Comparative Analysis of Star KIC 8462852 – "Tabby's Star"

A Photometric and Radio Wave Research Project Investigating the Star's Magnitude Variations

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Dr. Keith Woodman

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ABSTRACT

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KIC 8462852 is host to strange variations in its magnitude, as discovered by the Kepler spacecraft, which led to many hypotheses to explain this star; with ideas ranging from planets to star spots. Nicknamed Tabby's Star, it has drawn the attention of many astronomers as these explanations have been investigated. The purpose of this research is to conduct a comparison between optical and radio wave data, exploring the presence of hydrogen gases associated with the Milky Way band surrounding Tabby and its magnitude variations. The study used a 24 inch CDK telescope, Kepler and TESS archives and 1420 MHz radio observations. Additionally three other stars were added to the study as reference points based on their locations relative to the Milky Way band. This study found no correlation between planet hosting stars and Tabby's light curve; however it did uncover one between dense hydrogen intensity and several of the magnitude spikes of Tabby. Also seen was a paired pattern of increased brightness that remains mysterious. It is concluded that Tabby is showcasing dense regions of gas as a result of the Earth’s motion through the Milky Way band and that future radio observations can reveal more about this strange star.

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Introduction

Positioned at roughly 1470 lightyears away, a seemingly normal yellow dwarf star would become famous after being seen by NASA's Kepler space telescope launched in 2009 (the 400th anniversary of the telescope) (Schaefer, 2016). Discovered by accident, this citrine colored star has helped change perceptions about stellar science and continues to perplex astronomers.

History

Launching on March 6, 2009, Kepler began its main objective to observe a small area of the sky containing over 150 thousand sun-like stars, in order to capture the dimming of light caused by exoplanets crossing in front of those stars (Johnson; Dunbar, 2017). In all, Kepler produced data that led to the confirmation of 2741 new exoplanets, including its extension mission K2; together both parts of the star survey found 3311 additional candidate planets (NASA; Caltech, n.d.). Kepler observed a total of 530,506 stars, and also detected fluctuations in brightness indicative of variable stars rather than transiting planets (Brennan; NASA:JPL, n.d.). The telescope was retired at the end of 2018 after a successful nine year run, providing data to sort and analyze for decades to come (Johnson; Dunbar, 2017). Some of the variables found by Kepler were previously unknown or too dim to detect without its aid; but one such star had been in a centuries old archive and was now designated KIC 8462852 (Becker, 2018).

The collaborative effort of amateurs working in a program called Planet Hunters, maintained by the online citizen science organization, Zooniverse, helped to sort the Kepler data on potentially transiting planets. This garnered the efforts of thousands of people worldwide, all looking at the same sets of patterns as a star's light would dip and rise. In 2011, these volunteers spotted KIC 8462852 for exhibiting something unusual in its dip, it was not like the rest but rather asymmetrical and irregular in its pattern; it was first noticed by the Canadian volunteer Adam Szewczyk (Becker, 2018). The lead professional scientist who eventually analyzed this star was Yale postdoc, Tabetha Boyajian, now a professor at Louisiana State University, for whom the system was given the nickname of Tabby's Star (Becker, 2018). It was discovered that this star already existed within the archives of the American Association of Variable Star Observers (AAVSO), with observation dates as old as 1890.

The AAVSO was founded in 1911 by the Harvard College Observatory (HCO); and began from the work performed by a large group of women astronomers there under the employment of Edward Pickering (AAVSO, 2019). Together they cataloged several thousand stars and measured their magnitudes with high precision, such that they discovered many varying in brightness. They detected new types of variables and plotted their magnitudes, as images were taken on photographic plates and analyzed (AAVSO, 2019). As the collection of these stars grew, William Olcott and Edward Pickering founded the organization, and it has become a joint effort of professionals and amateurs alike continuing such work. There are now over 100 participating countries, and the organization hosts a database of more than 34 million variable star observations and data (AAVSO, 2019). Today, the AAVSO continues to put out campaign calls for variable star observations, as was the case with Tabby's Star. Given both the public interest and request for further study by Professor Boyajian, the AAVSO put out the call to their members to keep this star at the forefront of their members' observational attention. From this call many more observations came into the AAVSO international database (AID) and provided more points for further study by Boyajian and others. Like many other stars, this one had its brightness measured at least once in 1890 and infrequently afterwards as the hunt for variable stars continued at HCO (AAVSO, 2019; Schaefer, 2016).

Over the years, Tabby's Star has shown a trend for irregular dips and peaks in its light curve with odd intervals that currently remain unexplained, but this is not the first star to do so. Among the millions of observations and thousands of stars in the AAVSO database, there are a vast number of "irregular" type variable stars that also display an unusual set of highs and lows with some unpredictability as well. What has set Tabby's Star apart from the rest of these however, is that it was discovered by the work of average citizen participation in a scientific endeavor, along with its catchy name. It has since driven public interest, which has swollen the desire and urgency to understand its irregularities, even propelling some unusual and outlandish explanations like alien technology. The study of stars, including Tabby's Star, persists with ongoing sky surveys by both ground based and space based observatories, such as Hubble, Kepler, All Sky Automated Survey for Supernovae (ASAS-SN), Pan-STARRS, private university observatories, and more. Each of these surveys supplies data on countless millions of stars with parameters including distances, metallicity, spectral class, age, magnitude, temperature, and any companion(s).

The HCO was also responsible for the discovery and configuration of the Hertzsprung – Russell diagram, relating temperature, luminosity and spectral class together. This revealed the main sequence pattern followed by stars for the duration of the hydrogen fusion stage as well as where other class stars relate to this life cycle, like giants and dwarfs. For reference, the HR diagram in Figure 1 shows the main sequence and corresponding instability strips that stars cross upon departing the hydrogen fusion phase.

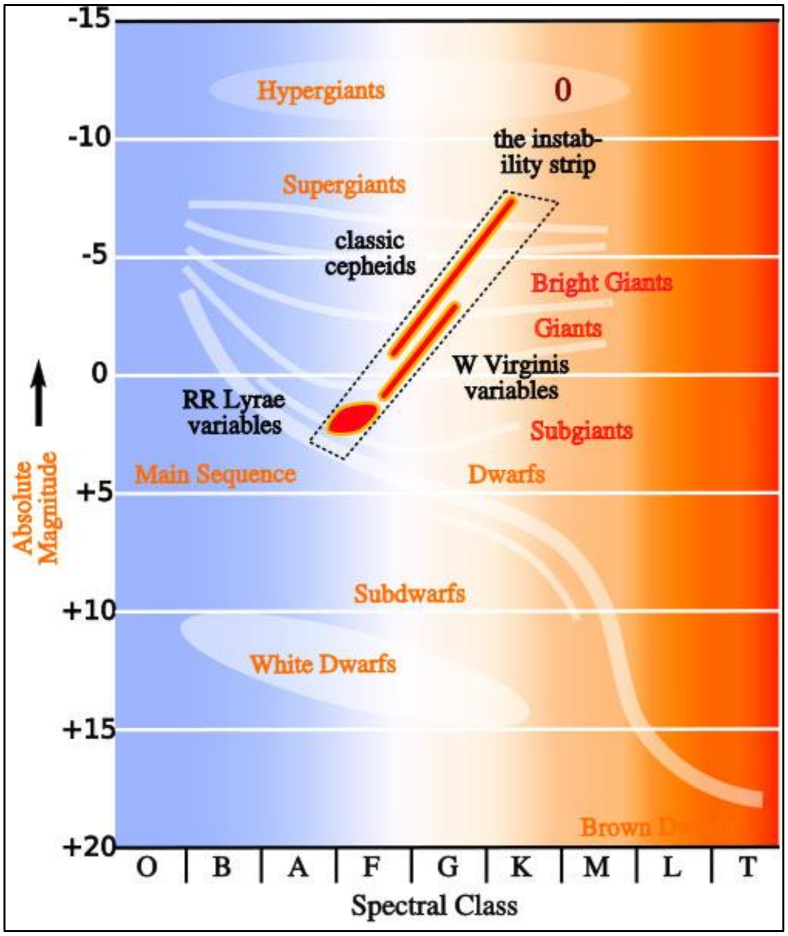

Figure 1. Hertzsprung-Russell Diagram (Pennsylvania State University, 2018).

There are a wide variety of properties that can be exhibited by stars while following that journey of hydrogen fusion, and it is the mass and composition of a star that dominate the determination of a its continued life and behavior over other intervening factors. Thus some information on the formation and evolution of stars is important to review before delving into the properties and current studies of Tabby's Star.

Star Formation

The gravitational collapse of a hydrogen and helium gas cloud with trace amounts of other elements and a smattering of silicate dust grains is determined to occur when the mass reaches a sufficiently high value so as to efficiently promote the fusion of hydrogen and the stability of hydrostatic equilibrium in its core (Salaris; Cassisi, 2005). The relationship that describes such an occurrence is:

$\boldsymbol{M > M_J = (\frac{3}{4\pi\rho})^{\frac{1}{2}} * (\frac{5K_BT}{G\mu m_H})^{\frac{3}{2}}}$; where M is the minimum mass of the cloud, MJ is the Jeans mass (which for fixed compositions, and typical cloud densities and temperatures is 10^5 solar masses), ρ is the cloud density, T its temperature in Kelvin, G the gravitational constant, K_B the Stefan Boltzmann constant, m_H the reduced mass of hydrogen in the cloud and μ is the molecular weight of the cloud (Salaris; Cassisi, 2005). Once a successful collapse takes place and the internal pressures have risen to the minimum of $\boldsymbol{\frac{Gm_r}{r^2}}$, hydrogen fusion can begin (Salaris; Cassisi, 2005). The actual fusion process is completed by the method of two nuclear chain reactions, the proton-proton chain (p-p), which accounts for 85% of the gained energy from nuclear fusion, and the carbon-nitrogen-oxygen (CNO) cycle, making up the other 15% (ATNF, 2018). Other characteristics play a role in the materialization of a star, such as rotation, magnetic fields and metallicity. Internal radiative energy streaming from the core is disrupted by high velocity rotation, and fosters the mixing of plasma through the star's layers; this does cause some variability in luminosity as does the percentage of metals contained therein, especially in stars formed at masses greater than 30 solar masses (Brott; et al., 2011). While the rotation of a newly formed star can cause fluctuations, it also provides some angular stability to its motion and aids in internal mixing, whereas the presence of a magnetic field can constrict this free flow, but maintains the convective layering distinctions as hydrogen fusion continues (Petermann; et al., 2015). Star formation is a delicate process that involves many participant factors, each bearing weight on the resultant star characteristics, including Tabby's Star.

Proposal

As an individual star, KIC 8462852, or Tabby's Star, represents a point of stellar evolution in a long life cycle, and it warrants further research, for as more is learned about this star, more will be learned about the lives and evolution of stars as a whole. Not everything learned about one star can be applied to the entirety of stellar evolution, however it can relay information about an interesting situation, just as each star studied has led to the current understanding of star formation described above, and allows for the exploration of new possibilities in physics. This star in particular is an oddity among its stellar class, among variables, and its surrounding stars. It displays strange light curve characteristics that has propelled many investigations and continues to drive scientists' curiosity. Until the questions surrounding Tabby's Star's properties and fluctuations causes can be answered, this star must remain a topic of study. Tabby's Star has additionally accomplished public attention with its intriguing history and the current endeavors of stellar research that have been engaged to understand this star. It is likely to continue garnering public interest in space science. This study will analyze optical and radio data of Tabby's Star to determine the nature of the magnitude fluctuations it has exhibited. It is believed and so analyzed here, that the motion of the solar system through the galactic plane has introduced a denser region of the interstellar medium in the line of sight of Tabby's Star and Earth. So the analysis will be examining the dominant hydrogen gases in radio wavelengths for Tabby and three other comparison stars (5 Aurigae, HIP 26587, and 14 And). Concurrently photometric observations will also be utilized in this research for any optical correlations with hydrogen density. The next section begins with a review of current research on Tabby as it relates to this project and the progress made in understanding the star; followed by this study's methodology and the results from those obtained observations. The study will conclude with a summary of the analysis conducted herein and a point toward future work.

Literature Review

Tabby’s star has been on an interesting road of discovery as discussed above, and it has come to light at a good time for more advanced observations to unravel its mysteries. Tabby is not just a star, but one that is so peculiar that it has evoked a popular response from the amateur and professional community alike. Understanding this star may very well prove to be a stepping stone in comprehending a massive bank of other stars, no matter what the true cause behind its brightness changes. Since its observations show up so strangely, when plotted it represents an oddball object among whatever stellar category it fits into, and it will remain a hindrance to fully grasping the physics of that group of stars as long as Tabby maintains these secrets. The quest to understand this star goes beyond just astronomical curiosity however, for learning about stars ultimately means learning about the solar system’s star. The importance of this specific star has driven many projects, and the body of knowledge currently available covers the data collection on Tabby and possible explanations for its irregular variances, however none of these have completely confirmed its mystery. A hole in the scope of knowledge regarding this star lies with radio data, which is to be addressed in this research paper. Radio observations and methods (to be discussed in detail in the next section), have potential to help explore the subject of this odd star. The use of a different wavelength and the comparisons of many hypotheses will ultimately add more data available on Tabby, and eliminate some of those propositions.

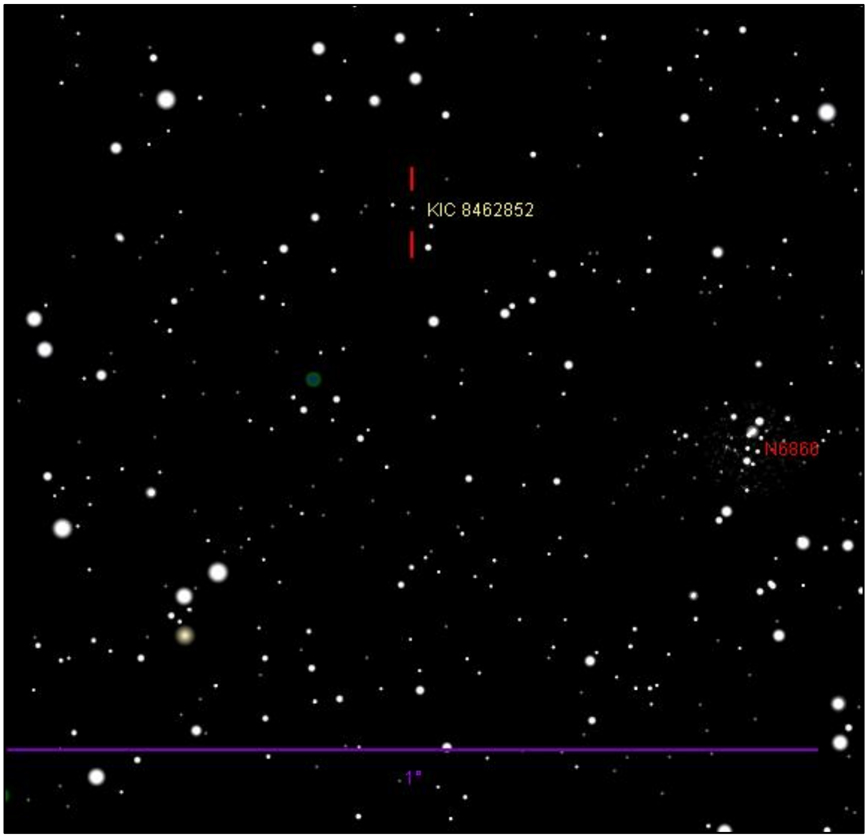

Figure 2. Tabby’s Star. This star chart maps out the position of Tabby against the background of stars in a 1 square degree field of view, as provided by Pulse Headlines (2017).

Tabby Twins

Finding similar cases to Tabby’s Star would help alleviate the singular instance of its study and allow for the inclusion of precedent data on other stellar systems for comparative review. Thus the hunt for other stars that exhibit the same or similar patterns to Tabby has been taken up, albeit with little success, but the search has returned some interesting doppelgangers. VVV-WIT-07 is one such match, an aging, red star detected toward the central bands of the Milky Way and discovered by the ESO in Chile (Redd, 2018; Minniti; et al., 2010). The survey used the 4 meter VISTA telescope and obtained over 1900 hours of observations, which yielded this star whose dimming has also been erratic (Minniti; et al., 2010). Back in 2012, it steadily and only barely decreased for a span of 11 days before plummeting for the next 48 days, making determining a period for the magnitude changes difficult, because its pattern was inconsistent (Redd, 2018). The dips in its starlight were noted by both LSU astronomer Tabetha Boyajian, and NASA JPL's Eric Mamajek to be stark enough that the interfering object(s), would have to amount to a length of more than 1 million kilometers across, which seems unlikely (Redd, 2018). There remains that possibility however that the interference is caused by dust and gas, or an intrinsic source, but as noted by Mamajek and other scientists, any dust would be extremely dense and unusual, and would have to match that which a non-transparent object can accomplish in reducing this star's light so quickly (Billings, 2016; Redd, 2018). Mamajek made the estimates for a supposed object's parameters orbiting VVV-WIT-07 (Redd, 2018). Mamajek had done similar, successful work on the discovery of a second stellar Tabby twin, J1407 (Redd, 2018). As a result of his work, the fluctuations in variability at J1407 are now believed to be caused by a large ring system, over 200 times wider than Saturn's (Redd, 2018). The light curve subsequently mapped from this star (shown below in Figure 3) displayed a pattern synonymous with other newly formed planets where remaining debris is still present and has yet to be swept from the region; it is also similar to that which is seen in planets with ring systems (Billings, 2016). With the initial data of J1407, the discovery team deduced the presence of at least 100 rings, however the expected host planet has yet to be detected, this massive ring system was seen during an exiting transit in 2007 and further ones are awaiting confirmation (Billings, 2016).

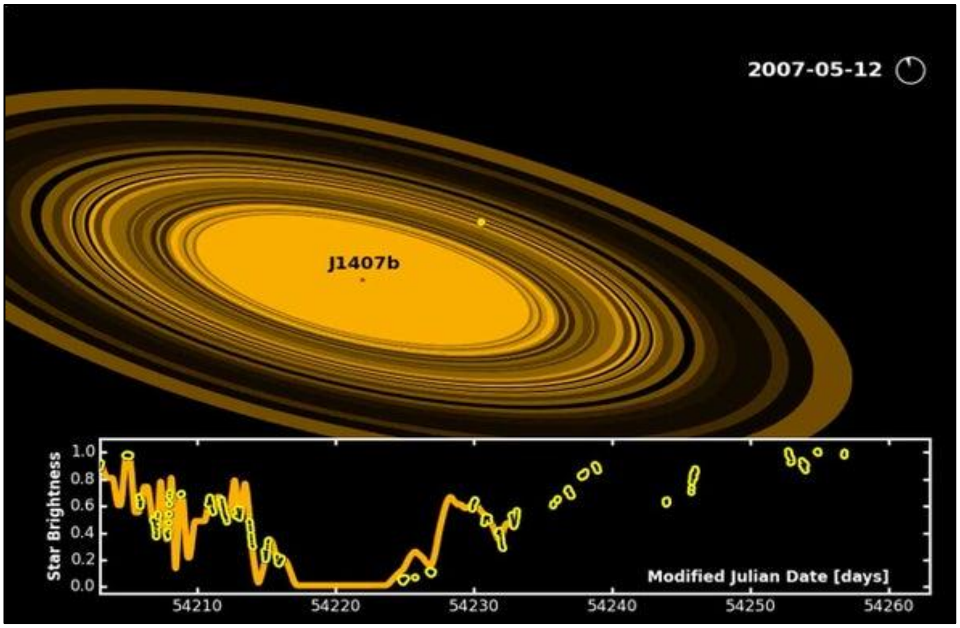

Figure 3. Artist’s rendition of J1407’s light curve; it shows an irregularity to its pattern like Tabby does, but has plateaus and less consistency than Tabby’s Star (Billings, 2016; Leiden University, 2007).

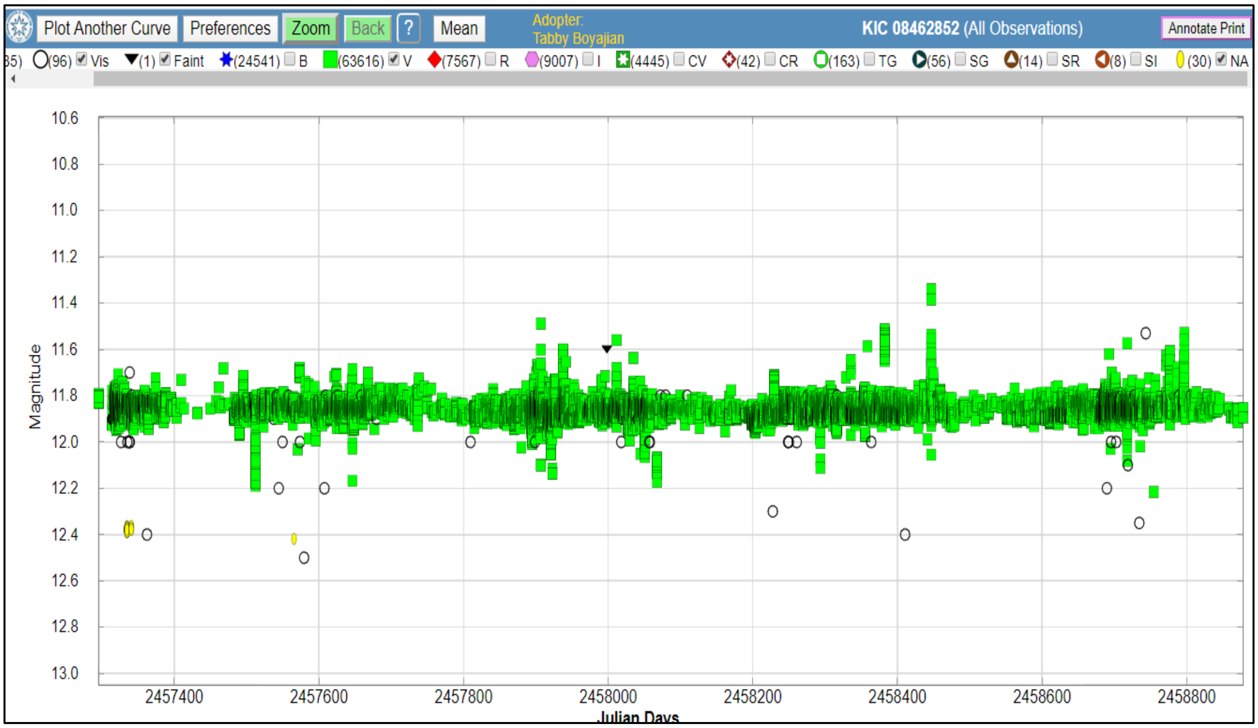

Figure 4. Tabby’s light curve; it shows all Johnson V filter photometric data available on Tabby’s Star from the AAVSO international database for comparison to J1407 above (AAVSO: LCG, 2020).

