Studying TDE candidate ASASSN-18ul/AT2018fyk

Abstract

The study of partial disruption events (TDEs) provide the unique opportunity to understand multiple processes behind accretion, black hole physics, and the creation of outflows from accretion disks. The case of AT 2018fyk provides a special case of a repeating TDE, which has the potential to uncover previously unknown physics. Optical data of At 2018fyk was taken over the span of years and was used to construct a model that follows a power law with time. The resulting power law was compared to a power law similar to what was presented by Coughlin & Nixon (2019) for the mass fallback rate for partial TDEs and it was found that there is a noticeable discrepancy between the two. Multiple factors are identified to have affected the outcome of these measurements, including, but not limited to, an inconsistency with theory, incorrect magnitude values used to find luminosity, and only using optical data of AT 2018fyk. AT 2018fyk and similar TDEs should continue to be studied to gain insight on the processes that occur around black holes.

Introduction

The study of Tidal Disruption Events(TDEs) began with John A. Wheeler's proposition that the destruction of a star near a black hole could cause the released gas to be accelerated to relativistic speeds(Wheeler, 1971). This theoretical concept was further developed as a result of the widespread speculation that supermassive black holes existed at the centers of most galaxies(Hills, 1975). The theory was further developed from 1975 and onwards, with major contributions from Frank & Rees (1976) and Carter & Luminet (1982, 1983, 1986). It was not until 1991 when the first TDE candidates were first discovered by NASAs All sky ROSAT survey, and subsequent observations are still being made today, with at least 56 TDE candidates reported in literature (Gezari, 2021).

As astronomers continue to study the phenomena of TDE's, it is first important to understand the characteristics that define them. A TDE refers to the phenomena where a star passes close enough to a black hole such that the tidal forces from the black hole's gravitational pull is stronger than the star's own self-gravity, which tears the star apart, sometimes referred to as spaghettification. As a result of this encounter, much of the debris that is ripped off falls back into the black hole(Gezari, 2021), which is expected to emit a luminous flare of radiation, ranging from radio(Alexander et al., 2016), infrared(Jiang et al., 2016), ultraviolet and optical(Gezari et al., 2008), x-ray(Greiner et al., 2000), and even γ -rays(Bloom et al., 2011).

TDE's are worthy of observation since they allow insights into black hole physics that cannot be examined in a lab setting. Characteristics of black holes such as mass and size can be deduced from studying the emission spectra of these events. Additionally, TDEs also provide insight into the accretion process. Since much of the star's contents will go on to circularize the black hole, observers can study the complex processes that take place in accretion physics.

Furthermore, since the fallback time of the debris is within the timescale of months(Gezari, 2021), TDEs allow observers to track the real time creation of outflows from accretion disks.

While TDEs generally provide useful insights into black holes and accretion physics, the specific case of AT 2018fyk has proven to show distinct characteristics from its counterparts. TDE candidate ASASSN-18ul/AT2018fyk was discovered by the All-Sky Automated Survey for Supernovae(ASASSN) in September 2018(Stanek, 2018). This event is distinctive based on the fact that it is a possibly repeating partial TDE, meaning that the star's core survived its initial encounter with the black hole, and is predicted to have encountered the host black hole again, with the possibility of a third interaction(Wevers et al., 2023).

In this work, we seek to provide an analysis of the transient AT 2018fyk's light curve over time, using data that was accessed through the Digitized Sky Survey (DSS). We are interested in learning more about the power law relation for partially repeating TDEs, and compare it with theoretical models. According to Coughlin & Nixon (2019), the light curves of a partial TDE follow a power law with respect to time that is proportional to $t^{-9/4}$. Through analysis of AT 2018fyk's magnitude curve, we will seek to model AT 2018FYK's light curve and compare it with the relevant literature.

Methods

The optical data of AT 2018fyk, which was taken by the UK Schmidt Telescope located at the Siding Spring Observatory (SSO) in New South Wales for the Digitized Sky Survey (DSS), was accessed through the High Energy Astrophysics Science Archive Research Center (HEASARC) website. This telescope is a classical Schmidt Telescope, which is a catadioptric astrophotographic telescope with its properties listed in Table 1.

