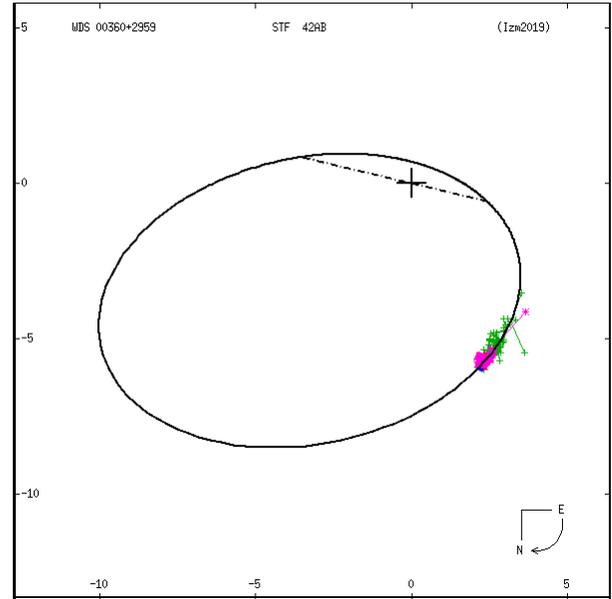
STF 42 Historical data		
Year	$\rho$ (SEP) [arcsec]	$\theta$ (PA) [deg]
1824.88	6.55	33.7
1895.92	5.56	28.3
1948.71	5.76	25.6
1984.877	6.120	22.879
2015.632	6.2838	20.945
2020.74	6.037	20.82
2022	6.26	20.41

Data above is yielded from WDS Catalog and our data is requested from LCO observatory.[12]



The above data are from VizieR Catalog and Kisselev et al.[5] Image at the top shows the orbit and the local data plotted. Image at the bottom shows the zoomed in area where the historical data are plotted. Our observed data correspond to the historical data, and numerically speaking they are in the same region. Note that this is the orbit

calculated in 2009 by Kisselev et al.[5]



The above data are from VizieR Catalog and Izmailov et al.[8] Image at the top shows the orbit and the local data plotted. Image at the bottom shows the zoomed in area where the historical data are plotted. Our observed data correspond to the historical data, and numerically speaking they are in the same region. Note that this is the orbit calculated in 2009 by Izmailov et al.[8]

Data of STF 42 shows that the two stars are getting closer to each other, and the secondary star is approaching from beneath the horizontal axis in a 2D plane of the binary star.

## B. My opinion of the theory

The theoretical framework of AMP method contributed by Kiyaveva, Kisselev and Izmailov, as mentioned in [6][5], addressed that orbit calculations are primarily based off of 2 parameters, but the other 3 parameters are of equal importance. One may argue that the other three parameters do not differ too much over the years since locally the data is somewhat indifferent, but notice that the trajectory past 200 years is when the two orbits no longer overlap. If the orbit is treated as a Lissajous curve, its "eigenvalue" would drastically differ, resulting in many different changes, including its geometric phase, to the system that are out of context in this paper. One should keep in mind that the nature of this theory can only provide a trajectory forecast as oppose to finding its deterministic solution.

## C. Possible Improvement

If our group was to carry out some theoretical calculations, and to improve the theory ever so slightly, one could have used Monte Carlo Simulation to generate random sampling data in or slightly past the local region for possible scattering points for the orbital calculation. Note that Monte Carlo Simulation is a computation method taught in 129L.

Also, we could have generated our own orbit and compared how close our orbit is to the other already available theoretical calculations, compare the calculated period and to compute its discrepancies among other orbits. In the model of STF42, two calculations have been done previously by the same group of researchers, their period was roughly 1000 years in 2008[5], the latest calculation in 2019 was 4000+ years.[8]

In the error analysis, mass-luminosity relation can also be used as a double check for how far off our calculation is for the stellar mass  $M_{AB}$ . Our group could have also attained the parameter  $\mu$ , or learned to calculate it had we realized sooner finding mass-luminosity relation was also possible.

In the data analysis section, the standard error is calculated, and the error should be minimized since the different filters gave results that are not as coherent as desired. Possible solution to this would be to find the sum of the images of 4 different filters together and see if  $\theta$  and  $\rho$  are still consistent and within acceptable range. However, since the images are taken at a different location on earth, the parallax is something to keep in mind and it needs to be addressed mathematically. Otherwise, it may affect the quality of the image sum, resulting in effects similar to chromatic aberration even though the telescope has no issue with refraction. If enough assistance is presented, our group could also have attempted back estimating the binary star's stellar mass.

## VI. ACKNOWLEDGEMENT

I would like to take my time and thank our TA Jeonghwa Kim for taking the time to review my draft and essay, as well as helping me with ideas and some portion of the coding, and Miranda Lawrence and Emily Gates for allowing me to discuss with them as well as the collaboration. Thanks to their advice, I was able to reorganize my thoughts and convey the ideas clearly.

This work makes use of observations from the Las Cumbres Observatory global telescope network (LCOGTN), Washington Double Star Catalog maintained at the U.S. Naval Observatory, stelledoppie at <http://www.stelledoppie.it> and the VizieR catalogue access tool, CDS, Strasbourg, France.

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