Tabby, VVV-WIT-07, and J1407 all display strange light curves and a current unpredictability in their magnitude changes, yet these two twins lack a truly duplicative nature to Tabby since they both hold reasonable explanations for their variability that stands out above other hypotheses, that being a ring system and forming planets. The long standing mystery of Tabby's Star remains, since many explanations have warranted research and returned inconclusive results.

Planetary Disk

Upon the examination of the scattering of light in infrared and blue filters scientists considered that because redder wavelengths were passing easily between Earth's observations and the star itself that blue scattering dust may well have a hand in the behavior seen at Tabby (Young, 2018). Dust perhaps, from a proto-planetary disk where new planets are being formed around Tabby's Star, which could be an explanation for the seemingly random peaks and dips in brightness here. Researchers at Thacher School in California found that the estimated sizes of such blue scattering dust would be akin to that of ash, or the same microscopic grains in Earth's atmosphere that similarly hinder blue light during sunset hours (Young, 2018). Such sized dust particles would easily be dissolved from the Tabby system's stellar winds, especially considering that Tabby's Star is hotter and larger than the sun, thus allowing for stronger winds (Wall, 2016, Young, 2018). So then, any fine dust must not have been present for very long and it could represent the source of its fluctuations; dust of this nature does indeed result from planet forming processes and may well prove to be the responsible party (Young, 2018). In observing planetary disks about stars, several factors are sought in determining whether or not one is present, to include a flat and thin geometry to the distribution of said dust, supplemented by infrared observational confirmation (Dutrey; Etangs; Augereau, n.d.). Determining the periodicity of the dips in light from Tabby might better illuminate any hidden transiting bodies or forming ones. Looking at the Kepler data, the 6 largest dips occur at phases of 24.2 days apart, which could represent a closely orbiting body, however the statistical significance was determined as being weak after a sampling of 2000 periods were searched between 10 and 700 day intervals (as well as supplemental mock samples) determined the median period to be 20.8 days (Wright; Sigurdsson, 2016). Also, assuming a wide disk of dust (where the semi-major axis = 10^3 au) is in the process of forming a ring about the star only allows for a roughly 10% chance of detection, and decreasing to a smaller disk size of 10^2 au reduces this chance to 1% (Wright; Sigurdsson, 2016). Rotation of a dust ring is another factor, which is also detected with infrared and spectral measurements looking at radial velocity of the gas and dust within a proto-planetary disk, as it accelerates and begins to settle or disperse (Dutrey; Etangs; Augereau, n.d.). Tidal fluctuations from the star can of course disrupt the regular flow of dust within the disk, but this is most notably an occurrence in binary star systems like many T Tauri type stellar systems, of which Tabby is not one (Dutrey; Etangs; Augereau, n.d.). The recent discovery of a proto-planetary disk about the star Epsilon Aurigae, is a prime example of planet forming disks and their light curves; TW Hydrae and Beta Pictoris are others (Garner; Dunbar, 2019). Epsilon Aurigae has a light curve where the steady magnitude of the star dips to a plateau before rising slightly, remaining at another then higher plateau before dipping once again and finally returning to the steady magnitude initially observed, as displayed below in Figure 5 (Stencel, 2014).

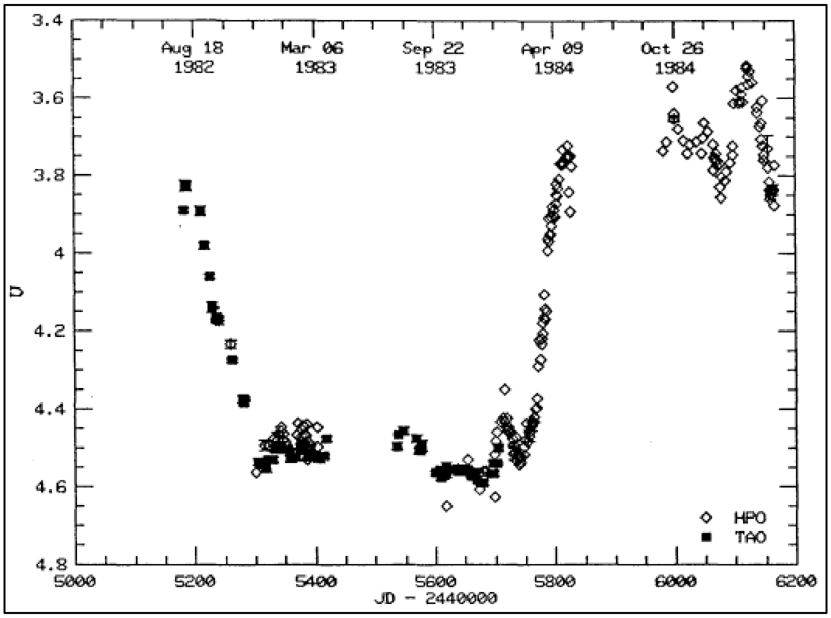

Figure 5. Epsilon Aurigae light curve pattern seen during its 1982-1984 transit (NASA; Stencel, 1985).

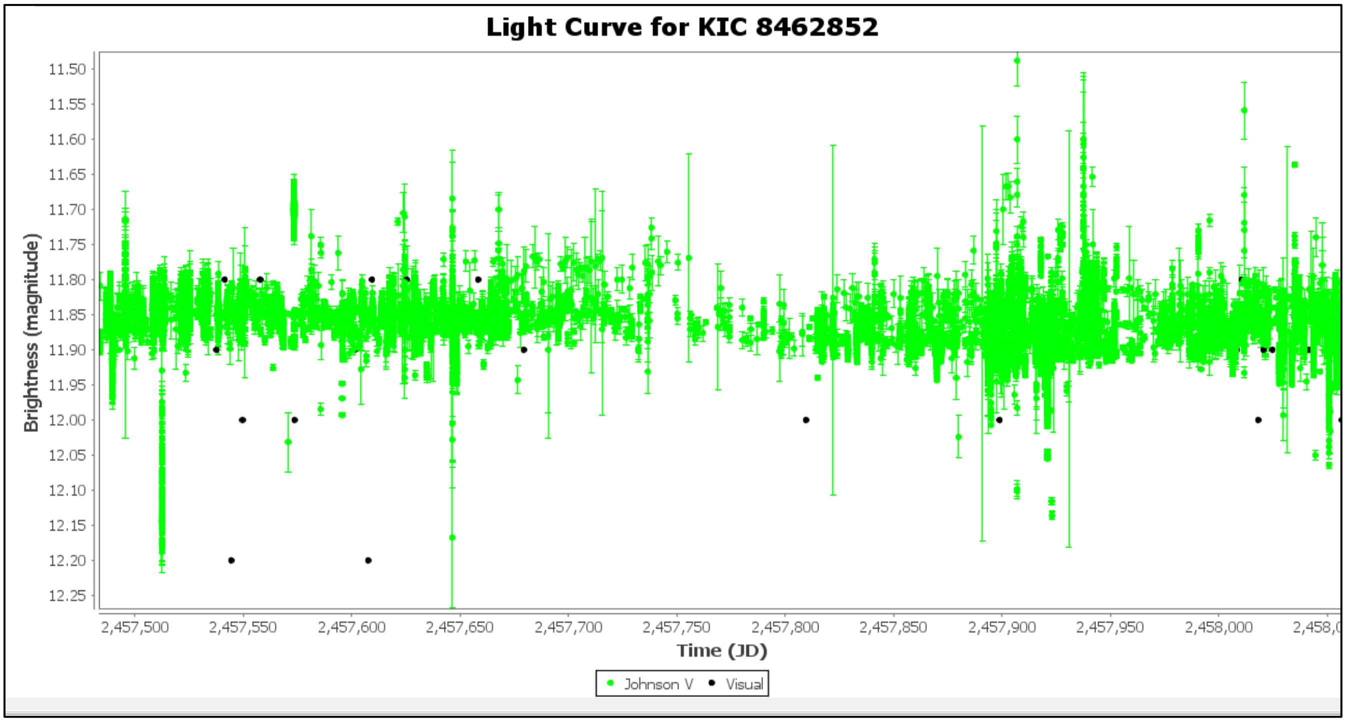

Figure 6. Tabby's light curve with Johnson V filter data obtained from the AAVSO international database for a two year period spanning Jan 1, 2016 to Jan 1, 2018

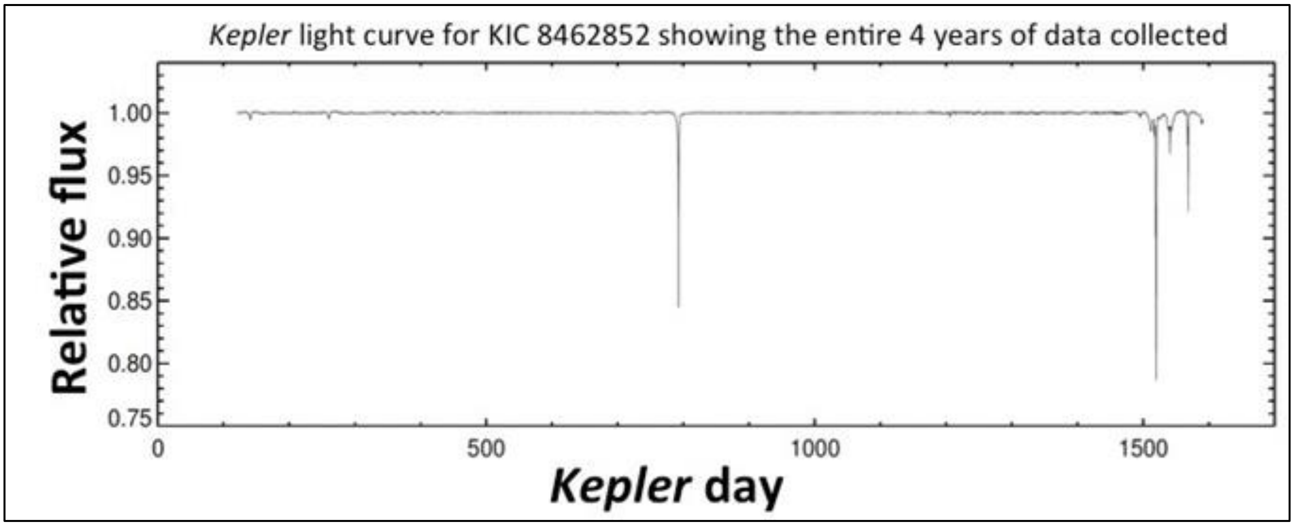

Figure 7. Kepler's light curve data for Tabby over 4 years (Boyajian, 2020).

The light curve in Figure 5 is indicative of a dust disk surrounding a companion star whose central regions have been swept out by the smaller companion's stellar winds. In Figure 7 we see a light curve similar to that of a star with a dust disk or planet and they can both be compared with Tabby's full light curve in Figure 6 to see the dissimilarities (Stencel, 2014). Figure 7 represents a small instance of time as compared to the star's broad lifespan and data from the AAVSO seen in Figure 6 (Stencel, 2014; Boyajian, 2020). The presence of a disk at Epsilon Aurigae mainly provides a baseline observation set against which to examine Tabby in seeking out the answer as to whether or not it too has such a planet forming ring. The other two noted stars, TW Hydrae and Beta Pictoris however, were spotted by the Hubble Space Telescope (HST) and believed to harbor rings of dust surrounding them, that was later confirmed with infrared (IR) and light curve data (Garner; Dunbar, 2019; Stencel, 2014). That follow up data showed an increased scattering and absorption in the infrared from the surrounding disk, and magnitude differences from the disk area by using the comparative space farther from the star (Garner; Dunbar, 2019; Stencel, 2014). This is still a viable option for Tabby, despite the negligible observation probabilities and dissimilarities in long term light curves, because a dust disk could be associated instead with the newly discovered, but widely separated companion star of spectral class M4, situated at over 900 AU away (Wright; Sigurdsson, 2016).

The primary drawback to this hypothesis however, is that the light curve of Tabby exhibits few such consistencies or plateaus in its light curve data as one would expect were a proto-planetary disk present. It does show recent dust causing activity, which may very well be from a newly forming planetary disk, but with the lack of rotational data on that dust and less structured geometry (where a flat, thin disk is expected from planetary formation models and not found at Tabby), it does not seem as plausible. This proposition of a planet forming disk alone may not be compelling enough for scientists to back it as the definitive culprit behind Tabby's magnitude variations.

Cometary Debris

Another line of thought concerning dust in the Tabby system is that such debris may be the result of comets; where the source of both the newfound dust and the dimming of Tabby may have transpired from cometary or asteroidal debris. The sun and even Jupiter have provided precedent for comets being broken up into dust and leaving behind trails that were monitored for days, as with comet ISON or Shoemaker-Levy 9. It does pose the prospect of such an event occurring at Tabby; however at about 1470 light years away it may be difficult to surmise this as the originating source (Starr, 2019). Comet dust is mostly composed of volatiles and silicates and stream off of the nucleus to form a tail as stellar wind sublimates ices, thereby releasing pockets of gases along with the dust they carry. With an average mass of $5.97 * 10^{24}$ kilograms, comets often sport halos and tails that are several million kilometers across or long, and they have the capability to produce a great deal of dust if completely shredded by a star's gravity, for instance comet ISON produced an average of 50,802.35 kilograms of dust per minute during its close approach (Lang, 2010; Phillips; NASA, 2013). So if this is taken as a representative mean, then one can reason that with a comet nucleus' average mass of $5.97*10^{24}$ kilograms it would take $1.959 * 10^{18}$ hours or $2.236 * 10^{14}$ years (that is over 200 trillion years) before the nuclei of the hypothesized comets would be completely dissolved by sublimation alone (Phillips; NASA, 2013). This is longer than the lifetime of the star itself and the universe, so the comets would have to be only partly broken up and largely remain together, still in orbit for observation, much like exoplanets or exomoons, of which no consistent transits have been observed over the last 100 years to support that notion (Phillips; NASA, 2013). This does not rule out cometary debris however, for once its dust is dispersed it will obey Newton's laws of motion and remain in orbit as it trails through the regions where the comet passed, quite possibly interfering with observations of the star. Similar darkening was witnessed at Jupiter as the 21 broken strands of the larger Shoemaker-Levy 9 comet collided with the gas giant in 1994 and remained visible for weeks afterward as its dust covered much of the planet's atmosphere (NASA, 2019). The challenge then is in distinguishing comet dust from that of another source like a forming planet, or the interstellar medium (ISM). In an examination of the dust and gas released by comet Halley in 1986, NASA found that 1/3 of all dust grains contained carbon, hydrogen, oxygen and nitrogen, giving rise to the commonly seen C-H infrared emission lines at 3.4 micrometers (Puget, 1989). Examining the interstellar medium has shown this emission at the same wavelength before, suggesting that using this band for a comet's signature could yield some success in spotting comet dust from the rest of the ISM (Puget, 1989). Detecting it out at Tabby's Star did not turn up results however, as scientists Massimo Marengo, Alan Hulsebus and Sarah Willis (2015) examined it using Spitzer data and scanned in the range of 3.6 micrometers with an excess of plus or minus 0.43 micrometers during a 2 year period of considerable dimming (Puget, 1989; Marengo; Hulsebus; Willis, 2015). A hesitation abounds to continue to hunt for fine comet dust signatures because as other scientists Benjamin Montet and Joshua Simon subsequently discovered in the Kepler telescope data, the star's gradual reduction of 0.3% in magnitude per year has increased to a more rapid pace of 2.5% per year (Young, 2016). This equally challenges the prospect of comet swarms interfering with Tabby's brightness fluctuations since such a quickly dimming event would be difficult to be so hurriedly accomplished with comets.

Interstellar Medium

The medium of dust and gas that fills the space between stars is but another proposed source of Tabby's dimming events, especially since the star is centrally positioned within the galactic plane in the constellation Cygnus, a particularly dense area in the interstellar medium (ISM). Estimates on subtracting out such reddening interference caused by the blue light scattering dust (E(B-V)) results in high extinction values of 0.95, nearly 9 times as much as the measured magnitude extinction value of 0.11 (Wright; Sigurdsson, 2016). This indicates that the higher value of dust to be subtracted out lies farther behind Tabby, since Tabby is yielding lower magnitude extinction values (Wright; Sigurdsson, 2016; Swinburne, 2020). This is where extinction subtracting the ISM and measuring magnitudes in the visual filter bands (discussed more in the next section) is AV: AV = 3.2E(B-V) (Wright; Sigurdsson, 2016; Swinburne, 2020). Also many other stars in this constellation do not exhibit the dimming and unpredictability that Tabby does, hinting that it indeed may not be interstellar bound dust but perhaps a thick cloud at the outer fringes of the solar system (Wright; Sigurdsson, 2016). Detecting such a structure would be a difficult task however, for a gas cloud at the edge of the solar system would unlikely be as large as a molecular cloud in the ISM, and clouds at the fringe of the solar system are typically too low density to cause the optical dimming recorded at Tabby, too low by a factor of 100 (Wright; Sigurdsson, 2016). Additionally, the unreliable dimming of Tabby has complicated distance measurements to the star such that the best statistical fit of the above extinction calculations are only really sufficient for distances beyond 500 parsecs (1631 lightyears, about 200 light years farther away than where Tabby lies) (Wright; Sigurdsson, 2016). Pinpointing thicker dust as a tail near the edge of the solar system, rather than farther out in the ISM situated between Earth and Tabby is a challenging factor. Completing a dust density measurement to within a reasonable accuracy of 90% or higher is moreover the issue rather than obtaining measurements themselves (Wright; Sigurdsson, 2016; Boyajian; Deeg; Alonso; Nespral, 2018). Further strengthening the case for ISM interference is the precedent that stars within dark dust clouds have revealed their presence and that of the dust in front of them before, by means of irregularities in stellar magnitudes (Wright; Sigurdsson, 2016; Boyajian; Deeg; Alonso; Nespral, 2018).

The Planck and Arecibo telescopes also help in understanding the ISM, for it was used it to take an isolated, collaborative survey of molecular gas and dust clouds in the ISM at sizes of or exceeding one square degree of sky, and removed some interference of the galactic plane (Reach; Heiles; Bernard, 2018). They examined dust clouds where the extinction of the solar system’s inherent dust from the zodiacal light and the background CMB normally interfere (Reach; Heiles; Bernard, 2018). This was done in order to compile a 353 GHz map of the sky as they observed clouds from various galactic latitudes and at temperatures ranging from 16.7 Kelvin to 19.3 Kelvin; the result is shown below in Figure 8 (Reach; Heiles; Bernard, 2018).

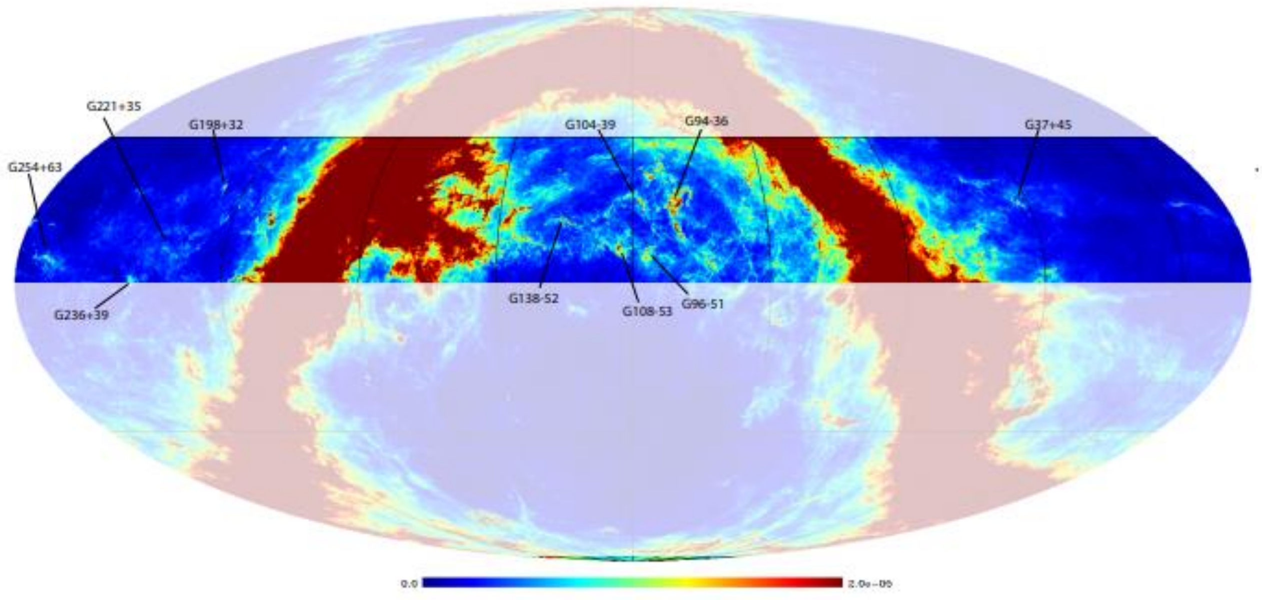

Figure 8. Planck 353 GHz map of the sky (Reach; Heiles; Bernard, 2018).

This study is helpful in that it revealed a disparity in the radio intensity from the optical density of the clouds, even when the researchers estimated a standard gas to dust ratio of 124 in an optically thin cloud (Reach; Heiles; Bernard, 2018). They found that the dust was not heated by the stars within or surrounding the clouds, but rather the space surrounding the clouds exhibited a warmer temperature (above approximately 17.0 Kelvin) (Reach; Heiles; Bernard, 2018). In the case of Tabby's Star, this indicates that a lack of typically warm infrared emissions from dust surrounding Tabby's Star does not mean that a cloud in the ISM does not exist, but that it could be responsible as a cold molecular cloud (Reach; Heiles; Bernard, 2018; Wright; Sigurdsson, 2016). Furthermore, the polarization of dust and gas peaks in the V band of light at 5500 angstroms as described by Serkowski's Law: $\mathbf{p(\lambda) = p_{max} \exp[-K \ln^2(\lambda / \lambda_{max})]}$ (Draine, 2011). So the polarity tends to be measured at larger values in the ISM for stars with greater reddening or denser interlaying gas and dust in the ISM, which should be found at Tabby given its spectral class as an F3V main sequence star (Draine, 2011; Universe Guide, 2020). The polarization of intervening dust and gas would result from magnetic field alignment in the ISM and greater alignment in the V band pass should also mean a greater dimming effect and density when the polarity is out of alignment (Draine, 2011). Even if molecular clouds between the solar system and Tabby were thin, the misalignment in viewing that cloud could be enough to continually dim the star as both star systems move throughout the galactic plane (Draine, 2011). As Boyajian and others studied the spectrophotometry of Tabby in the pursuit of intervening gas and dust clouds, they found a persistently high opacity and dimming in the bluer portions of the spectrum (beyond 580 nm) and at seemingly random intervals, suggesting that such a cloud would be non-uniform in structure and may continue to displace light with greater reddening (Boyajian; Deeg; Alonso; Nespral, 2018).