Table 1:

Aperture diameter	1.83m
Mirror diameter	1.24m
Focal length	3.07m
Radius of Curvature at focal plane	3.07m
Plate Scale	67.12 arcsec/mm
Photographic plate size	356mm square, covering 6.4 x 6.4 degrees of sky
Photographic plate thickness	1mm
Unvignetted field radius (nominal)	2.7 degrees

Using data points that spanned several years(9/22/2018 - 5/23/23), we were able to get the apparent magnitudes of AT 2018fyk, using the Astroart 8 software, with respect to nearby reference stars, as listed in Table 2, whose magnitudes were acquired using the The Fourth U.S. Naval Observatory CCD Astrograph Catalog (UCAC4). These stars were chosen based on the requirements that they be in close proximity to AT 2018fyk, present in all data points that were used, and were listed in the UCAC4. The error from each data point is based on the calculated signal to noise ratio S_N computed by Astroart. With this signal to noise ratio, the resulting error in the images was calculated using,

$$\sigma_N = 1/\sqrt{S_N},$$

where σ_N is the uncertainty.

Table 2: Coordinates, magnitudes, and calculated signal to noise ratios. These reference stars were acquired through Astroart using the UCAC4 catalog.

RA (deg)	Dec (deg)	mag	S/N
342.576207	-44.823906	15.224	590.44
342.565229	-44.858941	14.503	751.77
342.577587	-44.895797	13.426	906.97
342.521137	-44.829099	12.835	932.23
342.569243	-44.8195	12.78	985.52

The natural log of the acquired magnitudes were plotted over the natural log of time, so that the resulting plot can be fitted by a linear function. The fit was computed using the linfitxy function in MATLAB, where the full code is in appendix D. Through this method, the slope, and therefore, the magnitude m of AT 2018fyk can be computed, as well as the initial magnitude m_0 based on the fit. Solving for the magnitude we will find the following equation for magnitude as a function of time,

$$m(t) = m_0 t^a \tag{1}$$

We find the relation between magnitude and luminosity using the flux-magnitude relation given by

$$m =- 2.5log_{10}(f) \tag{2}$$

where f is the flux from AT 2018fyk. Solving this equation for f, we find

$$f = 10^{-m/2.5} \quad (30$$

The uncertainties from the magnitude were propagated accordingly, using the following error propagation formula, to find the error in f,

$$\sigma_f^{\ 2} = \Sigma \left(\frac{\delta f}{\delta x_i}\right)^2 \sigma_i^{\ 2} \quad (3)$$

Where σ_i refers to the uncertainties in the i^{th} variable of $f(x_i)$.

Using the flux-luminosity relation, given by

$$L = 4\pi d^2 f \quad (4)$$

Where $d = 274$ Mpc is the distance to AT 2018fyk as found by Wevers et al. (2023). We are then able to find luminosity as a function of time based on our observations. The uncertainty was once again propagated using the same formula as before. Based on this derivation the luminosity of AT 2018fyk as a function of time will have the form of a power law.

Results

A number of assumptions were made when analyzing the light curve of AT 2018fyk. We assume that this event radiates isotropically, so that the light curve that will be computed from it will be the same in every direction. This assumption was made based on the fact there are no close proximity, high resolution images available of TDEs in general, so we adopt a geometrically simple physical model of a TDE, which is that of a spherically symmetric radiating blackbody.

A second major assumption that was taken was that AT 2018fyk would radiate equally at all wavelengths, so that the analysis of its light curve in the optical band can be compared with the power law that was acquired from literature.

The form of the power law as presented by Coughlin & Nixon (2019) takes the form of,

$$\frac{dM}{dt} \alpha\, t^{-9/4} \tag{5}$$

which describes a power law for the mass fallback rate of a partial TDE, rather than for the luminosity. The same power law for luminosity had been extrapolated from eq. (5) based on the form presented by Gezari (2021) for TDEs, which implies that this fallback rate can be used to derive,

$$\frac{dE}{dt} \alpha\, t^{-9/4} \tag{6}$$

Thus luminosity follows the same power law as the mass fallback rate.