Magnetic Field

Among the possibilities considered and researched as a potential cause behind Tabby's Star's dimming and brightening, is interference from the star's own magnetic field. This would manifest in the form of star spots, forming near the photosphere as a result of the suppression of convection at that area due to a clustering of magnetic field lines. As a star's magnetic field twists upon itself from the star's continued rotation, individual lines begin to group together and can form a stronger barrier preventing the ionized matter that is cooling and rising from reaching the surface. As that area of the photosphere cools it becomes dark compared to the surrounding zones where convection remains an open flow from interior to surface, thus showing a dark spot. These dark spots have been easily seen and cataloged for hundreds of years on the sun and do in fact cause magnitude fluctuations of the sun as a result (though minor). Only recently have stars been directly or indirectly imaged to show that they too host these occasional dark patches as their magnetic fields interfere with perfect convective processes. Zeta Andromedae was one such star where the process of interferometry was used to image the star's surface and it revealed star spots bound mostly to the polar regions (O'Callaghan, 2016). Located at 181 light years away, this star gives promise that stars at those distances and perhaps further like Tabby at 1470 light years (over 8 times as far away), could reveal the same detail (O'Callaghan, 2016). Another star where stellar spots were successfully detected is one found within the Kepler data, HAT-P-11 and it was discovered using the presence of the star's exoplanet (HAT-P-

11b) as it helped to dim the star enough to detect smaller star spots than those found on Zeta Andromedae (Redd, 2018). Similarly, the spots detected here hovered in the polar latitudes and were of comparable sizes to those seen on the sun, ranging between 40,000 and 170,000 kilometers across (Redd, 2018). Kepler data has been used in this fashion before and found star spots on at least 3 other stars, proving that this feat is possible with current observation tools and techniques (Redd, 2018). So if it is the cause of Tabby's dimming then it would be within astronomers' grasp to find them (Redd, 2018; Choi, 2016). On that level it is more important to determine the amount of dimming that star spots cause on average, as done by Peter Foukal when he modeled a sun-like star's flux and resultant magnitude with the addition of just a 1000 km wide star spot (2017; Kohler, 2017). The result provided a steady degradation in luminosity such that the star overall dimmed by 0.1 – 1% per year, depending on the depth of the star spot(s) within the chromosphere and photosphere as well as the spot's width (Foukal, 2017; Kohler, 2017). This report aligns nicely for explaining a gradual declination in magnitude seen in stars, such as that seen with Tabby (Kohler, 2017). It also allows for the irregularity in the fluctuations seen at Tabby, given how a magnetic field can change throughout its cycle, especially in those with higher rotation rates; Tabby spins once every 21 hours, which is relatively fast (Choi, 2016). Also, the other three aforementioned stars seen by Kepler had quick rotation rates for their type of star (Choi, 2016). The main points preventing a consensus of scientists on this theory is that it does not account for the sudden drop in magnitude measured over the last two years, nor can it keep pace with a *100 year* general decline and erraticism to sudden brightening (Choi, 2016). In stars with higher rotation rates and strong magnetic fields, changes do not generally take months or centuries, but can happen much more rapidly, even the sun (less luminous and with a weaker magnetic field compared to Tabby) has a quicker cycle of 11 years. Nevertheless this does not 100 percent dispel the theory, but has returned data useful for continued research, even though this remains a less likely possibility.

With these different hypotheses and theories expressed concerning the current standing of research on Tabby’s Star, the methods and tactics employed in this study will now be discussed for further expansion on examinations carried out on this star herein and why such measures were taken. This will include the telescopes, procedures and software for carrying out data collection and analysis so as to further validate the results discussed afterwards.

Methodology

This study used the following methods of photometry and radio scanning in a comparative look at Tabby as well as two other stars of the same spectral class as Tabby, 5 Aurigae and HIP 26587, for a deeper look at any hydrogen intensity differences, as well as one star with a known planet, 14 And (since this remains a leading hypothesis on Tabby). This section describes the types of analytical techniques and tools used for the research conducted and the justification for those approaches.

Photometry

Photometry is one of two methods used in this study of Tabby's Star, since it is the measurement of brightness changes in an object, and was observed in this project over the course of January to September of 2019. This process measures the stars in the field of view against known constant stars for magnitude changes and measures it using the logarithmic scale of flux determination: $\boldsymbol{m_1 - m_2 = -2.5 * log_{10}\left(\frac{F_1}{F_2}\right)}$; where m is the magnitude of star 1 and star 2, and F is the corresponding flux of star 1 and star 2, as derived from the electron count for star 1 and star 2 by the CCD camera's pixel values (Warner, 2016). The above equation is simplified for determining an instrumental magnitude, as was done in this project, such that it is not the difference of magnitudes but a single one: $\boldsymbol{m_1 = -2.5 * log_{10}(F)}$ (Warner, 2016). Instrumental magnitude is the raw magnitude found from each image as determined by a CCD (Warner, 2016). This can later be standardized with the proper calibration, and then referenced to a set zero point and accepted color index for the color filters used in imaging (Warner, 2016). The instrumental magnitude requires at least one reference and one check star before it can report on the brightness of the star in question (Rodriguez, 2017). In this way the measured magnitude can be seen from examining the target star and subtracting the difference from a reference star (Rodriguez, 2017). The reference star is also compared to the other check star(s), to ensure that the measured magnitude of the target star is what is really being reported, and not that of the reference star(s) (Rodriguez, 2017). For this project, one reference star was used and between one to three check stars (also called comp stars) for Tabby and the comparative candidates examined, largely depending on the specific star imaged, for not all stars of interest had multiple, previously determined check stars in the same field of view, which is a necessity for performing photometry on a target star. In measuring the brightness difference between stars it was also important for the project that the sky annulus size was set to include a wider background than just the target and comparison stars (Warner, 2016). That way the unevenness of the background sky can be more clearly defined from the star and superfluous effects like cosmic rays can be discarded by the CCD (Warner, 2016). An annulus size was chosen based on a report generated using AstroImage J, which instructed the best to apply for taking a photometric measurement. This was then set and used in the software processing the photometric observations of these stars, that software being VPhot.

Filters were applied to the data taken in by the CCD on a filter wheel, only one was used out of the Johnson-Cousins system filter set, which is the standard set of filters used by variable star researchers and easily allows for setting the measured instrumental magnitudes to standard magnitudes. The V (visual) and L (luminance) filter were applied interchangeably as the filter set was updated early on, a few months into the project, to omit the V, replacing it with the L filter. This system was devised by Johnson and Morgan in the 1950s and quickly was adopted to become the standard set of filters used for observing variable stars, with the V filter hovering over a median wavelength of 550 nanometers (nm), and the L filter in the same range (Warner, 2016).

A standard calibration was used with a few images only sustaining partial calibration, with the flats being the least updated due to weather difficulties. Despite this, only the images that were clear and produced enough of a signal beyond the remaining noise were processed for this project's research. The extinction of the images was only incorporated as far as the processing software would automatically account for. Information on the observatory including positional coordinates and technical details are to be shared next.

Observatories and Archives

One optical observatory and four database archives were used in the data collection phase of this research. The observatory being the one recently constructed at American Public University (APU) in Charles Town, West Virginia, and utilized the larger of its two telescopes, a 24 inch diameter CDK. Stationed on an equatorial PlaneWave A200 mount, this telescope uses an SBIG STX-16803 CCD camera, SBIG FW-7 color filter wheel and Astrodon Off-Axis guider, with PWI3 controlled focus varying between 5750 microns and 5432 microns (APUS; Observatory Solutions, 2016). The telescope has a focal length of 155.98 inches and a focal ratio of f/6.5 and is outfitted with Maxim DL Pro 6 for its imaging tasks (Observatory Solutions, 2016).

The first archive accessed was the AAVSO international database (AID) that had the entirety of records concerning Tabby including the observations taken and submitted by APU. The AID did not yield data on the comparison stars used in this study however, since they are constant stars or not yet established within the AAVSO's variable star index (VSX).

The second archive from which data was gathered came from the Kepler space telescope, described in the introduction section, and the nearly 4 years of observations on Tabby it compiled. It did not yield data on the other sets of stars (5 Aurigae, HIP 26587, or 14 And), but the Kepler data points were used instead for the main target of this project.

The TESS mission was the third database that lent information on the three comparison stars (5 Aurigae, 14 Andromedae (14 And), and HIP 26587). The TESS (Transiting Exoplanet Survey Satellite) satellite is a NASA mission led by MIT with the objective of discovering transiting worlds around other stars by implementing an all sky survey (NASA; MIT; Isaac Partnership, 2020). Launched in 2018, its three year mission has been scanning the sky in 26 segments with four different cameras each covering a field of view of 24 x 24 degrees and observing stars in the magnitude range of 9 to 15 (NASA; MIT; Isaac Partnership, 2020).

The data compiled by the AID, Kepler, TESS, were accessed through their publically available, online databases, some of which were found through the online portal MAST, hosted by the Space Telescope Science Institute, and then processed in conjunction with the data collected by APU's observatory.

Weather Conditions at APUS

Obtaining clear weather in Charles Town provided some challenges for this project; West Virginia is at an average elevation of 457 meters with clear skies for viewing only available about 56% of the year (Weather Spark, 2020; Geology.com, 2020). The best months for observations came in June through October and precipitation came at its highest rates in February to through May, averaging at 3.5 inches per month (Weather Spark, 2020). The light pollution of the area is at 20.075 on the Bortle brightness scale, in sky magnitude per arc second squared, as developed by John Bortle in 2001; this also affected clear imaging capabilities (Light Pollution Map, 2020; Light Pollution Map: Handprint, 2020). Given these weather conditions, there was a gap in the data which omitted much of the months of January and February. Tabby was visible and most prominent from June to September and through the early evening hours of the latter part of the year.

Imaging Software Maxim DL

Maxim DL Pro6 was used as the imaging software, on the 24 inch CDK telescope and calibration setting controller (Observatory Solutions, 2016). Standard Kernal, noise processing filters were applied for flattening the background (Keller, 2014). Image durations for this project were taken at 60 seconds as determined by the estimated magnitude range of the target star. The final photometric process of applying a sky annulus and recording the magnitude of the target star was done with VPhot.

VPhot

VPhot is the online photometry measurement tool hosted by the AAVSO, accessible to their members and is directly integrated for a system upload into the AAVSO international database (AID) of observations. For this project, the images that were taken by the APUS telescope were uploaded and inspected in VPhot for each target. The resultant reports included the measured airmass and signal to noise ratio in addition to a log of the instrumental magnitudes of the target star for each image. Once the poorer quality images had been discarded (these are identified easily with VPhot), the data points were submitted into the AAVSO database, listed under the author's observer code in the AID.

VStar

VStar, like VPhot is an AAVSO hosted and created software package aimed at the specific analysis of the plotted light curves conscripted by VPhot, such that the data that is uploaded into the AID can be retrieved for further inspection. Additionally, data from other telescopes can be loaded for an overlaid presence and inspection of uniformity across the observation platform and differing time periods, like the data from Kepler. For the purposes of this project this was how sets of photometric light curves were combined and analyzed. The observer code was filtered out to show the specific points that came from the author versus others for a reference on the data obtained by the APUS observatory. VStar allowed for the manipulation of the light curves it accessed such that the period could be computed using different methods in order to find the best fit with different trend lines, polynomial trends were used here. Phase plots were constructed to aid in this, which convert the reported times of observations into a phase using: $\boldsymbol{\Phi} = \frac{\boldsymbol{t-epoch}}{\boldsymbol{P}}$, where Φ is the phase, t is the observation time, epoch is the initial time, and P is the assumed period (AAVSO; BENN, 2020). The phase plots were enabled using a standard DC DFT periodicity scan to establish the most plausible trend. The observation details pane also was used to see the measured uncertainty value of the measurements made as well as the airmass, it was here that obviously discrepant data points could be seen (far off from the main light curve plot) and easily disregarded. VStar was a useful program for this project in fully analyzing the light curves and from multiple sources including the AID, TESS, and Kepler.

Radio Observations

Radio scans of Tabby and the other target stars' regions were obtained for this study because this wavelength of 1420 MHz examines the distribution of cold hydrogen gases in the interstellar medium, which remains a plausible contender behind the causes of variability in Tabby's Star. Specifically the HI 21.11 cm wavelength was scanned, as this wavelength's photons are generated from the flip in spin state of the 1s electron to either a parallel or anti-parallel spin relative to the hydrogen proton, while the electron drops to the ground state (Draine, 2011). This also allows for gas density calculations, often based on the observed intensity of the radio source; however that does require negating any HI 21 cm absorption (Draine, 2011). Such work in the radio spectrum adds an important, scientific tool in looking at Tabby for determining if the ISM is indeed the fluctuating magnitude source. The polarization of the ISM can also be detected by radio observations. The different signal intensities detected can denote the polarization angles of that radiation that was scanned, especially as it changes over time (or if it changes); for instance observations that contain information on the point source itself are indicative of a non-zero net polarization (Marr; Snell; Kurtz, 2016). For this project the resultant graphs of the data were analyzed for such information or changes to the incoming radiation of the ISM about Tabby and the other target stars.

This method involves using a radio dish to funnel inbound photons through the antenna feeds, confining them to the transmission lines and into the front end receiver, where the signal is amplified and frequency range is maintained (Marr; Snell; Kurtz, 2016). Afterwards it is passed along to the back end detector for power measurement and digital compression for computers on the ground or far from the telescope assembly for further analysis (Marr; Snell; Kurtz, 2016). Similarly to optical telescopes, radio telescopes also endure noise from the sky and mechanical set up, which must be accounted for in the data analysis. The temperature of the antenna and the noise itself are instrumental in isolating this and deriving the signal desired, as such the power of the total signal received incorporates the temperature of the antenna by: $\mathbf{P = Gk\Delta vT_A}$, where P is the power in Hz, G is the gain of the antenna, k is the Stefan-Boltzmann constant, Δv is the bandwidth of the inbound photons, and T_A is the temperature of the antenna (Marr; Snell; Kurtz, 2016). Subtracting this out of the measurements is more difficult than in the photometric process, here this is typically done after the observations have been taken. It is done by this equation: $\mathbf{V_{on} - V_{off} = aGk\Delta vT_A}$, where the scans of the radio source (in this case Tabby or the other comparison stars) are measured on point then measured off point to get a graph delineating the noise alone, the constant source of background and technological (dish and receiver) interference (Marr; Snell; Kurtz, 2016). The remaining signal is the true detection of the radio sources in the 21 cm line frequency of the areas scanned. In this study the difference of dish temperature is seen best at Tabby and can be reasonably reduced to accommodate the daytime temperatures versus night time observations.

The radio telescope used for this project resides on the grounds of the Pisgah Astronomical Research Institute (PARI), just outside of Pisgah National Forest in North Carolina. Originally owned and operated in the early 1960s by NASA for tracking Soviet satellites, PARI was eventually dismantled in the mid-1990s and transformed into a non-profit institute with several different sized radio telescopes and optical ones on site for private use (PARI; DELISLE, 2019). Of these telescopes, PARI's remotely operable 12 meter radio telescope was used to take continuum scans at 1420 MHz (1.42 GHz) of the target stars as it swept through a 15 square degree swath of sky surrounding them. The continuum setting measured the integration of each data point for the whole band of radiation being imaged as a function of frequency, thereby showing the intensity (brightness temperature) of the point in question over the duration of each observation (PARI; DELISLE, 2019; HartRAO, n.d.). This telescope was integrated with its own user interface to run, slew and scan the star in continuum mode at a data point per millisecond, and rate of 1000 milliseconds. 180 second scans were the average ones taken to remain closer to the targets, with intermittent 300 second scans for covering the fuller 15 degree diameter ISM observation space. Scanning time was conducted about once to twice weekly, weather and other operators' scheduling permitting, as this had to be scheduled in order to avoid operators conflicting or overlapping one another for its remote use. The scans were taken consecutively and had to be repeated since the Alt/Az mounting of the radio dish did not track targets. This feature was a necessary part for the calibration of the telescope to catch the on and off points of a target.

Weather Difficulties at PARI

Conditions of freezing rain or snow impact PARI, since this changes the shape of the radio dish, thus hampering incoming photon data (PARI; DELISLE, 2019; Weather Spark, 2020). For the duration of this project the snowfall was light enough that it did not cause much disruption. There remained a similar gap in the data like that at the APUS observatory, such that very little data exists for January and none in February. The months beyond September of 2019 endured too many scheduling conflicts on the part of the author to obtain data, however consistent observations were otherwise maintained with ease.

This section has covered the photometric and radio observation methods, software, and databases used in the following research along with the capabilities and limits of each. That includes Maxim DL Pro6, VPhot, VStar, PARI, Kepler, and TESS, in this way a firm standing has been laid to better expand the study of Tabby's Star and the extent of the data herein. The following section will show the results from the magnitude measurements and radio scans taken and how they relate to the dimming effects seen at Tabby as compared to the other three stars (5 Aurigae, HIP 26587, and 14 And).

Results

In this section as Tabby's Star is analyzed and it will be compared to the previously mentioned three stars, 5 Aurigae, HIP 26587, and 14 Andromedae (14 And). Each of these stars is located in different regions of the sky, giving a different contrast to Tabby, which is in the midst of the Milky Way band. Their photometry can then shed light on the role of the interstellar medium blocking some visible light for these sets of stars. This is important as explained in the literature review section because it is a candidate cause behind the variability of Tabby and the hypothesis proposed by this study. Looking out across different locations relative to the densest regions of gas and dust (the Milky Way band) photometrically will help to establish any correlation as it is then examined in the radio results. This becomes especially important in the review of the radio data collected on each, since that spectra band is looking at the hydrogen gas intensity verses distribution in the vicinity of each star. 14 And is in Andromeda, 5 Aurigae is in Auriga, and HIP 26587 is in the nearly circumpolar Camelopardalis. Two of these stars are in the same spectral categorization as Tabby (5 Aurigae and HIP 26587); they also lie partially in the band of the Milky Way. Both 5 Aurigae and HIP 26587 are of the F5 spectral class, while Tabby is an F3; this similarity was chosen because it could eliminate other possible differences between them and Tabby. So then the study could focus on the hydrogen intensity as related to the stars' locations nearer and farther from the Milky Way band (MAST, 2020; NASA, 2020). This was important to look at in the comparative analysis of Tabby because it is positioned in Cygnus, which lies in the central regions of the Milky Way band, where the abundant majority of hydrogen gas and dust in the galaxy is found. In the examination of the potential of obscuring gas and dust as the cause behind Tabby’s fluctuations, it is pertinent to look at this star under radio wavelengths alongside others farther away from that band.

14 And is a system that has a planet in orbit about the star; it is named 14 And b, and it is a gas giant nearly five times as massive as Jupiter (NASA, 2020; Universe Guide, 2020). The inclusion of this system is important in the further examination of the possibility that a surrounding disk or planet is responsible for Tabby’s dimming and brightening. This is a contender because disk transits have the capability of blocking star light or if a planet(s) are present then they could provide other patterns to the dimming and brightening effects. These two sets of comparison stars also allows for an examination of the differences in hydrogen intensity fluctuations for stars that have planets and those that do not. The collective separation of these stars can be seen in Figure 9 below, along with the two constellations that share a portion of the Milky Way band.

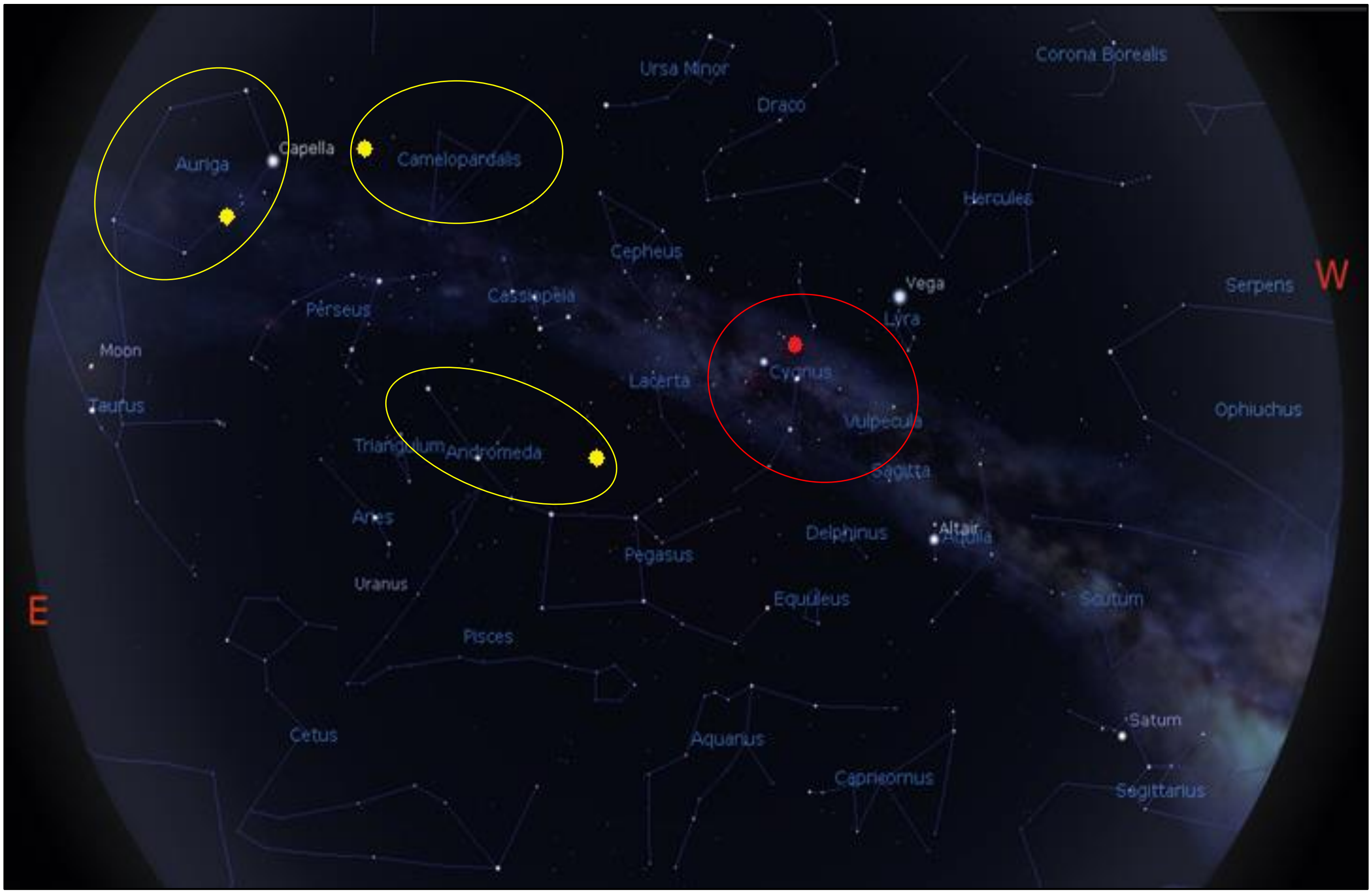

Figure 9. Constellation dispersion with each outlined relative to the Milky Way band and does not represent the constellation's actual boundaries. Cygnus is outlined in red because it is host to the main target star of this research and the yellow encircles the constellations of the comparison stars. Each target's approximate position is marked with a color correspondent dot (Stellarium, 2020).

First the photometry of Tabby will be shared with the comparative record of the other databases mentioned in the methodology section along with APU's data. Then the photometry of the stars sharing the same spectral class, 5 Aurigae and HIP 26587 will be analyzed before moving on to the planet hosting star 14 And. The same order and approach will then be taken in looking at the results from the radio data.

Photometry Observations: Tabby

When looking at the full spread of all light curve data from both the AID (Figure 10) and Kepler (Figure 11), one can see that the vast majority of measurements remained evenly distributed and stable in the magnitude range of 11.7 to 11.9, with Kepler detecting mostly 11.9 readings. The magnitude does spike both up and down into brighter and dimmer ranges of 11.2 to 12.3, a whole integer's difference, with additional though uncommon data of 10.9 (outside the scale of Figure 10) at the brightest and 12.7 at the dimmest.

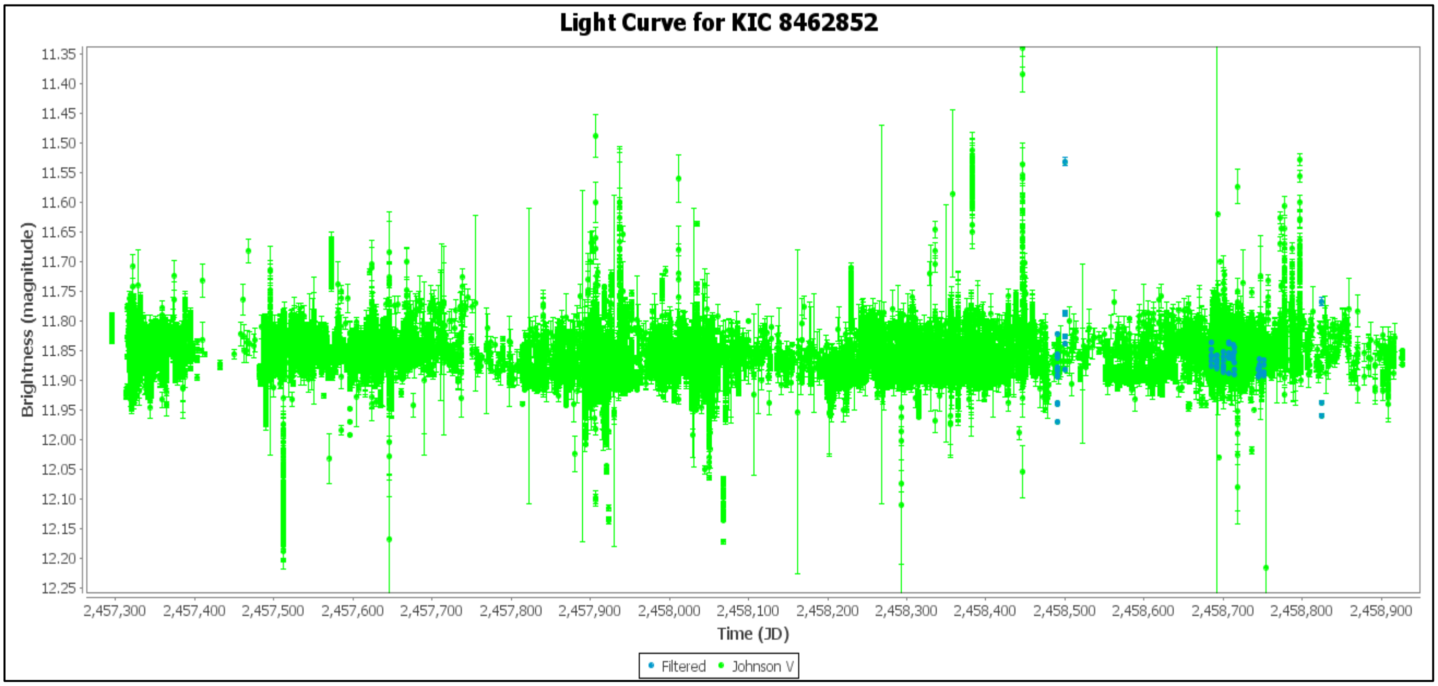

Figure 10. AID database of all light curve of all data on Tabby, with V filter CCD observations in green APU observations in blue. These were contributed from individuals and organizations dominantly in the USA, but some come from abroad as well.

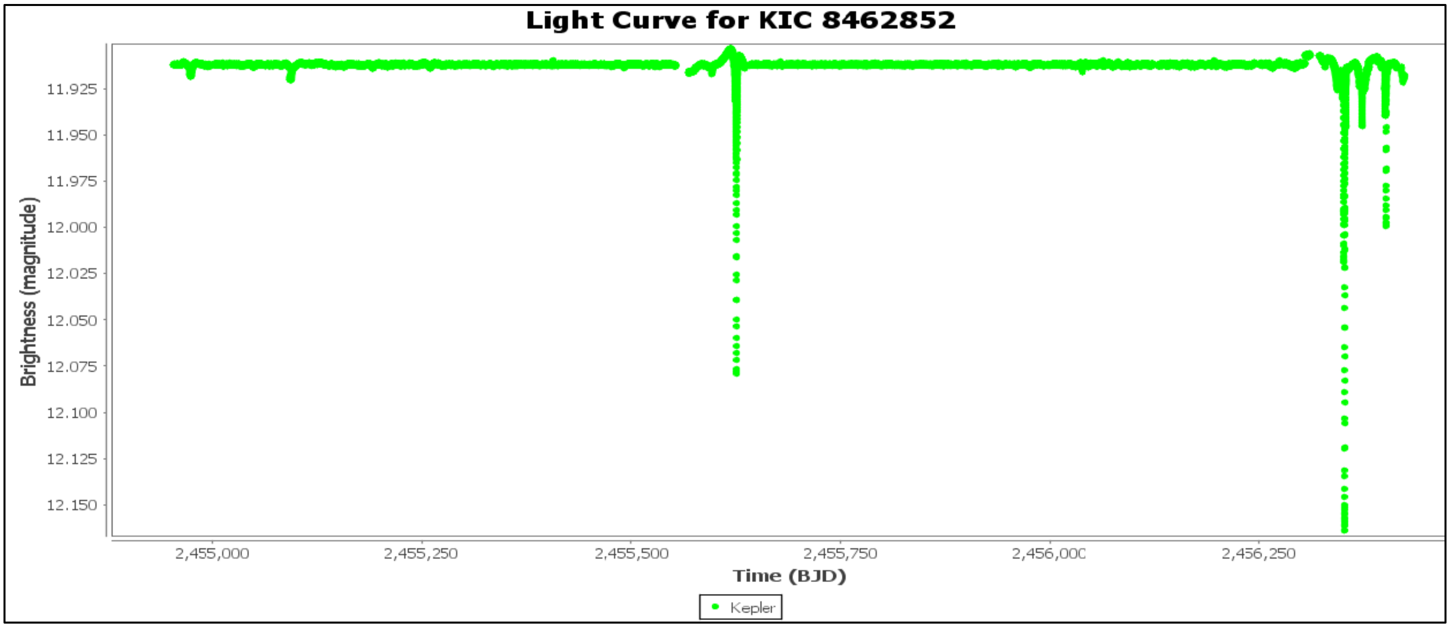

Figure 11. Kepler all light curve data for Tabby shown exclusively without AID data. The scale is adjusted to highlight the only three detected drops in brightness as shown on the Y axis labeling, stretching from 11.9 to 12.15.

The time frame for both of these observation sets is expressed in Julian dates, which equate to October 2015 to January 2020 for the AID in Figure 10, and June 2009 to November 2012 for Kepler in Figure 11. They both show minute variations, but variations nonetheless. Seen in the context of the AID however, the Kepler data becomes dwarfed due to the greater amount of observations made from many different instruments and scattered locations around the world as they point toward a certain level of stability. This is not to say that the Kepler data is insignificant, but rather that it has pinpoint accuracy and in the case of Tabby it may have overlooked a wider, and more constant luminosity in its detailed focus on minor variations. Constructing a phase plot based solely on the Kepler data yielded the curves seen in Figure 12. The statistically most likely period of Tabby that could be perceived by VStar was 24.985 days, however upon enabling this the composition became rather mixed on itself.

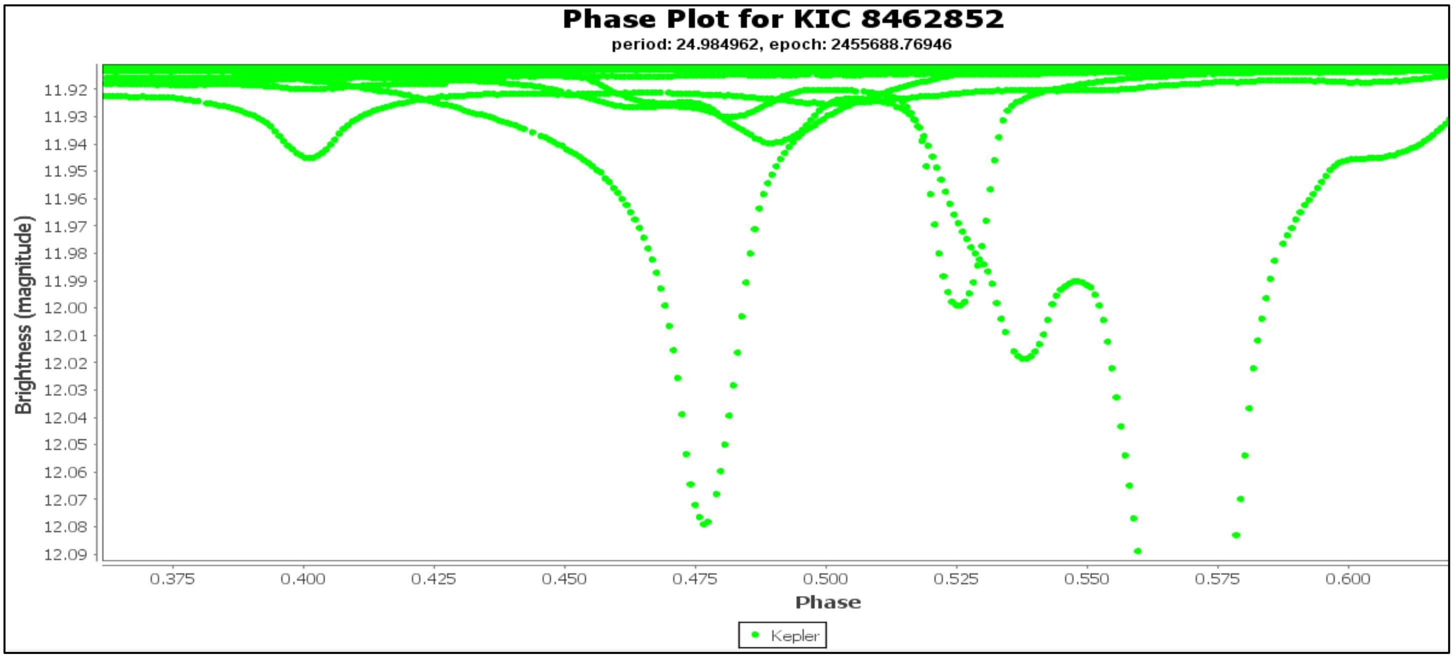

Figure 12. Kepler data's computed likely period for Tabby's Star based on its entire stretch of data collected, this resulted in 24.98 days and began crossing the peaks and troughs of observations.

Despite this odd intermingling of data points in deriving a period for Tabby, returning to the AID spread offered a better fit and very different likely period to the star's variations from using the same DC DFT scanning technique. Figure 13 offers the graph result of limiting the data range from the duration that the APU observatory was contributing images as well, which was January 2019 through March 2020. The light blue data points represents the APU observations of Tabby, seen below, while Figure 14 offers a closer scaled view of a month's worth of data from mid-July to mid-August.

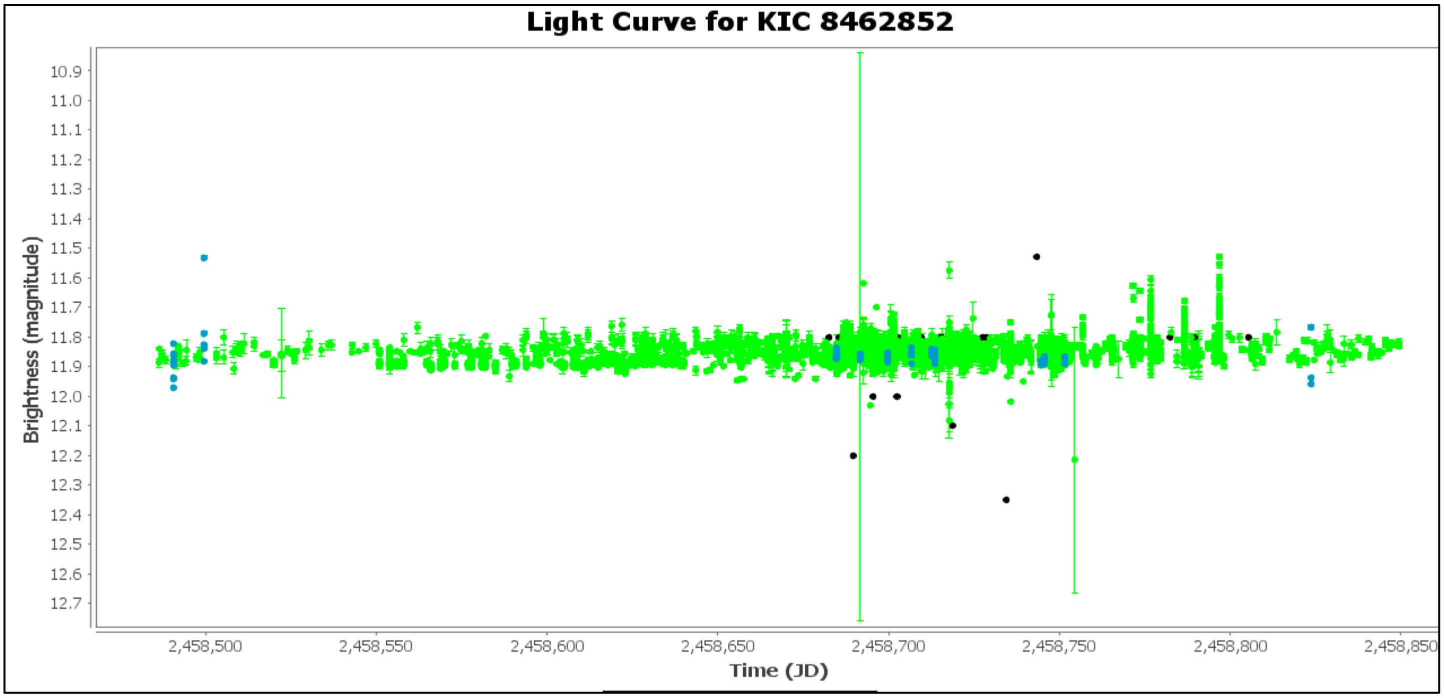

Figure 13. AID data spanning January 1st, 2019 to March 1st, 2020. The black dots are from visual observations from various contributors and the blue dots are the CCD data of APU.

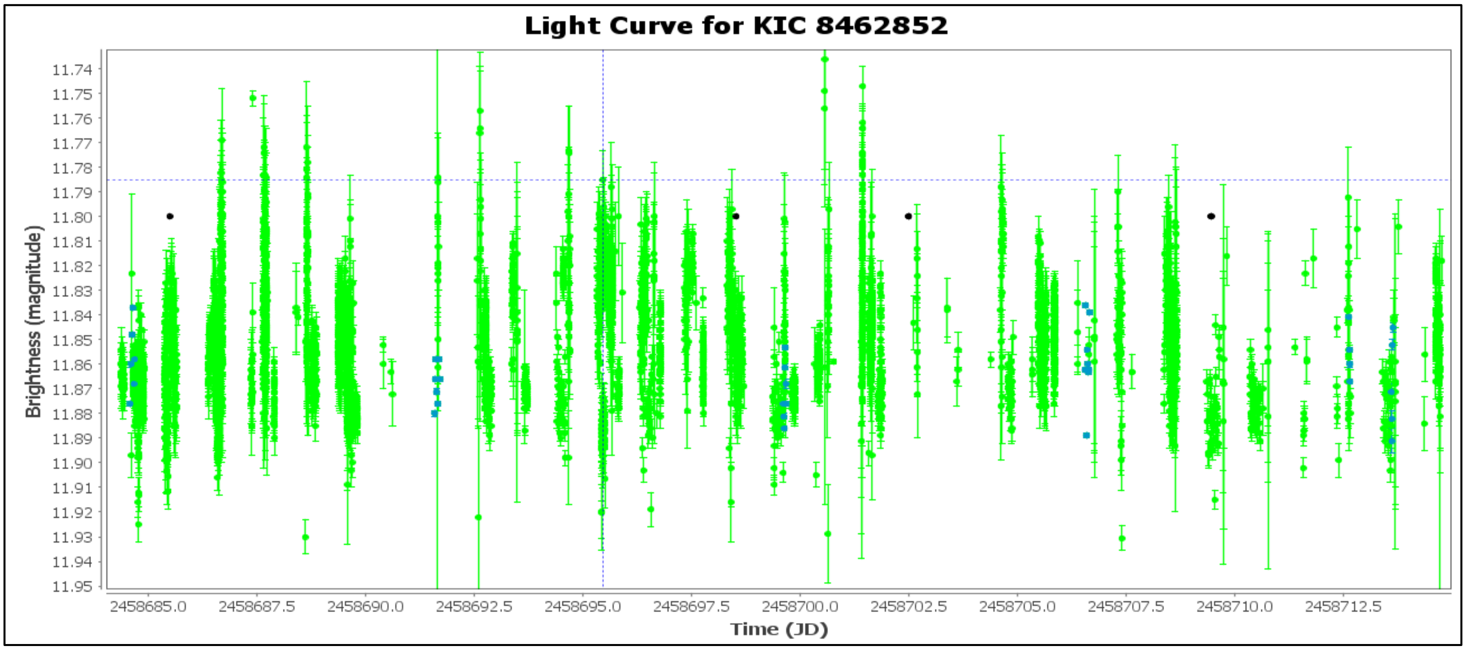

Figure 14. AID data covering July 17th to August 20th of 2019 with APU contributed data points highlighted in blue.

The period statistic search resulted in a 1.001485 day period or a small variation thereof for less likely periods, and in Figure 15, a polynomial trend line was fit to it, of the VStar standard 12th degree; this shows the data collected for the month of July 2019.

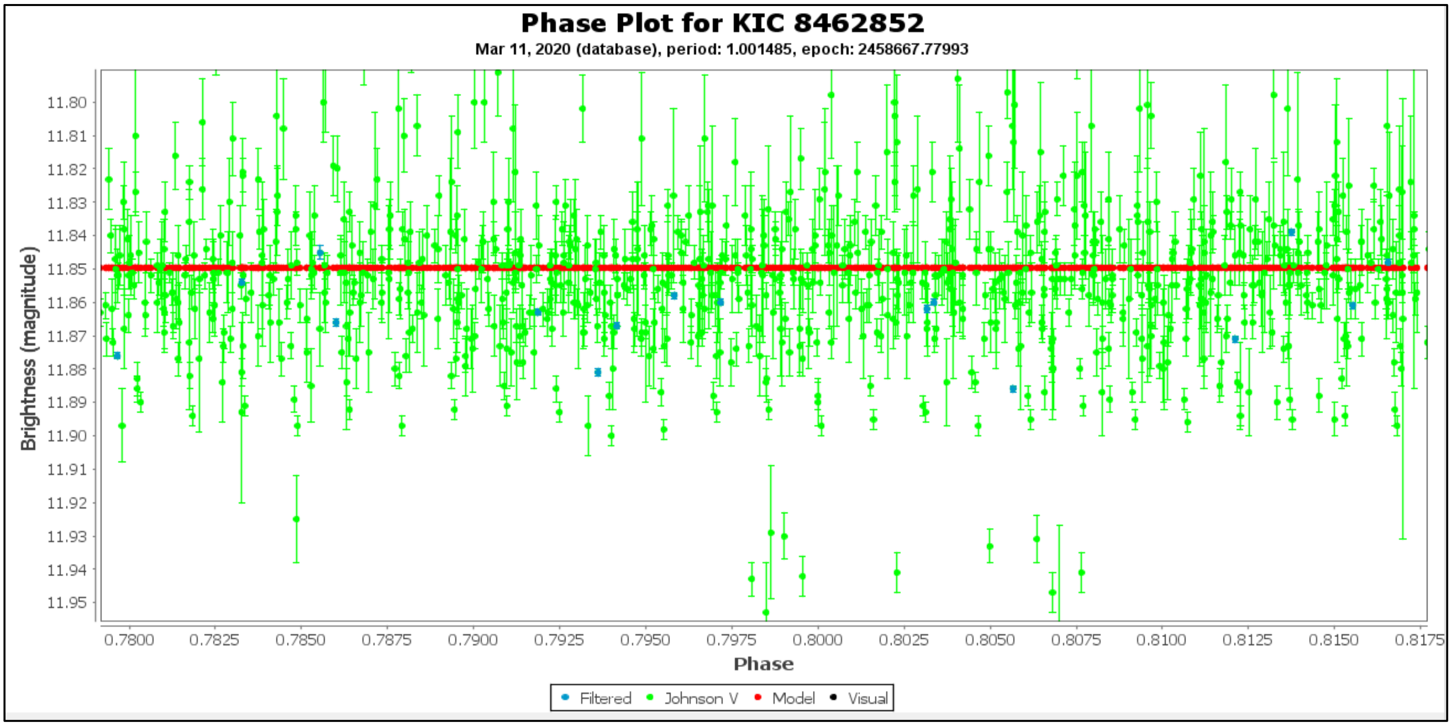

Figure 15. AID data spanning the month of July 2019 with a best fitting period of 1.001485 days and a 12 degree polynomial trend line shown in red, and APU observations in blue. The rest of the green data points come from other submissions using the Johnson V filter.