The magnitudes of AT 2018fyk that were retrieved from the data points are given in Appendix A, with the plot of this data included in Appendix B. Applying the previously discussed methods to these values, the slope of the linear fit, and thus the power of time is $a = 0.00048745$ with an uncertainty of $\sigma_a = 2.578 * 10^{-5}$. The apparent initial magnitude was found to be $m_0 = 15.4067$, with an uncertainty of $\sigma_{m_0} = 9.6048 * 10^{-5}$. Figures 1 and 2 depict the data for both the linear and nonlinear fits, respectively. Thus, the magnitude as a function of time is given by,

$$m(t) = (15.4067)t^{0.00048745} \tag{7}$$

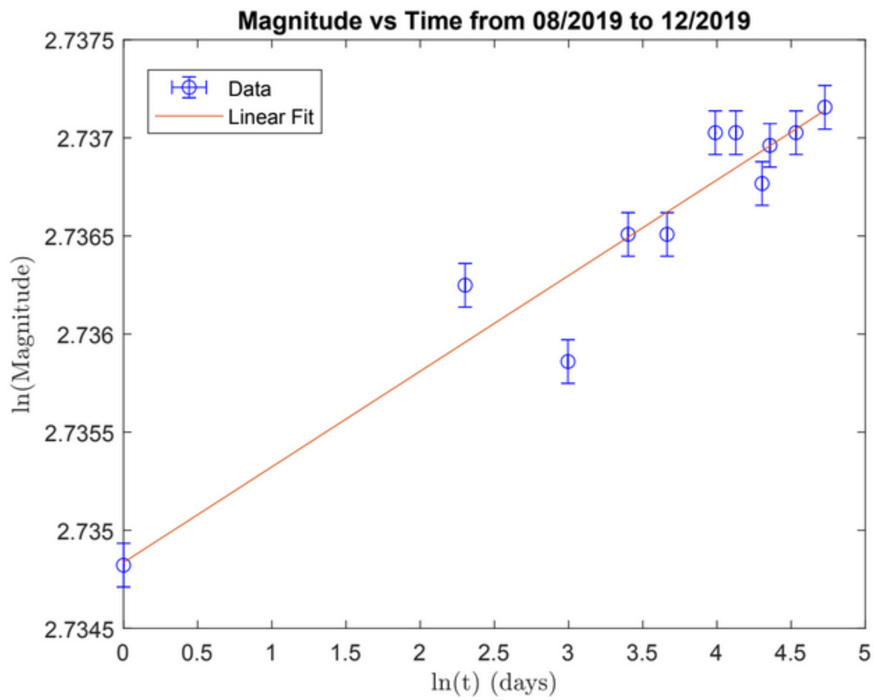

Figure 1: Linear fit of the optical data of AT 2018fyk ranging from 08/2019 to 12/2019, when an apparent dimming event occurs. The slope of this linear fit gives the power of time that this event follows which was $a = 0.00048745$ with $\sigma_a = 2.578 * 10^{-5}$. This linear fit had $\chi^2 = 3.69$, indicating a reasonable fit to this data.