This period yields a relatively flat curve and stays in line with the main consistency of Tabby’s variations, hovering around 11.85 to 11.83 magnitudes. It unfortunately means that it is neglecting the rather obvious and strange spikes in luminosity but it more closely matches the majority of the data in the AID. It also does not flip or cross any curving lines as was seen to occur from the Kepler data period scan. The added benefit that most likely averted this from happening in the AID spread, was the fact that this data comes from many equipment sets, more persistently and consistently observing this star and for a longer duration than the Kepler space telescope was able to devote. It does add greater confidence that the magnitude variations seen by Kepler were part of its more normalized trend for Tabby rather than what other observers have noted at this star. It further supports that a shorter time period is the more likely option for the fluctuations seen here.

Looking once again at the full data spread from 2015 to 2020 for Tabby by the AID, one can not help but notice the eight large magnitude hikes and dips seen in Figure 16 below, with these hikes denoted with red arrows.

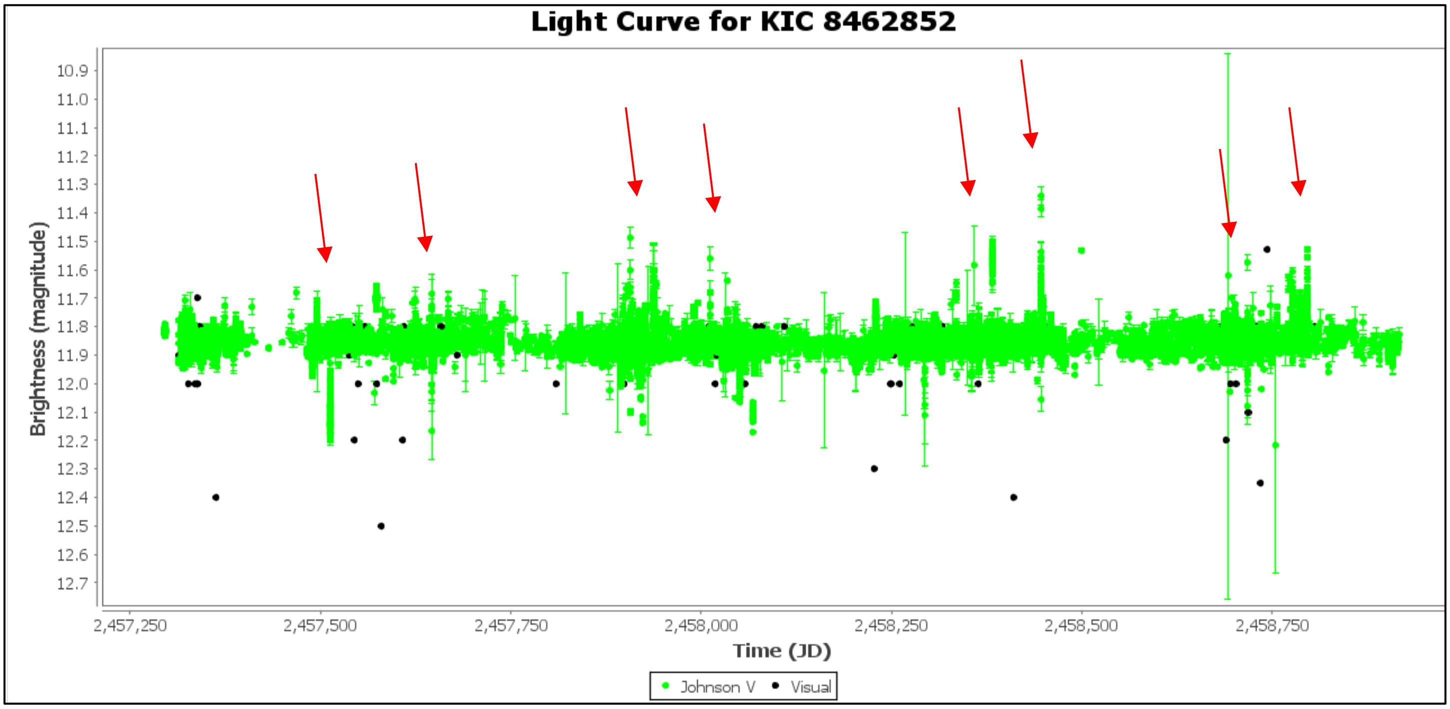

Figure 16. Tabby's Star with All AID data and the sets of drastic rises in magnitude pointed out by the red arrows. This data is all post Kepler and spans from 2015 to early 2020.

These occur in pairs at separations between each set of about six to eight month differences in dates, which is suggesting a longer term trend in luminosity changes at Tabby, however the DC DFT scan was unable to detect or confirm their occurrence as a part of the star's variation. They seem to come in pairs, which does elude to an embedded pattern, despite not being recognized by the DC DFT periodicity, statistical search. This means that a greater amount and continuation of observation data points is needed to help clear up whether or not these were oddities or conjoined in a larger cycle.

5 Aurigae and HIP 26587

In examining Tabby as compared to the two stars that are of the F type spectral class (5 Aurigae, and HIP 26587) there are different trends. 5 Aurigae is closer to the Milky Way band than HIP 26587, however neither location seemed to alter the fluctuations or consistency seen in their magnitudes under the Johnson V filters. Furthermore these stars did not share the eight month, paired spikes and dips in brightness, nor did they show significant differences indicative of their spectral class, seen in Figures 17 and 18.

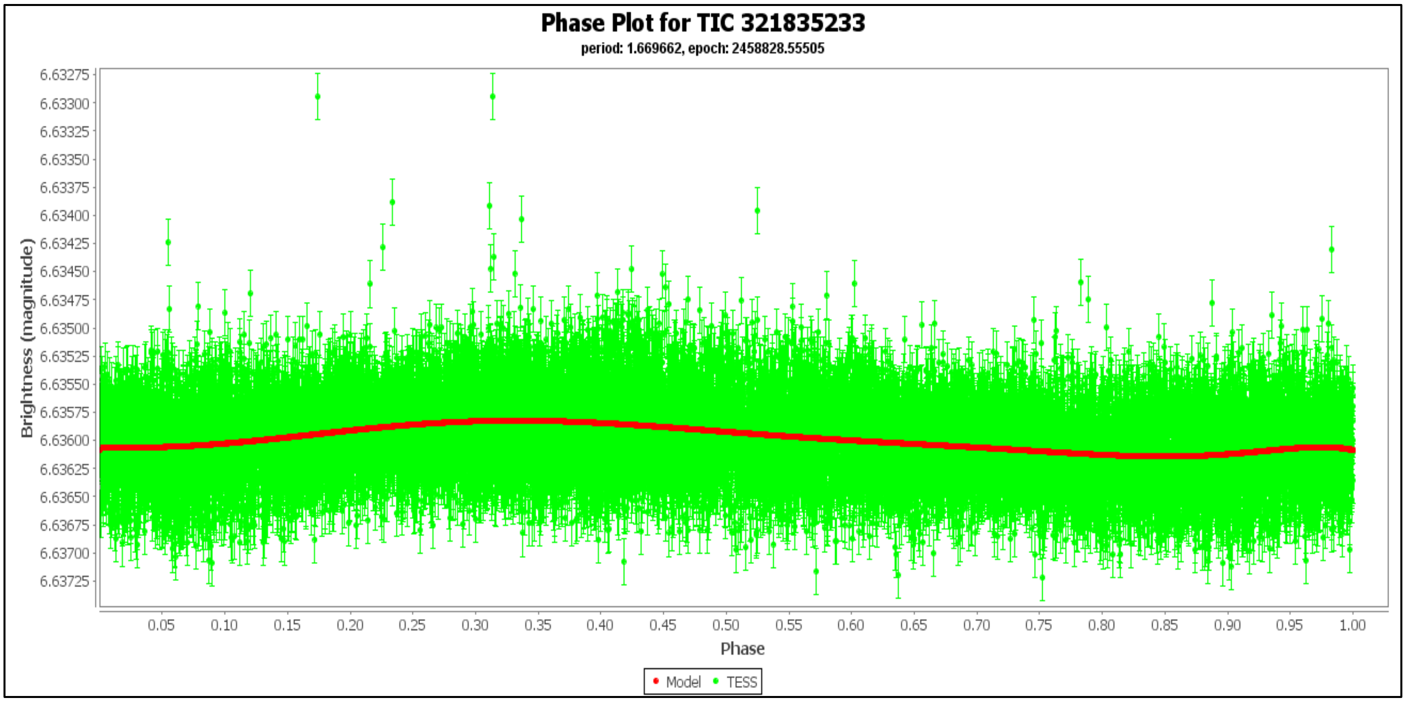

Figure 17. 5 Aurigae light curve as recorded by the TESS survey in optical wavelengths with 1.669 day period and 12 degree polynomial fit.

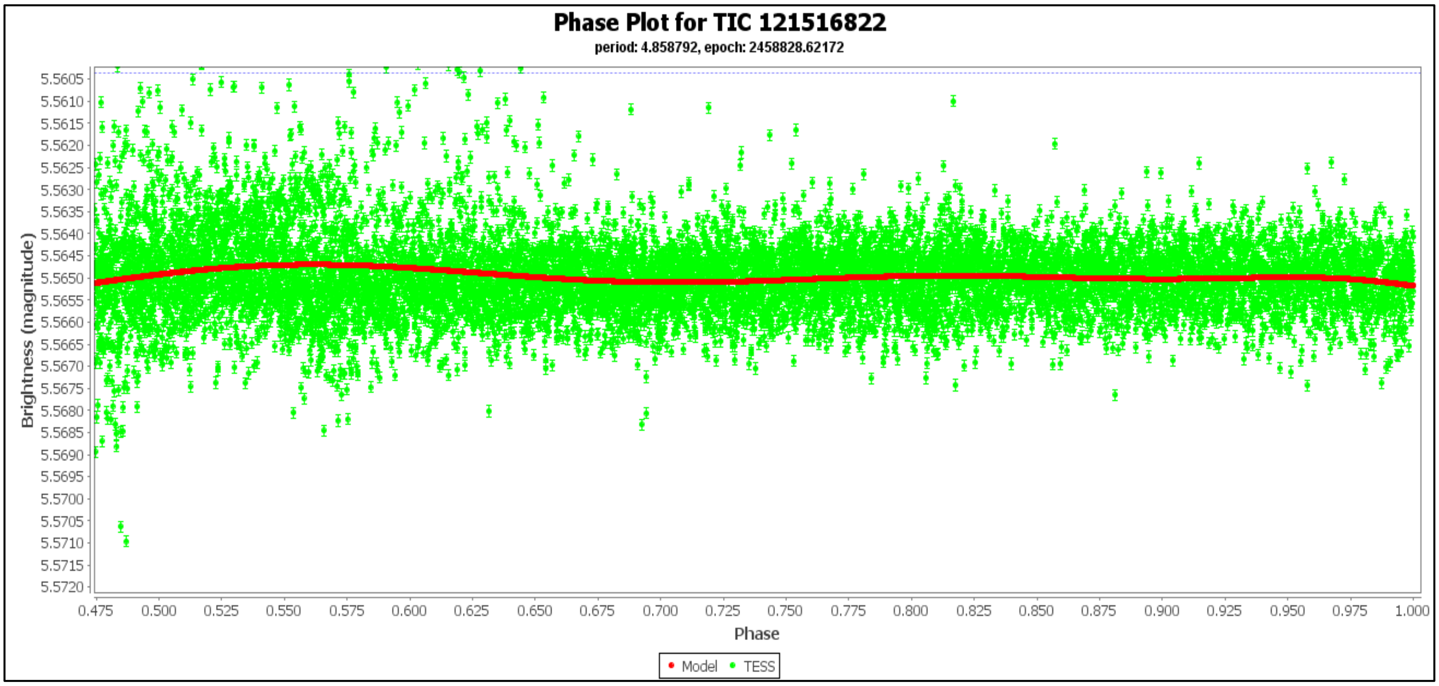

Figure 18. HIP 26587 light curve as recorded by the TESS survey in optical wavelengths with 4.858 day period and a 15 degree polynomial fit.

After having a phase plot constructed for these stars, the minor variances in their light curves seen above were calculated for having periods of 1.669 and 4.858 days respectively. Once the same 12 degree polynomial fit is applied (red trend lines), one can see that the stars remain constant, only changing from one to five thousandths of a magnitude. The period scan really then revealed that these two stars do not seem to share any photometric property with Tabby and their periodicity is indicative of minor changes, perhaps from stellar spots. It is therefore unlikely from this comparative analysis that the spectral classification is relevant in the odditiies recorded at Tabby, especially since the same paired pattern is not found in either of these stars. For both 5 Aurigae and HIP 26587 the APU observatory did record data, however it experienced an experimental error that rendered the data unusuable, so the TESS survey data was relied upon instead for both stars above. Similarly TESS data was utilized in looking at the next comparison star, 14 Andromedae (14 And).

14 Andromedae (14 And)

14 And claims a gas giant planet, and because this remains a leading hypothesis though not the one proposed by this project, it was important to examine it in substantiating the case here. When the established periodicity of 14 And’s planet (14 And b) of 185.8 days, is applied to its TESS light curve, the result is as seen in Figure 19 below (NASA, 2020). The time period addressed here spans from the beginning of September into mid-October of 2019.

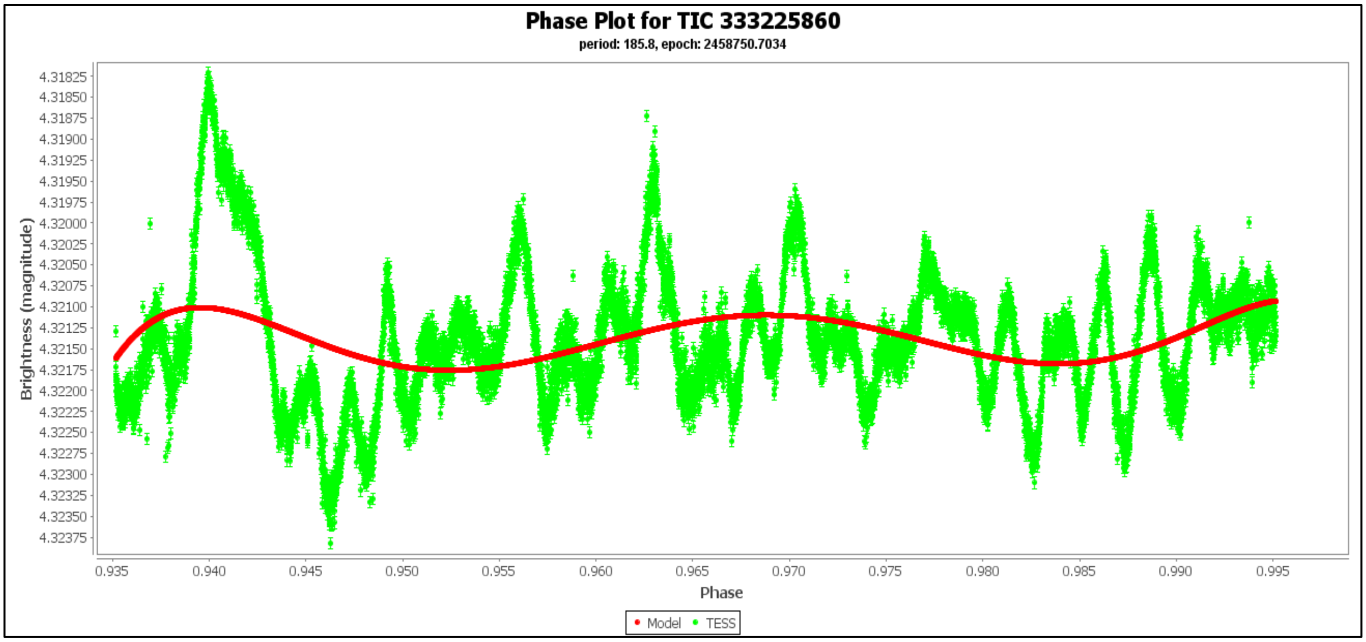

Figure 19. Light curve as recorded by the TESS survey of 14 And in optical wavelengths with a period of 185.8 days and a 12 degree polynomial fit.

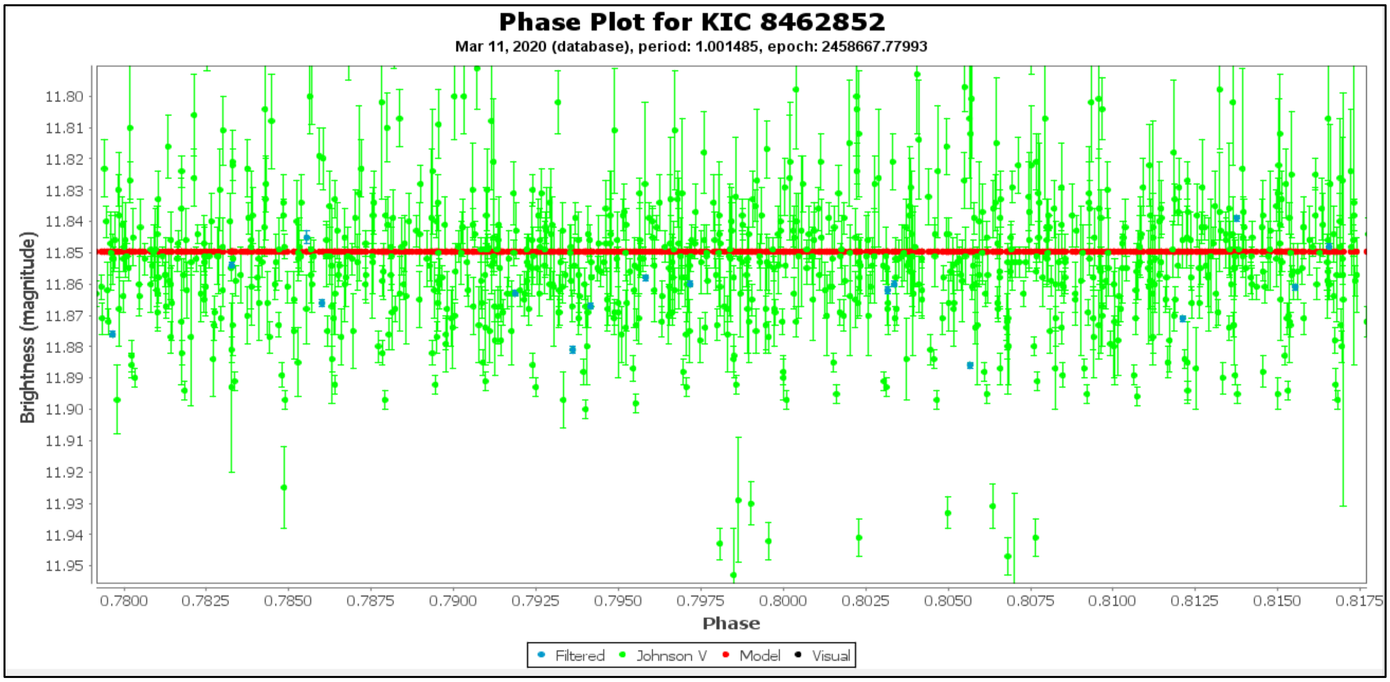

Figure 20. Tabby's Star for reference here with the AID full database submissions and APU contributions highlighted in blue, set to a period of 1.001485 day with a 12 degree polynomial in red

The disk hosting star exhibits minor changes in the hundreths of a magnitude, which in the case of 14 And has revealed a hidden planet. Tabby on the other hand has seen brightness changes across a whole integer with most variations in the tenths of a magnitude, but more intuitively, the shape and characteristic of the disk star is dissimilar from Tabby's. Tabby does not appear to hold the appropriate light curve that typicaly indicates an orbiting planet, however the fact that its sharp rise and fall pattern in brightness measurements occurs every four to six months does seem to indicate a more persistent pattern, reasonably associated with a planet or other extrinsic factor.

Radio Observations: Tabby

The photometric data best revealed the optical changes in Tabby and the three comparison stars, which highlighted the discrepancies as well as an intriguing possible similarity between Tabby and the planet bearing system. Radio wave observations were thus needed and useful in shedding light on further ISM interference and the Milky Way band's affiliated interference.

In Figure 21, the raw data for Tabby's Star is shown taken at 1420 MHz frequency for the duration of 2019 with three axes clearly shown. The first axis shows hydrogen intensity levels on the Y axis as the surface brightness of the object, or the flux density per unit solid angle, with units of Watts per Hz per square meter per steradian (Marr; Snell; Kurtz, 2016). The second axis, the X axis, is the time in months, and the third axis shows the right ascension coordinates through which the scans were obtained for those associated time periods. Together this forms a picture of the fluctuations of hydrogen intensity through each month as well as where the intensity was registering relative to the point of Tabby's Star itself.