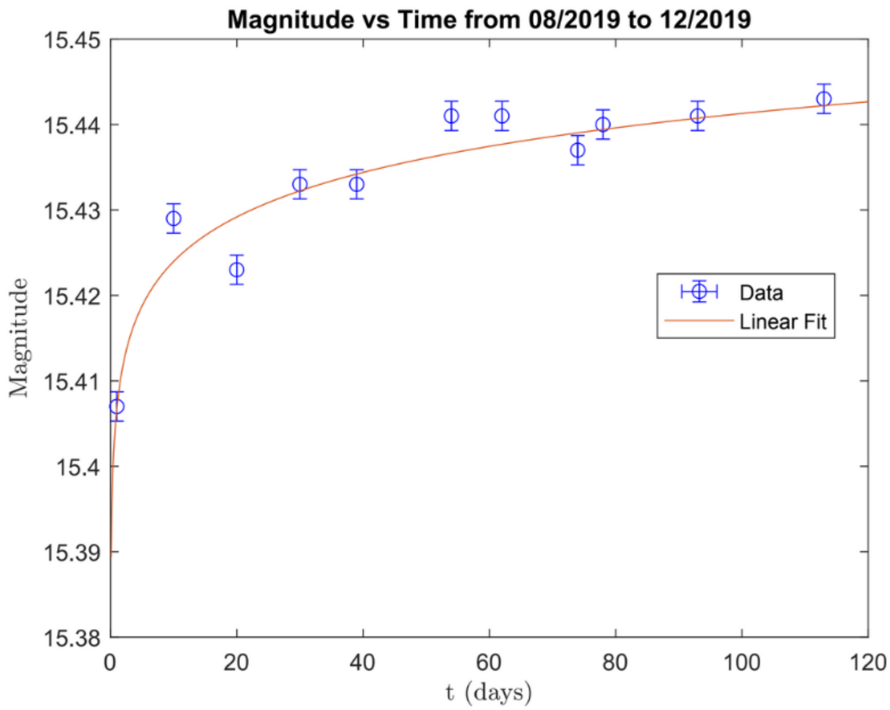

Figure 2: Linear fit as presented in Figure 1 once the natural log of the time and magnitude over time was undone.

With these values for the magnitude function, we were then able to find the initial luminosity, given by $L_0 =- 0.50786$ W/m^2 with an uncertainty of $\sigma_{L_0} = 0.00059795$ W/m^2, and the power of time, given by $b = 0.00015958$ with an uncertainty of $\sigma_b = 0.00015958$. This fit had $\chi^2 = 19.221$, which is indicative of an inconsistency between the data and the linear fit. The luminosity was then found as a function of time to be,

$$L(t) =- 0.50786t^{-0.0069571} \tag{8}$$

Similar to the fits for the magnitudes, the fits for the luminosity are shown in figure 3 and 4.

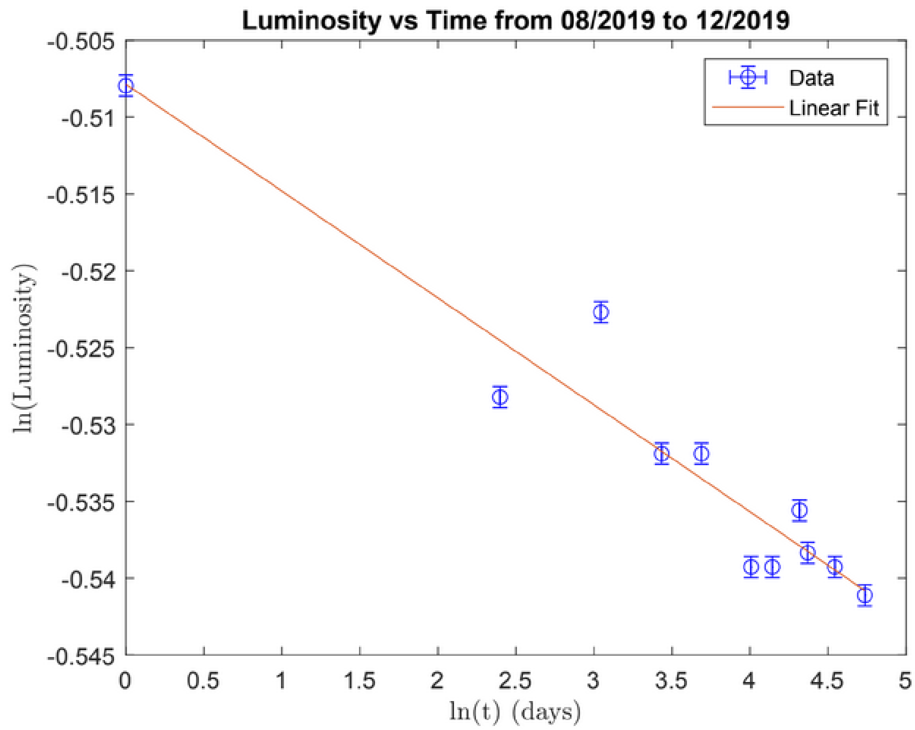

Figure 3: Linear fit of the optical luminosity as found through the derived magnitude as a function of time. The slope of this linear fit gives the power of time that this event follows which was $b = 0.00015958$ with $\sigma_b = 0.00015958$. This linear fit had $\chi^2 = 19.221$, indicating a discrepancy between the model and the data.