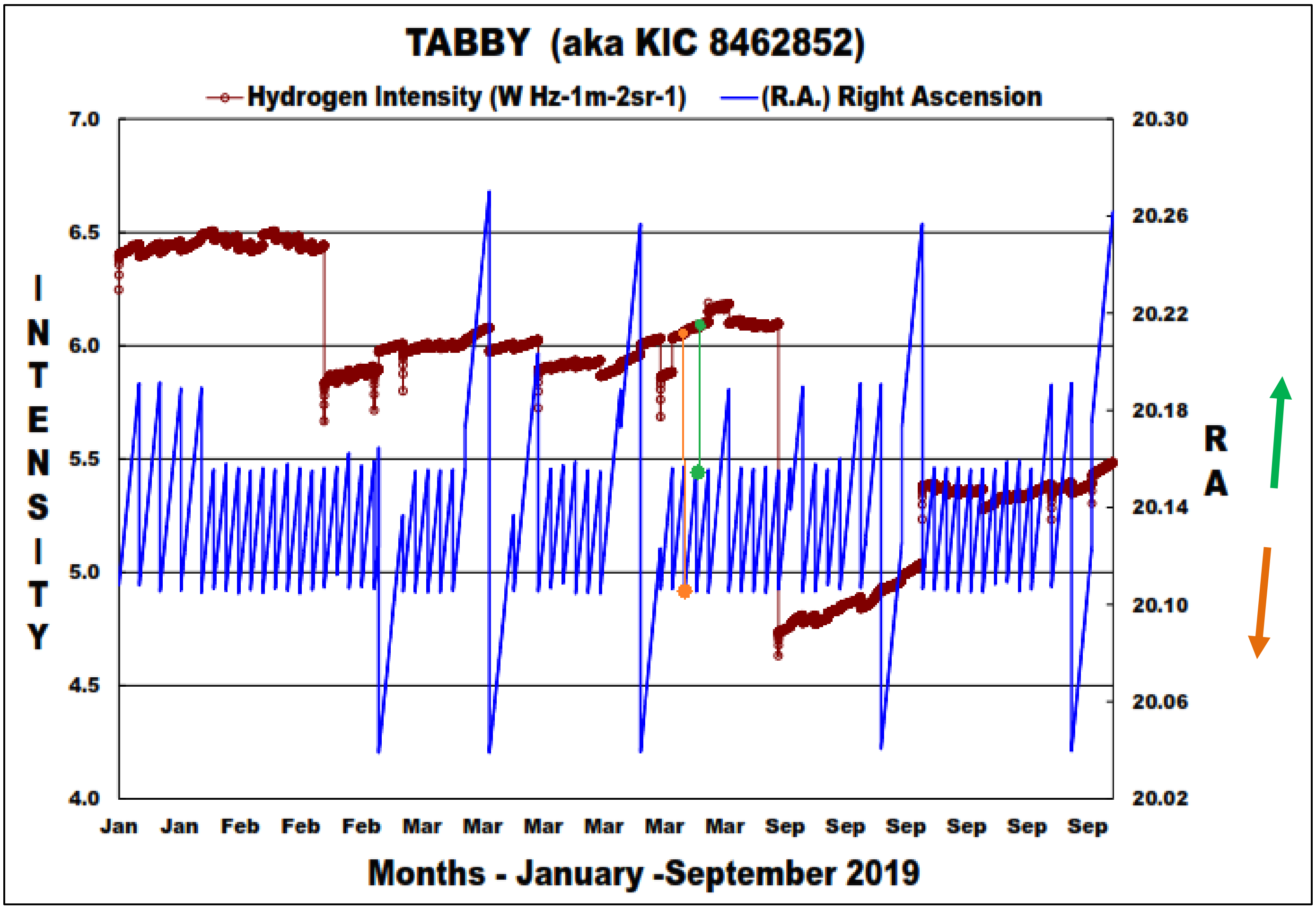

Figure 21. Tabby's radio graph at 1420 MHz with RA coordinate scans graphed in blue and the intensity in red. The direction of increase in RA coordinates 20:15:30 to 20:26:00 is noted by the green arrow, and the decreasing direction in RA coordinates from 20:10:79, to 20:08: is noted by the orange arrow. The corresponding orange points show the decreased intensity matching the decreased RA, and the green corresponding points show the increased intensity matching their increased RA coordinates.

From Tabby's readings here, the tighter circle of coordinate scanning is denoted by the shorter blue lines verses the longer ones that observed a greater area surrounding the star. Despite the width of the observations, there appears to be no correlation between the immediate vicinity of Tabby and its surrounding hydrogen, except for the area range of where the right ascension was greater, anywhere along the graph's third axis from RA 20:15:30, to RA 20:19:00 (marked by the green arrow in Figure 21 above). The rise seen there indicates a denser portion of hydrogen gas in this region than further toward the center of the star's position at RA 20:06:15.46, and it also shows a thinner distribution in the smaller range of coordinates anywhere along the third axis from RA 20:10:79, to RA 20:08:00 (marked by the orange arrow in Figure 21 above). As an extension of this thinner and denser distribution, the larger sweeps follow this same pattern and show a slight increase in intensity at right ascension measurements toward higher values of RA 20:26:00 and lesser in the regions approaching RA 20:04:00. This means that in the vicinity east of Tabby and farther from the star itself, there is a denser cluster of hydrogen gases than toward the west nearer to Tabby and further westward away from the star. Heading east of Tabby delves deeper into the Milky Way band, so this is as anticipated.

The gap in the months of observing time from March to September represents the time frame when the star was no longer visible in the daylight hours. It then required additional time before Tabby had sufficiently risen high enough in the night sky for more radio observations to take place. Though Tabby is out in the months of June through July and August, it had yet to reach a high enough altitude for the dish to observe clear of an adjacent forest at the PARI location. Note the drop in intensity, is seen more clearly in Figure 22, upon the beginning of September observations. This is the raw data excluding dish temperature adjustments and the same is shown in Figure 23 but with a 6 degree polynomial trend line. This was chosen because it best fit the median data although it did display a bit of end exaggeration due to the survey's cessation. The 5 degree polynomial fit, inserted for comparison in Figure 24, was less fitted to the annual measures but did offer a smoother approach. The temperature difference between night and day is the cause for the decrease in detected intensity levels in September, which is compensated for in Figure 25 to give a more consistent look at the fluctuations and its trend line.

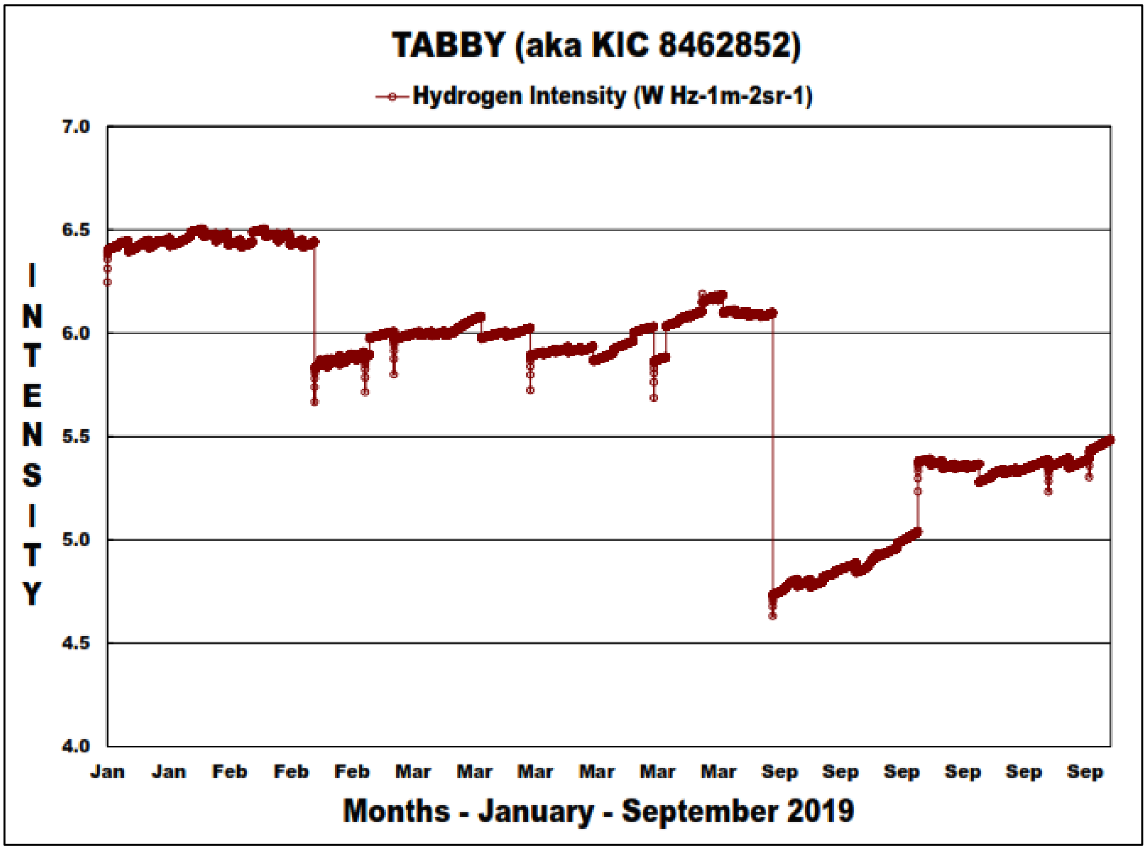

Figure 22. Tabby's intensity only graph, shown in red with the drop in September readings indicating dish temperature decreases.

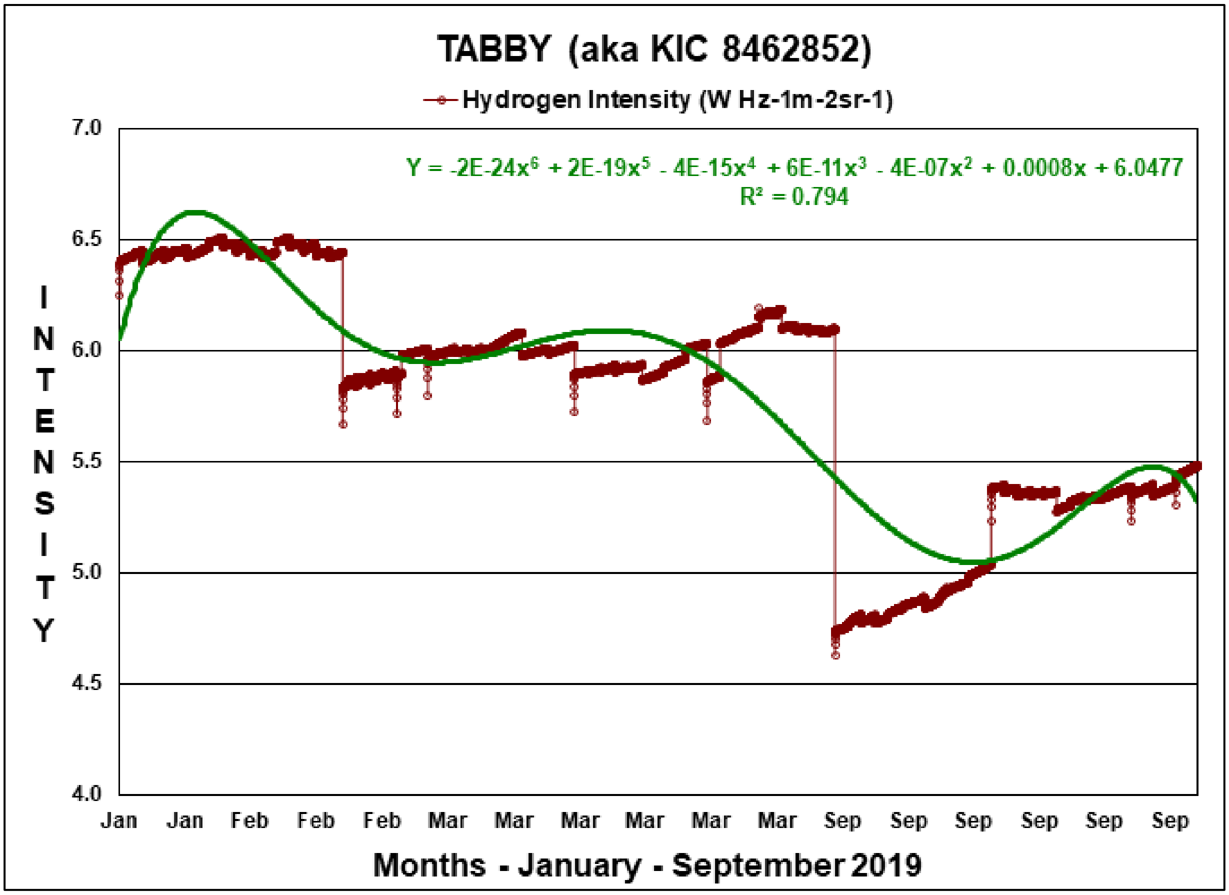

Figure 23. Tabby’s intensity with a 6 degree polynomial trend line in green and the raw data

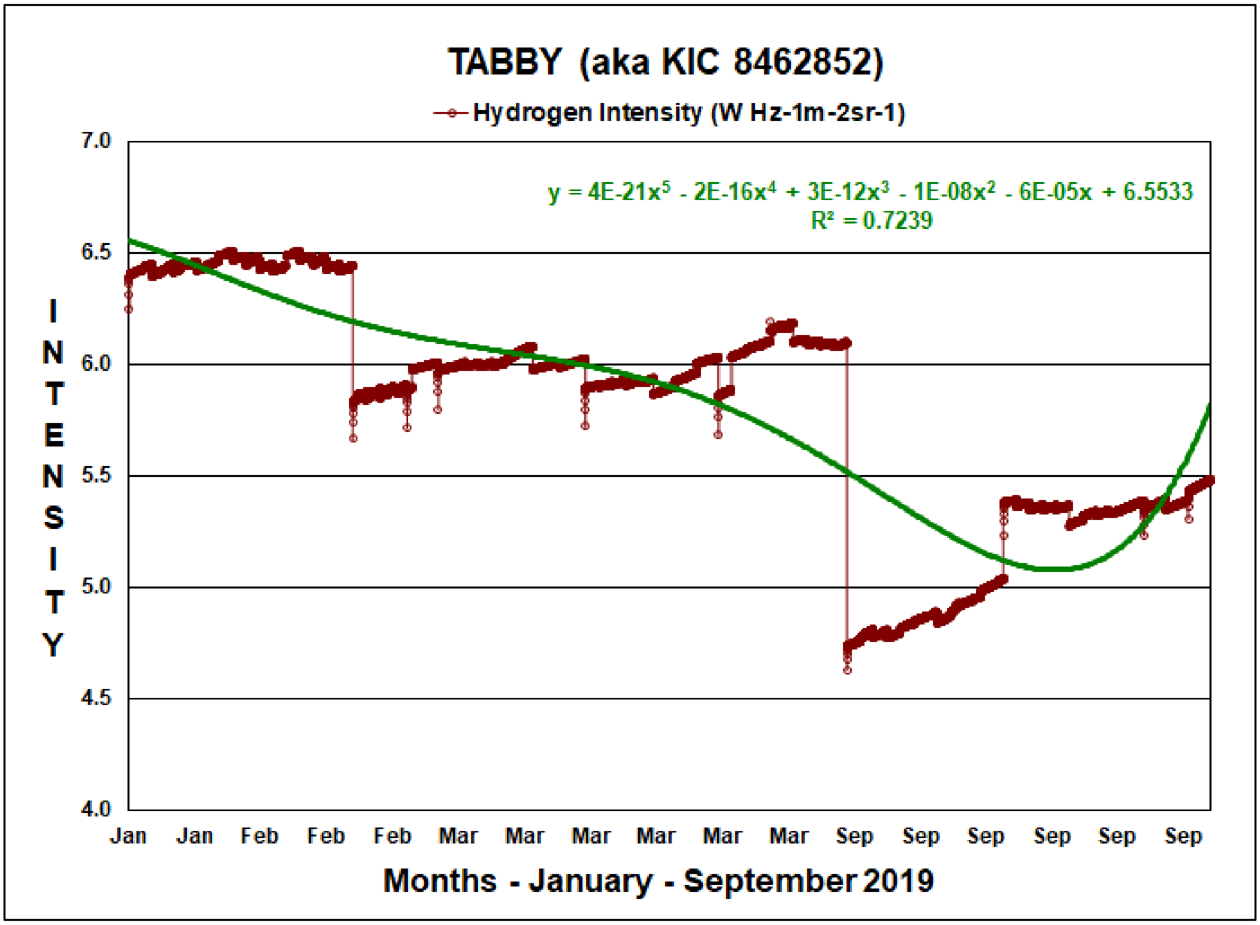

Figure 24. Tabby’s intensity with a 5 degree polynomial trend line in green, showing a smoother trend but less accurate median fitting

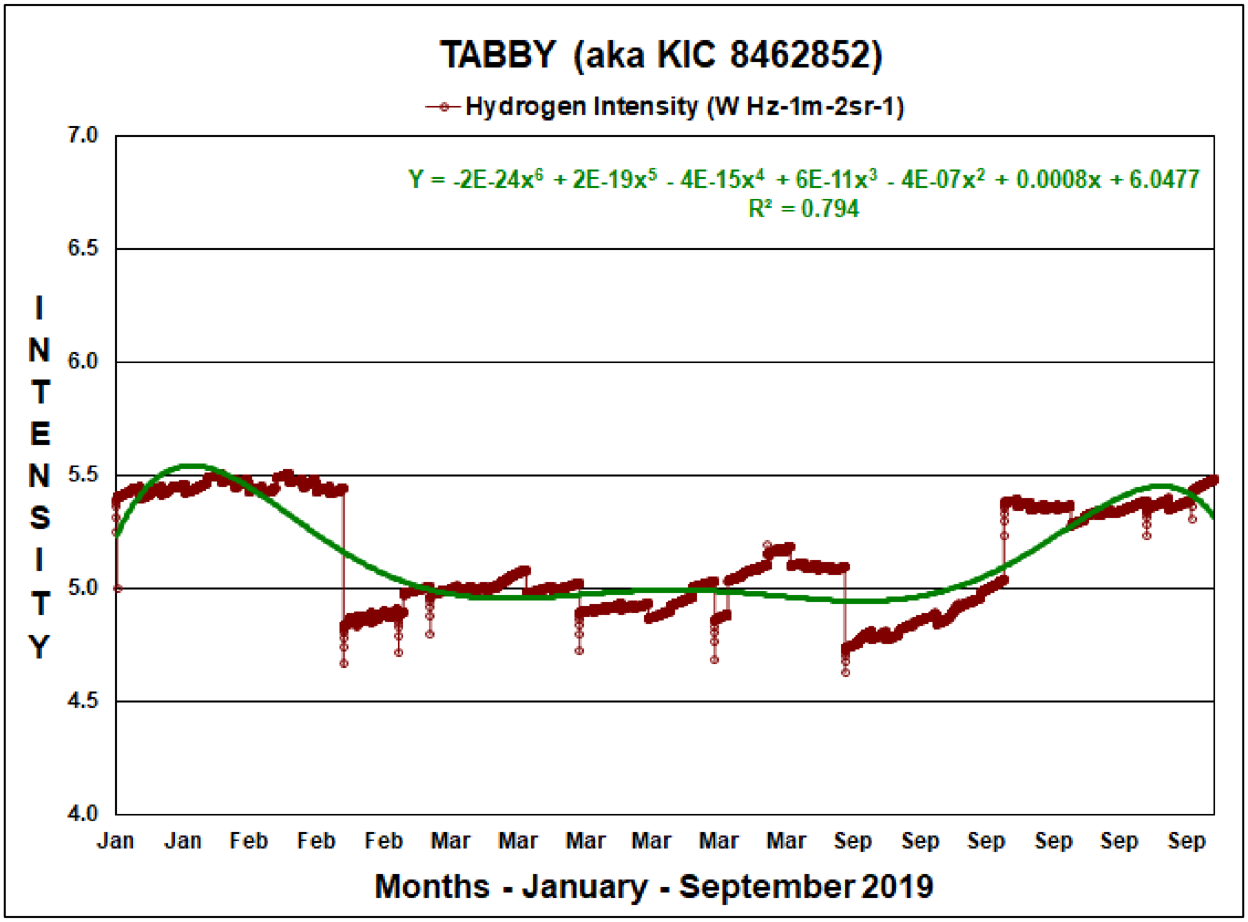

Figure 25. Tabby's intensity with a 6 degree polynomial trend line in green and adjusted for temperature variation in the radio dish

Without the depth of curvature due to temperatures, the fluctuations trend is more gradual, and highlights the difference in readings from the beginning to middle and end of the year. Both the beginning and last month(s) of the survey show an overall increase in intensity, while the mid months display a comparatively lower intensity. That trend could be better associated with the Earth's position in its orbit about the sun. This could mean then that the graph is displaying the parallax difference of hydrogen between the Earth and Tabby. It is difficult to tell if this is in fact the case from a single year's trend however, and so it is unwise to calibrate the graph without further annual data collection. The other rather abrupt drops or spikes in intensity imply a potential polarity shift that accompanied the lesser or greater intensities, resulting in a more sudden change in the recorded values. This also seems to indicate that motion relative to a denser portion of the ISM revealed a polarity increase or decrease based upon the incident angle of viewing, as discussed in the literature review section. Again though, more than a single year's worth of radio observations would be needed to confirm this and dispel the notion that it is a product of the Earth's motion about the sun. Either solar system or ISM based, this bodes well in the support of hydrogen gas interference occurring at Tabby. Comparing Tabby's radio data to the other stars reveals further trends that may be useful.

5 Aurigae

The first of the two stars sharing a spectral class with Tabby, 5 Aurigae, is shown in Figure 26, which plots the hydrogen intensity against both time in months and right ascension. Range sweeps of the star's stellar neighborhood were done as with Tabby, are also shown. In examining the hydrogen signals surrounding this star, it is important to recall that it bore a constant light curve in optical wavelengths, especially because it shows more erratic intensity fluctuations than Tabby. Therefore from this star's graph as a contrast, it suddenly seems less likely that hydrogen intensity is solely responsible for Tabby's magnitude variances.

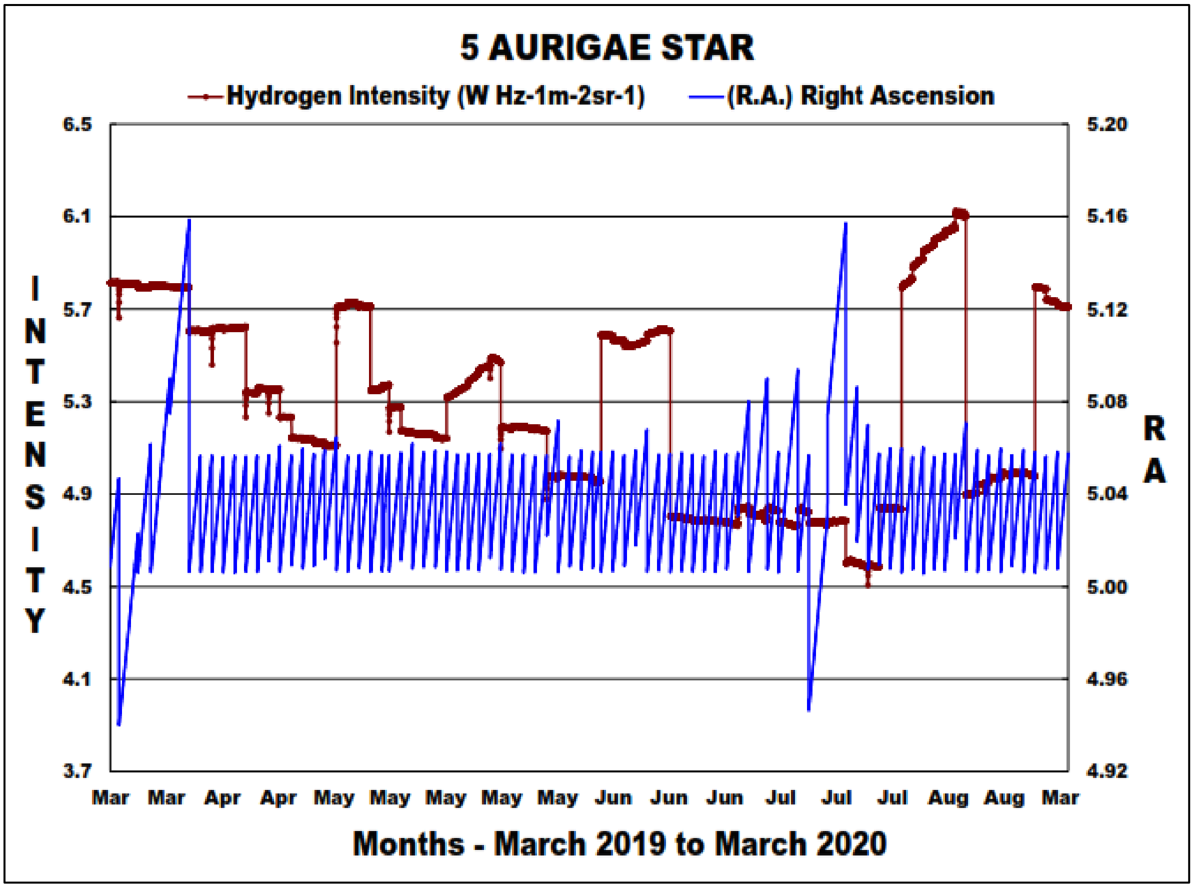

Figure 26. 5 Aurigae radio graph at 1420 MHz with RA coordinate sweep graphed in blue and the intensity in red, no night time observations.

The suddenness of the spikes, potentially from polarity shifts, were unexpected as they happened mid-month or mid-season and the star was clear of horizon obstacles and they were not affiliated with any equipment errors. What Figure 26 also shows is that the distribution of interstellar hydrogen here is not steady; however since this is nearby to the Milky Way band, that may serve as the most likely culprit with combined stellar winds of more densely crowded regions impacting 5 Aurigae's spatial sphere. With 5 Aurigae no night time observations were taken and given the unpredictability of the resultant intensities recorded, reducing the levels for dish temperature were not reasonably achievable. With Tabby the reduced levels lowered the ratio of recorded measurements but did not alter their resultant graph shape, just as it would not be altered in this instance. Figure 27 below shows this same graph without the overlaying coordinate axis, and is overlapped with a 6 degree polynomial trend line.

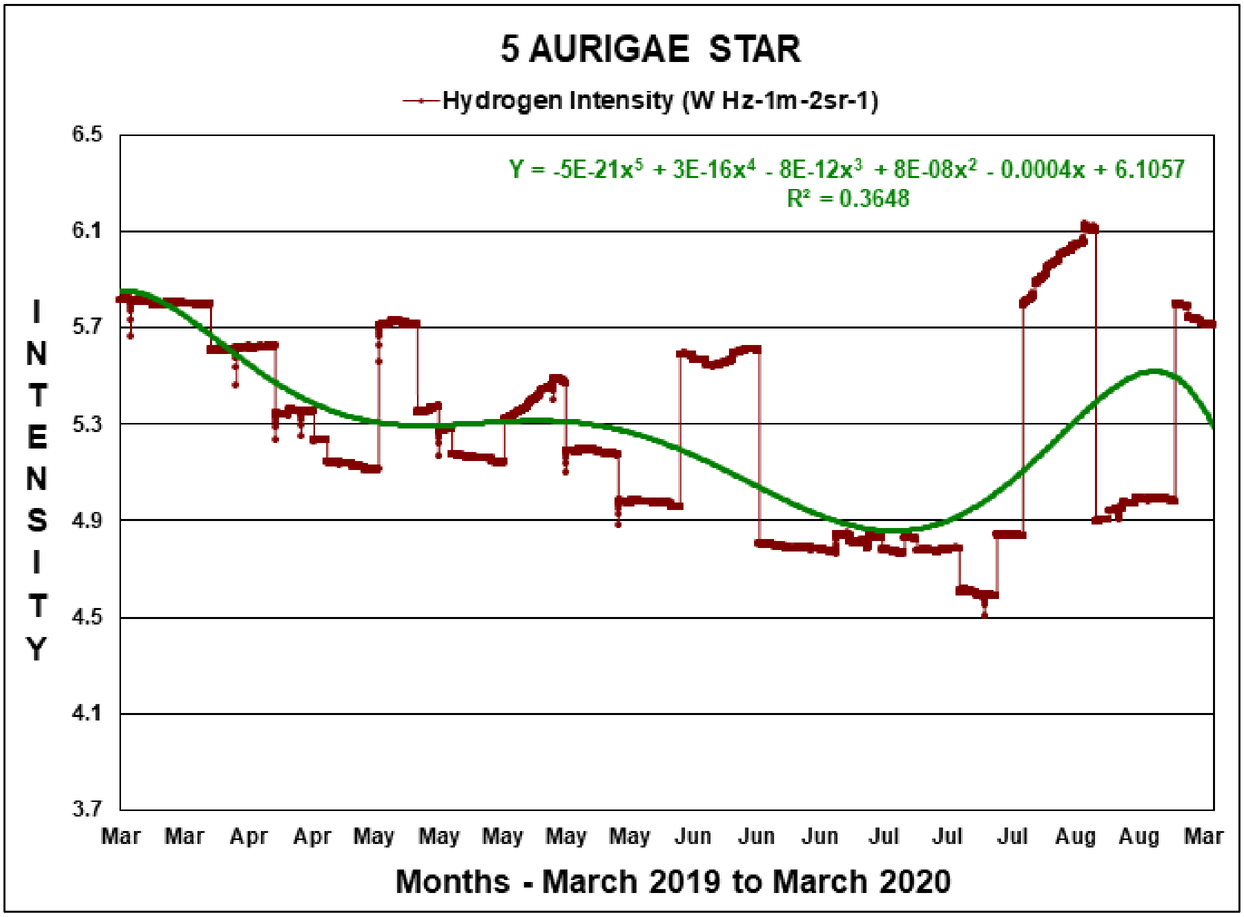

Figure 27. 5 Aurigae’s intensity with 6 degree polynomial fitted trend line in green.

The trend line average shows a relatively smooth transition between readings as it spans between values of 5.7 and 4.9 with outliers of 6.1 and 4.5; more consistent annual scans may be able to better highlight the radio nature of this star’s neighborhood to further clarify regular and outlier data points. The repeated March readings however do register at the same levels of 5.7 to 5.8, indicating that the fluctuations could indeed be a part of the star’s natural cycle. Another property worth noting is that the measurements are approximately one integer point lower than those found for Tabby, even once dish temperature is accounted for.

HIP 26587

Looking at the other F spectral class star, HIP 26587, shows a different pattern than 5 Aurigae's, but it too is similarly erratic, as seen in Figure 28 below. HIP 26587 did exhibit several peaks and troughs in hydrogen intensity, but they did not correlate with its coordinates, which is unlike the east and west pattern seen for Tabby, but similar to 5 Aurigae. HIP 26587 did experience a greater fluctuation between crests and dips than 5 Aurigae did however, with a whole integer number as the averaged range and outlier highs upwards of 6.3 and lows at 4.5 for intensity.

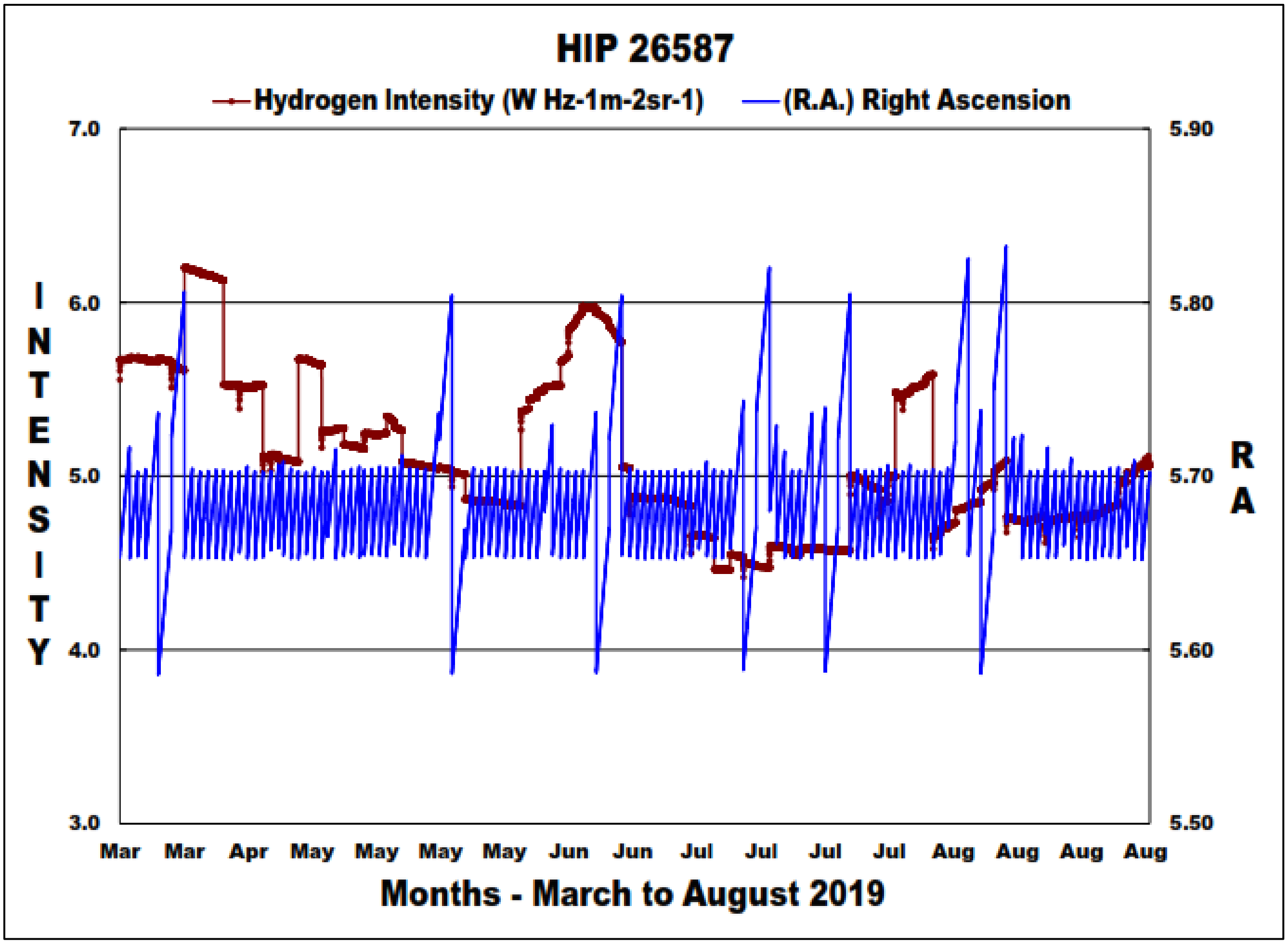

Figure 28. HIP 26587 intensity in red vs. time in months and RA in blue

Despite its wider range of recorded signals and the same 6 degree polynomial trend line, HIP 26587 yielded a smoother fitting trend line than 5 Aurigae did, as seen in Figure 29. The intensity measured at HIP 26587 is the most northern bound area of the sky that was examined in 1420 MHz and showed the highest peaks as it had just reached its highest daytime position in May and was slowly declining in the sky. Daytime observations were taken for this star as well, and it like 5 Aurigae, reported a steady light curve in optical wavelengths. This too then gives further evidence that hydrogen density is unlikely to be the only cause behind the variances of Tabby's Star.

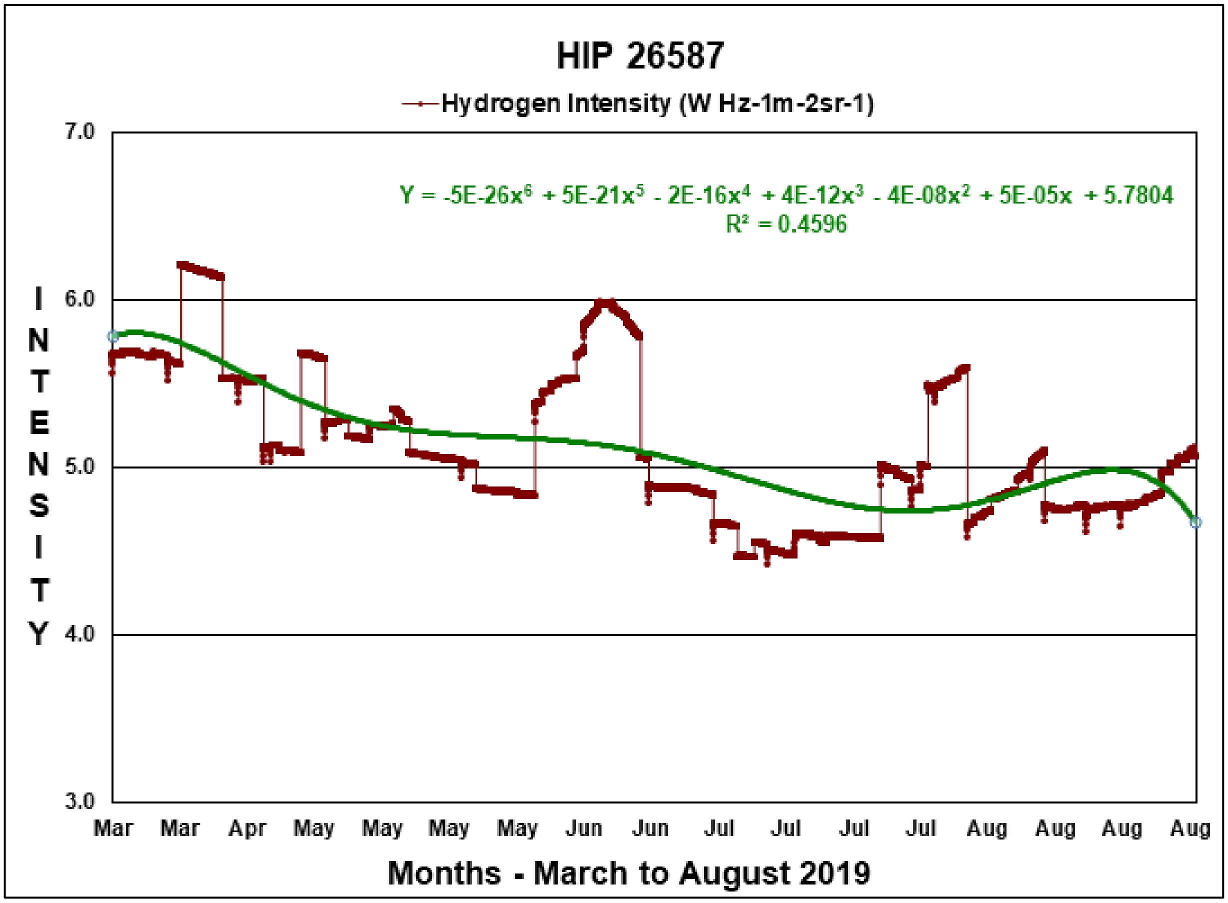

Figure 29. HIP 26587 intensity vs time in months with a 6 degree polynomial fitted trend line in green

14 Andromedae (14 And)

Coming to the last set of radio observations presents the planet bearing star, 14 Andromedae (14 And). Looking at 14 And first shows a rather stepped down curve, indicating a steady decrease in hydrogen intensity as it drops from measurements of 6.5 to averaged lows of 5.5 with outliers of 5.0, displayed in Figure 30 below. Recall that the planet's orbit about 14 And is 185.8 days long or about every six months. In the following graphs one can see this drop in light as the readings went down to levels of 5.0 on the intensity scale during May and it only lasted for a brief period of time. At this time the planet should have been transiting the face of its parent star, after which the measurements began to rise once more (NASA, 2020). So the recorded points here are more indicative of the presence of its planet and less indicative of its environment. This could also be showing that perhaps this star is more isolated from hydrogen gases than the other stars in this study. Again the coordinates did not correlate with the intensity readings here, but the star is also farther from the Milky Way band and its optical light curve was very different from both Tabby and the two F spectral class stars.

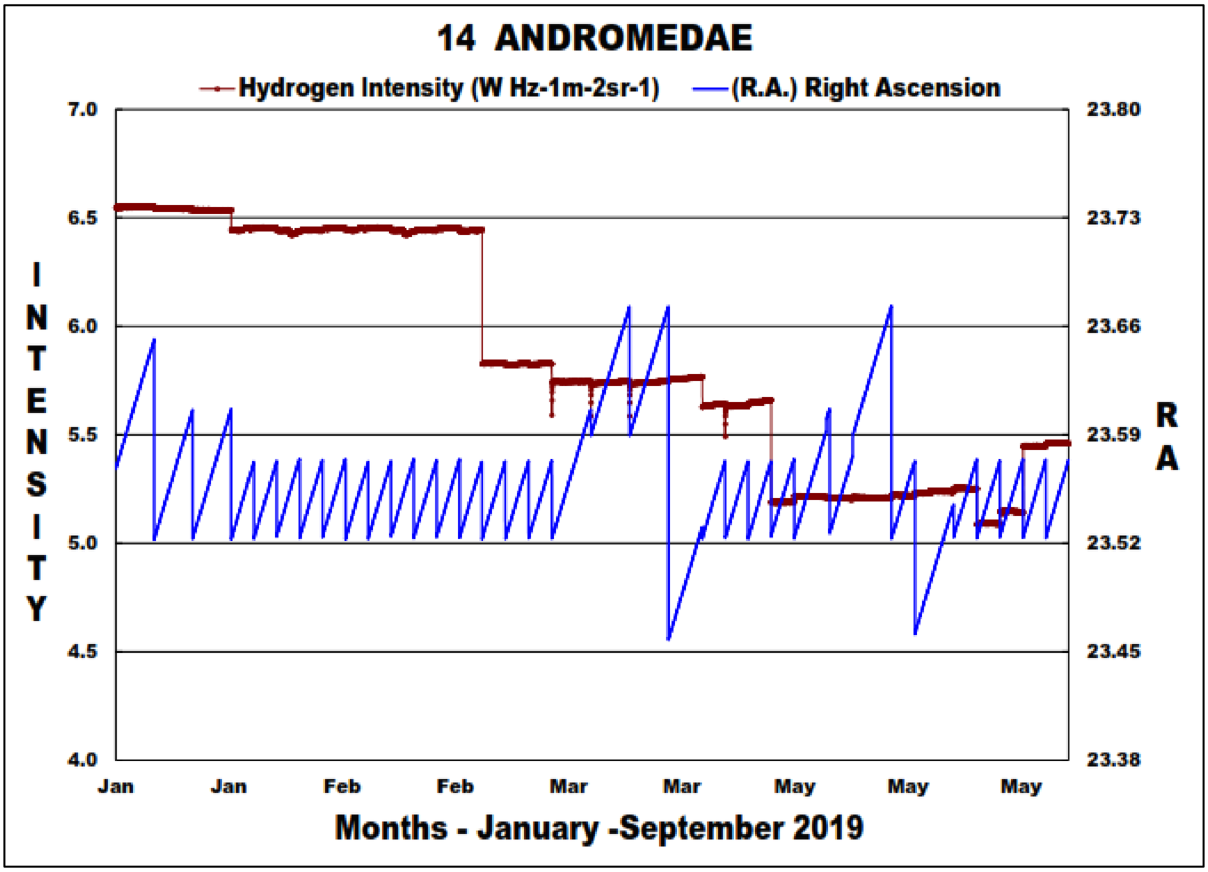

Figure 30. 14 And graph with intensity in red and RA coordinate scans in blue

Night time observations were not taken for this star. The lowest points taken in March seem rather isolated and they represent the beginning moments of the scan as the radio dish had just finished its slewing motion and residual elements of that dish motion faded into the initial moments of the readings. The most significantly erring measurements that occurred at the beginning of all the scans across Tabby, 5 Aurigae, HIP 26587 and 14 And (otherwise known as the zero second points) were all calibrated out as experimental flaws. The trend line in Figure 31 demonstrates the steady decline in hydrogen intensity as the transit becomes clearer in the year's mid-months, seen below. This means that the star's more isolated environment from interstellar hydrogen is thinner and the cold hydrogen likely comes dominantly from the 14 And system itself.