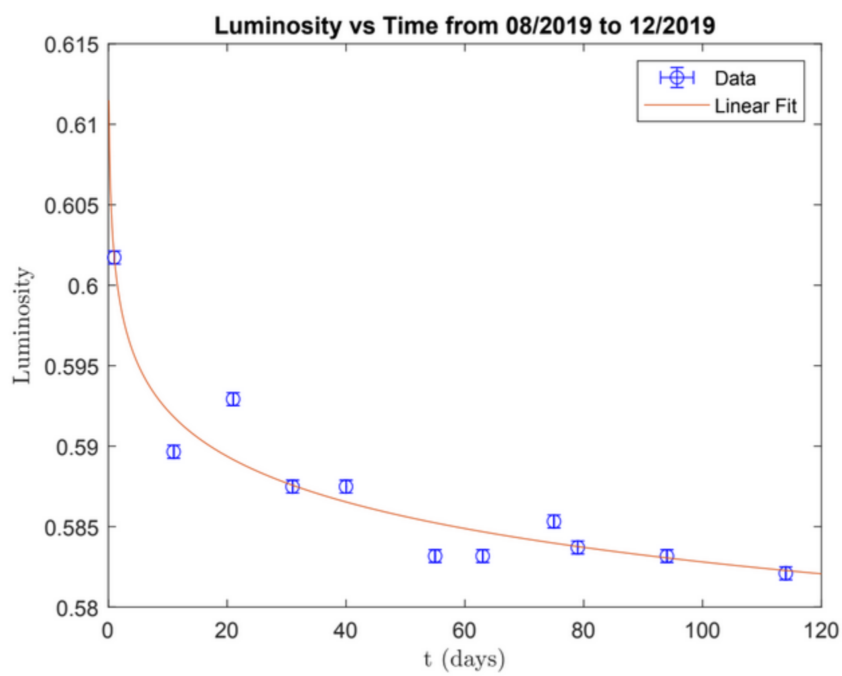

Figure 4: Linear fit as presented in figure 3 once the natural log of the time and magnitude over time was undone.

Discussion

According to Coughlin & Nixon (2019), the light curves of a partial TDE follow a power law with respect to time that is proportional to $t^{-9/4}$. The power law that we found is not consistent with this within several σ_b. There could be a few explanations behind this inconsistency. The first is that the assumption that AT 2018fyk radiates equally in all wavelengths is incorrect. Evidence suggests that at different wavelengths, the dimming/brightening of AT 2018fyk are more noticeable by factors of >6000(Wevers et al., 2023), and the brightness itself also may behave differently (Wevers et al., 2019).

The prospect that eq. (6) is incorrect can also have a large effect on the accuracy of the analysis since it assumes that all energy is being converted to radiation. Other mechanisms of energy loss include the absorbed matter from the black hole. This can have a large effect on the actual time dependence of luminosity, which would result in eq. (6) being inaccurate.

Another reason behind this inconsistency between the theory and the data analysis could also be due to AT 2018fyk's status as a repeating partial TDE. Not much has been studied about this special case of TDEs, although the population of this type of event is growing (Malyali et al., 2021; Liu et al., 2023; Payne et al., 2021). There is not yet a consensus or a proposition on the form of the light curve for repeating partial TDEs, thus there should be an expectation of a discrepancy between the data and the theory as it applies to partial repetaing TDEs.

Additionally, the χ^2 values for the linear fits of the magnitude and the luminosity are 3.69 and 19.221 respectively, which showcases an issue from converting from the magnitude function to the luminosity one. Since the χ^2 value is a measure of how close the fit is to the data points, with values closest to unity representing a more accurate fit, it is clear that the fit corresponding to the luminosity data points is inaccurate. There are two possible explanations for this, the first being the fact that the magnitude values used for the equation are possibly apparent magnitudes and not absolute. By not using the absolute magnitude of AT 2018fyk, the conversion from magnitude to flux will not give an absolute flux, but an apparent flux instead, which will result in an apparent luminosity rather than an absolute one. The second reason behind the inconsistency of χ^2 values may be due to the uncertainties of the luminosity getting smaller, thus demanding a tighter fit.