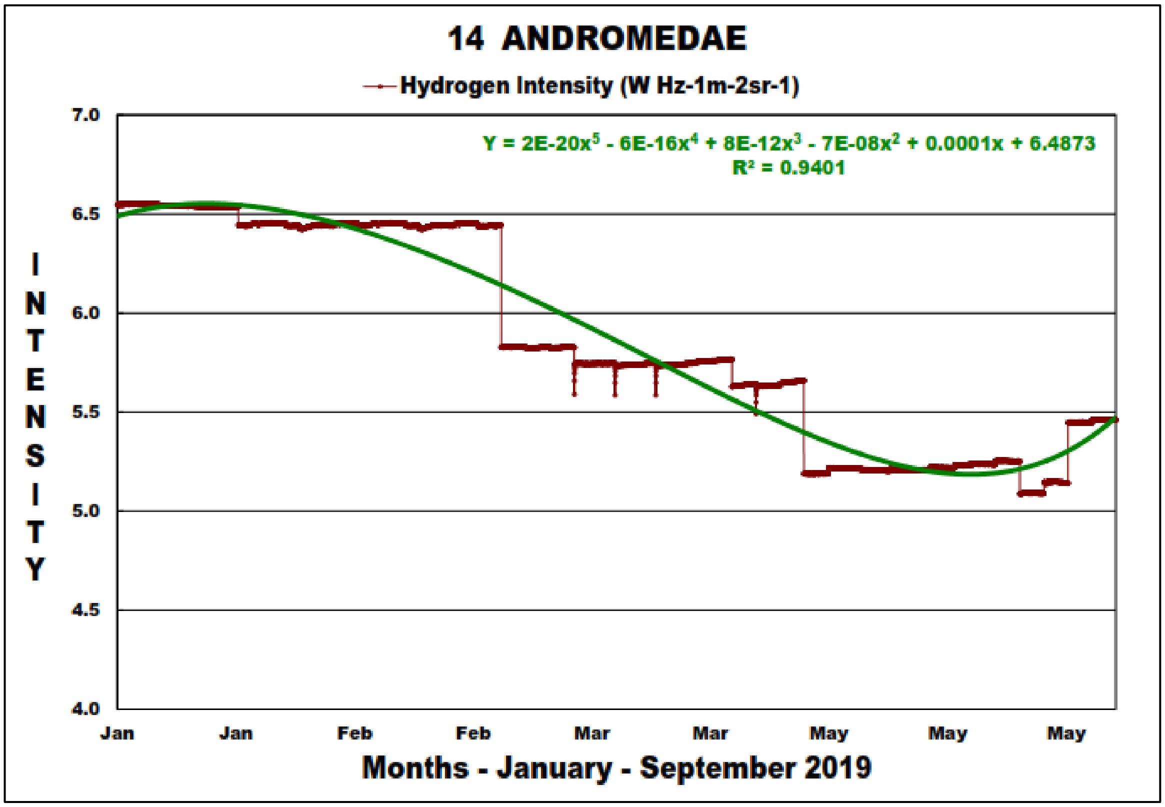

Figure 31. 14 And intensity data with a 5 degree polynomial fitted trend line

Collective Analysis

As expected from looking at these graphs collectively, Tabby's displays the most consistent and the overall highest intensities of hydrogen as compared to the other stars. This immediately communicates Tabby’s location in the Milky Way band, including the east and west pattern as intensity increased moving eastward, which was deeper into the band. Inversely, the intensity dropped off slightly as scans moved westward, which was toward the Milky Way band’s outer regions. The other comparison stars showed a more erratic trend of hydrogen intensity. In the case of the planet bearing star, 14 And, a more gradual decline are seen in hydrogen intensity, this star is also farther from the main Milky Way band. From these graphs it can be seen that hydrogen density seems to be of little relevance in the search for a correlation between gaseous distribution and optical magnitude variations. An optically dense, intervening cloud in the interstellar medium was suspected as the culprit for dimming Tabby, which proved difficult to discern from the 2019 radio examination alone. Tabby did however experience a few sudden changes over the course of 2019. It remains entirely possible then that coming years will bring more drops and brightening events for astronomers to measure the hydrogen intensities concurrently, like those done in this research. The last paired spikes in magnitude, as pointed out in Figure 16, took place in early August through mid-November of 2019. The pairs occurred at intervals of four months apart from the next set, with each increase separated by one to two months. If this preliminary trend is to be followed and a recurrence is expected, then Tabby ought to experience another set of increasing and falling magnitudes around April and May of 2020, with another in July 2020 to follow. Tabby then should be monitored closely, both optically and in 1420 MHz radio wavelengths. Through the radio data collection time period for Tabby in September of 2019, the star was steadily brightening and there was a spike in hydrogen intensity. This happened just as the next paired set of optical brightening was getting underway as measured in the photometric data. That increase in hydrogen intensity could have possibly been due to the ISM, or one of its denser clouds. It was a subtle change that did share a spike photometrically, a spike like those seen by Kepler. This took place on the date of September 13th, when the intensity had just begun to rise. It progressively rose higher throughout September 16th as detected by the radio telescope. This stood as an overall increase in the levels of intensity, aside from the general rise in these measurements from the coordinate shift further toward the center of the Milky Way band. These measurements were only recorded as increases in the hundredths or thousandths of a point, but the mid-September spike was in the tenths. Both photometric and radio data on these dates are illustrated below in Figures 32 and 33 for reference.

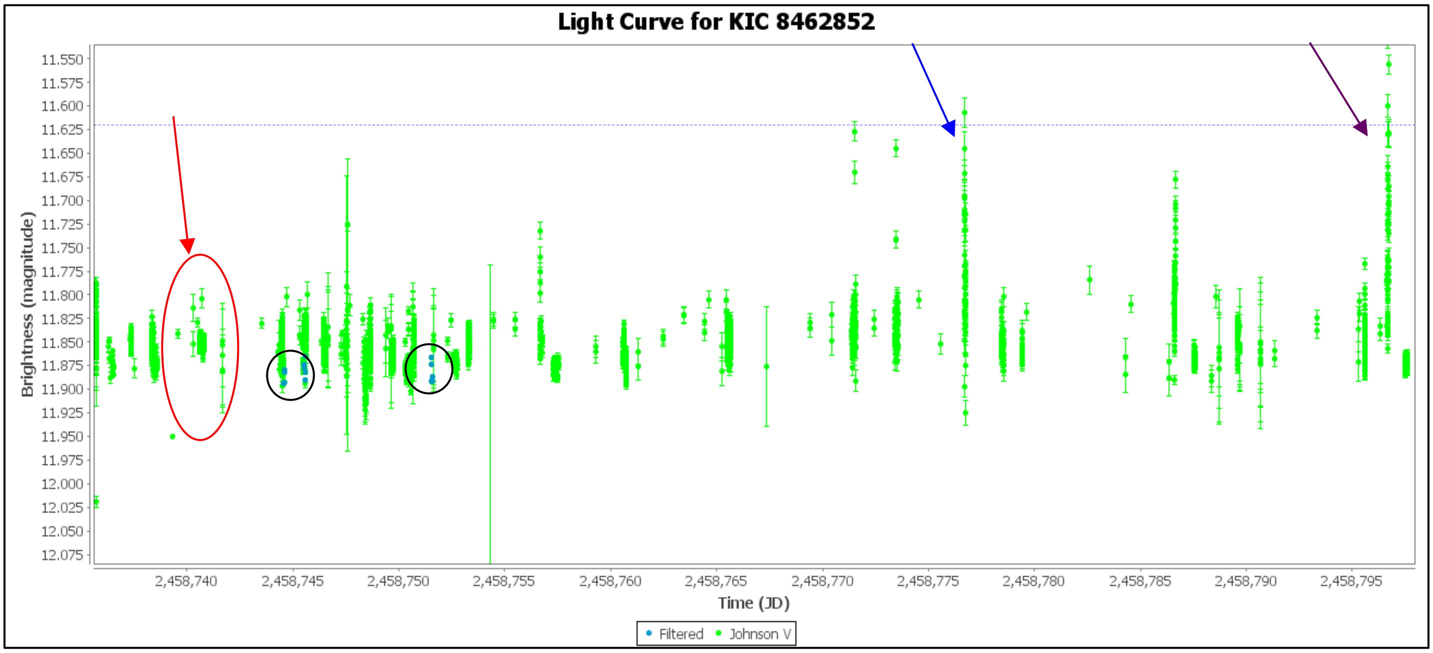

Figure 32. Tabby photometry data on September 13th (circled in red) as the brightening began all the way through October 18th (blue) and November 12th (purple) when it reached its peak optically. APU optical data is circled in black just next to the red circle

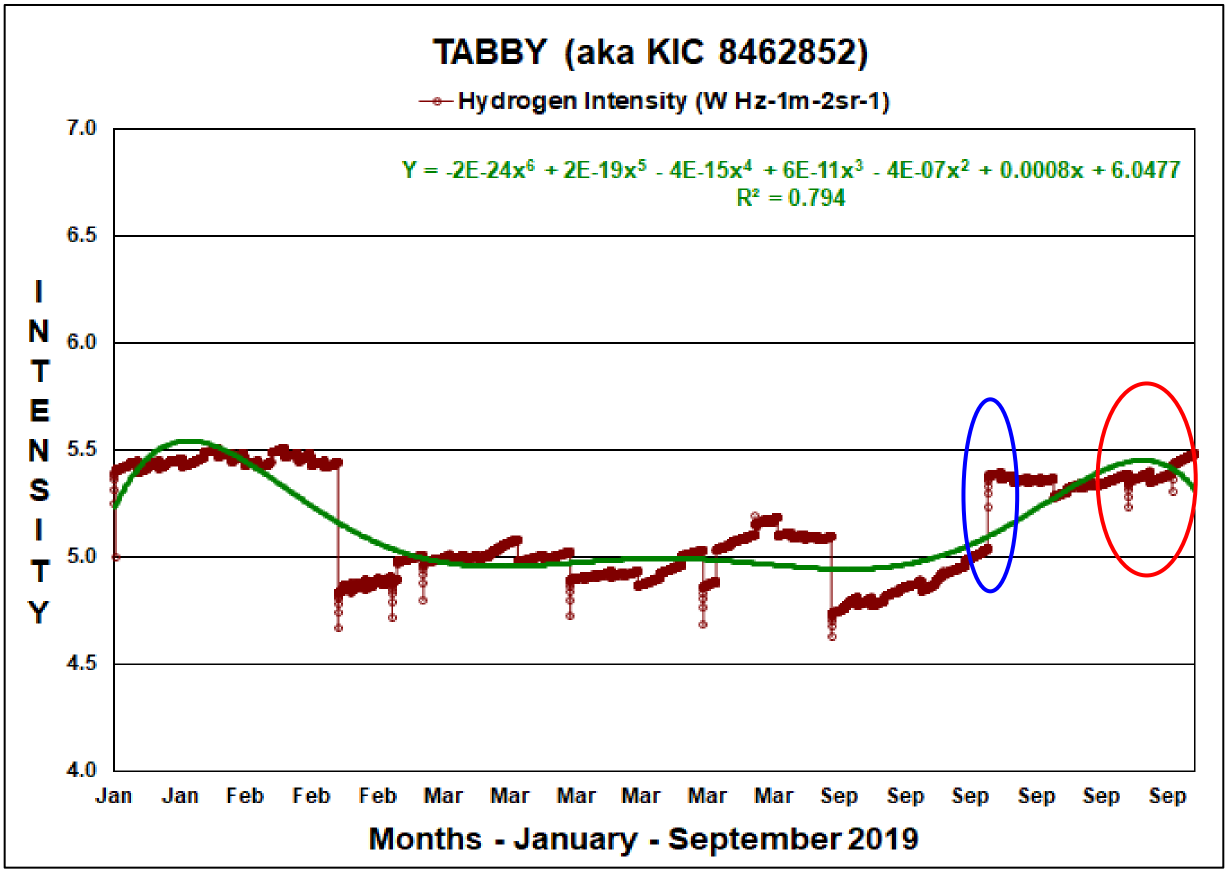

Figure 33. Tabby radio data on September 13th 2019 when the rise began circled in blue, September 16th is circled in bright red.

The September 13th spike, circled in blue, is one such increase that appears more suddenly as compared with others on the graph in Figure 33, it is worth noting though that there was an eight day difference between the last September measures before the 13th. As mentioned before, this more sudden increase is a potential instance of the polarity for that hydrogen shifting as a result of a changing angle due to the cloud's or Earth's (or both entities) motion. Seen on the opposite end of the radio wave graph in January through February is additional and symmetrical data compared to that of September, a higher intensity than the median months of the year. The rise is only a tenth of a difference on the intensity scale with those observed in September. This also coincides with predicted magnitude rises, unfortunately the most closely expected rise in May and June proved unreachable with the radio telescope due to horizon issues and time constraints in the project. In looking once more at the photometric data on Tabby at the time of Feb (the 14th was when the higher values were recorded) one sees that there are no large decreases or increases in magnitude. This is shown below in Figure 34, the star in fact remained relatively neutral at magnitudes of 11.8 to 11.85 and a few points at 11.9. This may have been the result of an optically thinner portion of the ISM that registered in radio waves and yet was not thick enough to cause a severe impact in visible wavelengths.

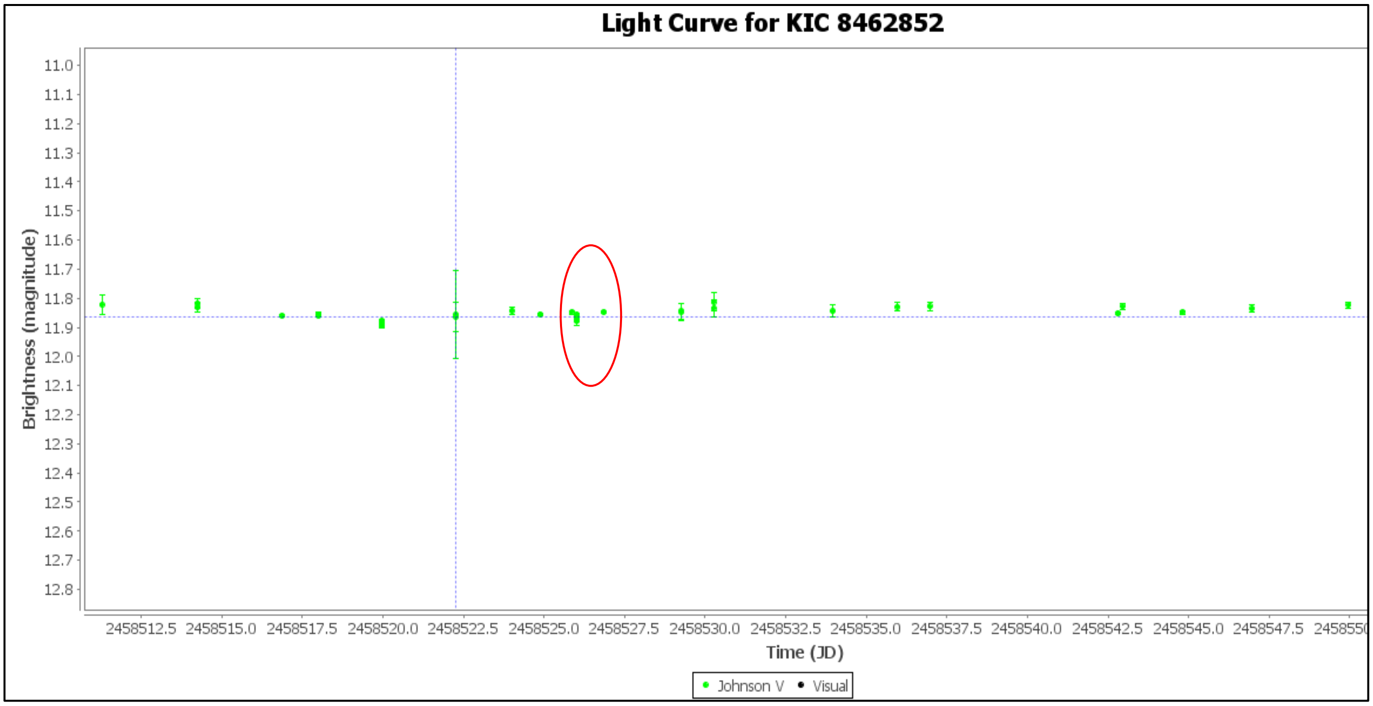

Figure 34. Tabby photometry data showing February 6th to February 26th measurements in the Johnson V filter from the AID. Feb 14th is circled in red.

The paired peaks of brightness go against the grain of the notion of a denser region of the ISM, which would yield more randomized events of brightening and dimming. This reinvigorates the hypothesis of a transiting object or disk, however one can see as in the case of 14 And that planetary transits decrease the intensity levels of hydrogen when scanned at 1420 MHz. This trend is not observed in Tabby, either photometrically or at radio wavelengths. Ignoring for the moment this perceived pairing pattern and recalling the photometry analysis section, there were several noted, divergent data points indicating some erraticism to the magnitude rising and falling. This can also be seen in the median radio values in the form of minor fluctuations. Whether Tabby next experiences a paired set of abrupt peaks in brightness or continued smaller and spontaneous ones, continuous radio data ought to help point out those denser portions of the ISM passing in front of Tabby. The smaller and random peaks and troughs from these radio and photometry graphs, indicate that the ISM is indeed having an effect on the magnitude of Tabby, while the larger, pairs of spikes point to an additional property that is altering telescopic views of Tabby. The 1420 MHz data seen thus far coincides with some of the higher peaks observed optically and denotes the density of hydrogen surrounding Tabby, thus establishing a baseline from which to continue scanning the star. These magnitude increases could well be a result of the Earth's position and motion through the Milky Way disk, which may explain the changes in density in the ISM. A look at the motion and position of the solar system shows that it rotates about the galaxy, imbedded in its Orion arm at a rate of approximately 10 to 14 miles per second on an elliptical orbit (NCU; Weissman, n.d.). Along its orbit the solar system weaves north and south through the disk about every 66 million years; it was only two to three million years ago that it passed through the galactic plane and is currently heading due north in its motion through the plane (NCU;

Weissman, n.d). For the next 30 million years the solar system will be moving to reach its crux of northward motion before resuming southward motion (NCU; Weissman, n.d). The Earth has already passed through what is the densest area of the galactic disk and currently then is in, and will continue to wade through less dense gaseous regions that are more heterogeneously distributed and compacted. The ISM tends to be non-homogenous in its optical density and so it could reasonably be then that Earth will continue to experience seemingly random fluctuations in both radio waves and visible light for Tabby. This ought to be especially true for Tabby since it lies in a more densely crowded region of the galaxy amidst the central plane of the Milky Way band. This is analogous to hurricane rain storms, where the midst of its densest regions has rain flowing continuously. Then as the outer edges of the storm are reached, the rain comes in disruptive spurts; such is the proposition of this research based on the included radio data and optical analysis. According to our current position, just north of the mid-center of the galactic disk, the solar system has already experienced the densest regions of gas and dust. It is now heading into the “spurts” of fluctuating hydrogen intensities, possibly disrupting the clarity of viewing Tabby’s Star. Along with this northbound drift, the angles on this heterogeneous mixture of hydrogen will also be shifting angles relative to Earth, therefore potentially disrupting the polarization of the gas between the solar system and Tabby. From this study the most likely process believed to be taking place at Tabby is the sporadic interference of heterogeneously mixed hydrogen in the ISM, observed at varying angles, as the Earth is traveling north through the Milky Way’s disk. This is believed to be a main cause of the general brightening and dimming events seen at Tabby, but another more regular component is also suspected. As shown in the photometry graph in Figure 16 of Tabby with all AID database input, that paired pattern of spikes in magnitude occurred regularly and these correlated with minor hydrogen intensity increases. The hydrogen intensity only climbed by minute amounts though, so while it is interesting to see this correlating increase in optical and radio waves, the pattern suggests a more permanent component as opposed to ISM interference. There is only one year's worth of radio data to make supportive claims; more observations are required in order to confirm the presence of hydrogen spikes in affiliation with optical brightening events. It otherwise could suggest that another extrinsic source may be responsible for these larger patterns, perhaps a dwarf companion star or even surrounding clouds at the edge of the Oort cloud that are seen to interfere seasonally and are thus separate from Tabby's system altogether.

Future work would benefit from expanding the observational wavelengths into higher energies of UV or X-ray for an additional, comparative look at Tabby's Star. The continued monitoring of this star system optically and with the use of radio **POSSIBLY REPLACE WITH** Future work would benefit from the continued monitoring of this star system both optically and with radio waves. This will be able to expand the work done here to include several more years' worth of observations and confirm or reject the pairing pattern with better certainty. Continued radio data can accomplish the same effort toward confirming or rejecting the perceived paired pattern in Tabby as well. Additional year-long surveys can monitor the density of clouds in the ISM as the solar system continues its slow trek northward, seeking out more correlations in radio intensity and optical magnitude increases. Further radio work to supplement what has been done here should also include radio mapping at the 1420 MHz frequency in addition to more continuum scanning.

This section has discussed and described the data points collected by both the sets of optical instruments and radio telescope in addition to sharing the graphs of that data and the implications of those results. These graphs have given a wider look at Tabby's star and have helped to limit the cause of this star's variations in examining the hypothesis that cold hydrogen gas is mostly responsible. The next section will summarize the findings and research project as a whole to conclude the study.

Conclusion

In summary, Tabby's Star has become an important stellar specimen because it shows unusual brightening and dimming sessions with erratic fluctuations in between larger spikes. It is a mysterious star that does not fit standard models of a periodic variable, nor one hosting a planet(s); however it has been an avenue for many hypotheses including the bizarre and natural alike, including alien life, star spots, obscuring gas or dust, and planetary disks. With its popularity growing out of the Kepler mission, Tabby helped to invigorate additional research efforts concerning this star and the search for others like it. It thus served to inspire continued efforts within the field of variable star science and attracted many from the public to join citizen science projects. Exploring the current research on these ideas has shown many of them to be less likely, such as star spots, magnetic field interference, and disrupted comets in orbit about Tabby. The literature review highlighted two hypotheses that hold more weight as potential solutions to Tabby's Star that of planetary systems, and the one proposed in this study, inhomogeneity within the hydrogen gas of the ISM.

This project used both optical and radio observatories to collect data on Tabby's Star, as well as three comparison stars, and analyzed them in conjunction with observations across several databases. The optical data on Tabby was submitted into the AID for future use by other astronomers and the radio data saved in the digital archives of PARI. Using a variety of processing and analytical software, the observations were measured and graphs constructed to see how data did, and did not correlate across the two spectra. The radio graphs showed an increase in neutral hydrogen at Tabby compared to the other stars as well as its intensity distribution in that region of the Milky Way band. Those radio scans revealed rises that correlated with both minor and major changes in magnitude across the visible wavelengths, suggesting that the ISM is a main aspect of the variations seen here. The motion of the solar system further promoted this with the likelihood of altered hydrogen gas polarities being indicated out in the radio observations, as the Earth treks north through the galactic plane. For Earth observations can only measure Tabby's light through the heart of the Milky Way band where there is much intervening gas. The graphs did reveal times though where the optical and radio wavelengths did not correlate, along with paired patterns of spikes photometrically over the last five years' worth of data contained in the AID, suggesting that another force is at work. In opposition of these correlations seen in radio and optical wavelengths for Tabby, are the observations of the comparative stars, which showcased more erratic radio signals to match with their constant optical ones. This is likely due to the fact that these stars had only one year of radio scans and several years of photometry observations. Interestingly, the star hosting a planet saw a steady decline in radio waves as the transit approached, whereas Tabby saw no such similarity in the 1420 MHz frequency scans. This implies that a planet is not the additional force causing the paired pattern of spikes and dips in magnitude at Tabby. Exploring the radio spectra of Tabby has opened deeper insights as to the changes in hydrogen surrounding this star and its reasonable potential for diminishing and brightening it optically. The astronomical community now has supplemental data across another wavelength and frequency band with which to continue analyzing this captivating star. More data is required in this important waveband in order to confirm the correlations seen in this study, for it spanned the course of one year, with some months where scans were unobtainable. In contrast, about eight and half years' worth of data exist with photometric observations for Tabby and more continues to be submitted to the AAVSO. To move forward in unraveling the mystery of Tabby's Star, KIC 8462852, and fully exploring its oddities, the efforts of research here are imperative. The work to study this star has been inspirational and informative for many both within and outside the scientific community, and it is hoped that this trend along with the data collection, continues.

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Appendix