For future analysis of AT 2018fyk's light curve, there also needs to be analysis of its spectra in both the x-ray and ultraviolet regimes. As stated before, the light curve of such events can vary with wavelength, so analyzing them throughout multiple wavebands can allow a better understanding of AT 2018fyk's light curve. Additionally, instead of applying $t^{-9/4}$ power law to the luminosity curve, it should instead be used in comparison to the mass fallback rate as originally presented by Coughlin & Nixon, (2019). These changes will allow for a more accurate analysis of AT 2018fyk in future studies.

The continued study of partially repeating TDEs will offer us insights into black holes, accretion physics, and the real time creation of outflow processes from accretion disks. Getting a better understanding of these processes will allow us to gain insight into the super massive black holes that inhabit the centers of galaxies, while also providing the unique opportunity to observe the interplay between stars and black holes. AT 2018fyk is one of unique instances of a repeating partial TDE, and gaining an comprehension of its properties will unlock more knowledge in the study of all TDE phenomena.

Acknowledgements

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The UK Schmidt Telescope was operated by the Royal Observatory Edinburgh, with funding from the UK Science and Engineering Research Council (later the UK Particle Physics and Astronomy Research Council), until 1988 June, and thereafter by the Anglo-Australian Observatory. The blue plates of the southern Sky Atlas and its Equatorial Extension (together known as the SERC-J), as well as the Equatorial Red (ER), and the Second Epoch [red] Survey (SES) were all taken with the UK Schmidt.

Appendix A:

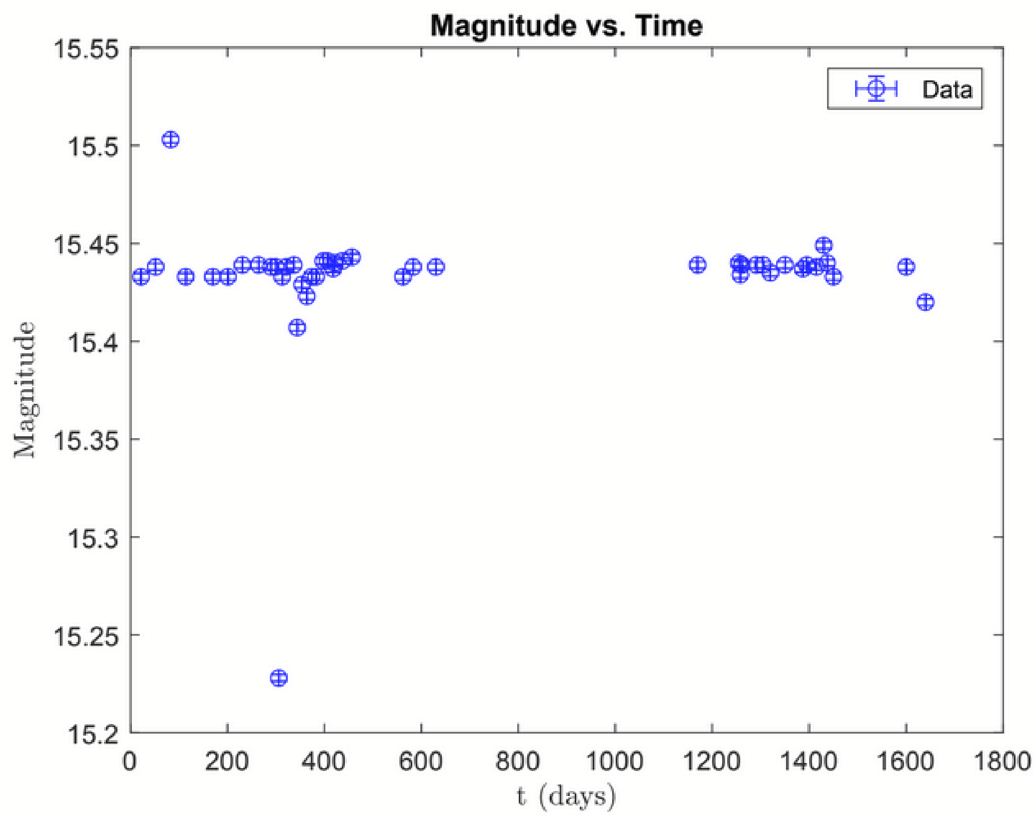
t (year/month/date)	Apparent Magnitude	Apparent Magnitude Uncertainty	Luminosity	Luminosity Uncertainty
18/09/22	15.433	0.001709401709	0.5874859614	0.0004016998027
18/10/22	15.438	0.001711742554	0.5847867086	0.0004004017176
18/11/23	15.503	0.001735508504	0.550804517	0.0003823703693
18/12/24	15.433	0.001709401709	0.5874859614	0.0004016998027
19/03/20	15.433	0.001709401709	0.5874859614	0.0004016998027
19/04/21	15.433	0.001709401709	0.5874859614	0.0004016998027
19/05/29	15.439	0.001712328767	0.5842483481	0.0004001701014
19/06/24	15.439	0.001712328767	0.5842483481	0.0004001701014
19/07/20	15.438	0.001712328767	0.5847867086	0.0004005388415
19/08/01	15.438	0.00171203561	0.5847867086	0.0004004702678

19/08/07	15.228	0.001708233686	0.7095736721	0.0004848470599
19/08/14	15.433	0.001709401709	0.5874859614	0.0004016998027
19/08/21	15.438	0.001712328767	0.5847867086	0.0004005388415
19/09/07	15.439	0.001712328767	0.5842483481	0.0004001701014
19/09/14	15.407	0.001712328767	0.6017242207	0.0004121398772
19/09/24	15.429	0.00171203561	0.5896543315	0.0004038036853
19/10/03	15.423	0.00171203561	0.5929219021	0.0004060413642
19/10/13	15.433	0.001709401709	0.5874859614	0.0004016998027
19/10/23	15.433	0.001709401709	0.5874859614	0.0004016998027
19/11/08	15.441	0.00171203561	0.5831731135	0.0003993652549
19/11/16	15.441	0.001712328767	0.5831731135	0.0003994336394
19/11/28	15.437	0.00171203561	0.5853255652	0.0004008392845

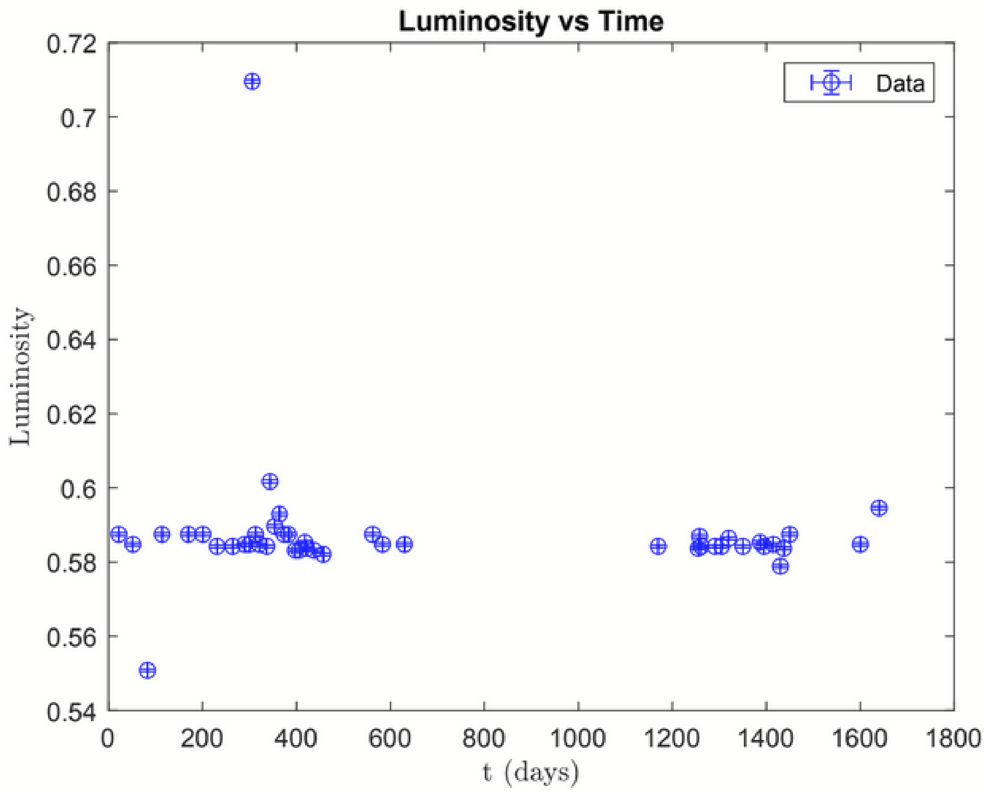
19/12/02	15.44	0.001712328767	0.5837104832	0.0003998017008
19/12/17	15.441	0.001709401709	0.5831731135	0.0003987508468
20/01/07	15.443	0.001714383679	0.5820998577	0.0003991769983
20/04/22	15.433	0.001709401709	0.5874859614	0.0004016998027
20/05/13	15.438	0.001711742554	0.5847867086	0.0004004017176
20/07/01	15.438	0.001712328767	0.5847867086	0.0004005388415
22/01/06	15.439	0.001712328767	0.5842483481	0.0004001701014
22/03/25	15.44	0.001712622024	0.5837104832	0.0003998701718
22/03/28	15.434	0.001709401709	0.5869451159	0.0004013299938
22/03/31	15.439	0.001711742554	0.5842483481	0.0004000331038
22/04/30	15.439	0.001712328767	0.5842483481	0.0004001701014
22/05/14	15.439	0.001712328767	0.5842483481	0.0004001701014

22/06/03	15.435	0.001709693965	0.5864047684	0.0004010290774
22/07/04	15.439	0.001712328767	0.5842483481	0.0004001701014
22/08/07	15.437	0.001712328767	0.5853255652	0.0004009079214
22/08/15	15.439	0.001712328767	0.5842483481	0.0004001701014
22/10/04	15.438	0.001709109554	0.5847867086	0.0003997858203
22/10/22	15.449	0.001715265866	0.578891927	0.0003971814251
22/10/29	15.44	0.001711156742	0.5837104832	0.0003995280515
22/11/12	15.433	0.001709401709	0.5874859614	0.0004016998027
23/04/14	15.438	0.00171203561	0.5847867086	0.0004004702678
23/05/25	15.42	0.001712622024	0.5945624713	0.0004073043133

APPENDIX B


Magnitude vs. Time
Data
Magnitude
15.55
15.5
15.45
15.4
15.35
15.3
15.25
15.2
0
200
400
600
800
1000
1200
1400
1600
1800
t (days)

APPENDIX C


Luminosity vs Time
Data
Luminosity
t (days)
0.72
0.7
0.68
0.66
0.64
0.62
0.6
0.58
0.56
0.54
0
200
400
600
800
1000
1200
1400
1600
1800

Appendix D

```
clc;
%% sheet is just an imported table containing x,y,uncertainty in x, uncertainty in y ↙
respectively.
%% you can import your excel sheets by clicking Import Data button in Home tab in ↙
Matlab.
%% if you are typing in your data, use format x = [x1 x2 x3 x4].
x=PE(:,1);%%converts the first column of your excel imported table named sheet into ↙
an array
y=PE(:,2);
ux=PE(:,3);
uy=PE(:,4);

xprime = x;
yprime = y;
uxprime = ux;
uyprime = uy;

p = linfitxy(xprime,yprime,uxprime,uyprime);%%performs a linear fit w/ equation ↙
y=mx+c & outputs slope and y-intercept with 1-sigma uncertainty
yfit = polyval(p, xprime);%% evaluates y values from fit to be used in plotting the ↙
best fit line

errorbar(xprime,yprime,uyprime,uyprime,uxprime,uxprime, 'bo')%%plots a scatter plot ↙
with x and y errorbars with green circles as markers.
hold on
%plot(xprime, yfit)%%plots the best fit line
x = 0.1:.1:120;
y = exp(-0.50786)*power(x,-0.0069571);
plot(x,y)
xlabel("t (days)", "Interpreter", "latex")
ylabel("Luminosity", "Interpreter", "latex")
legend("Data", "Linear Fit")
title("Luminosity vs Time from 08/2019 to 12/2019")
```

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