Study of Partial Tidal Disruption Events

Abstract:

Tidal disruption events are significant because they allow us to study black holes and accretion physics. In this paper, we analyze AT2018fyk's light curve over time, using data that was accessed through the digitized sky survey. Using data points that spanned several years (9/22/2018 - 5/23/25), we were able to get the apparent magnitudes of AT2018fyk. This gave us functions of $M(t) = (15.4067 \pm .0014)t^{(0.00048745 \pm 2.578e-5)}$ and $L(t) = (0.6018 \pm .0003)t^{(-0.0069571 \pm 1.5958e-4)}$ where M is the apparent magnitude, L is the luminosity, and t is the time in days. According to Coughlin & Nixon (2019), the light curves of a partial TDE follow a power law with respect to time that is proportional to $t^{-9/4}$, which is not consistent with our findings.

Introduction:

Tidal disruption events (TDEs) were first theorized in the 1970s as a dynamical consequence of massive black holes by John Wheeler. A tidal disruption event is an astronomical phenomenon that occurs when a star approaches sufficiently close to a supermassive black hole (SMBH) to be pulled apart by the black hole's tidal force, experiencing spaghettification. A stellar TDE happens when a star passes within the Roche radius of a massive black hole. In celestial mechanics, the Roche radius is the distance from a celestial body within which a second celestial body will disintegrate because the first body's tidal forces exceed the second body's self-gravitation. The Roche limit for a rigid spherical satellite is the distance, d, from the primary at which the gravitational force on a test mass at the surface of the object is exactly equal to the tidal force pulling the mass away from the object:

$$d = R_M(2p_M/p_m)^{1/3} \qquad (1)$$

where R_M is the radius of the primary, p_M is the density of the primary, and p_m is the density of the satellite. This can be equivalently written as:

$$d = R_M(2M_M/M_m)^{1/3} \qquad (2)$$

where R_M is the radius of the secondary, M_M is the mass of the primary, and M_m is the mass of the secondary. Typically, the Roche radius only applies to satellites orbiting around Earth, however, in the case of a SMBH, the Roche radius can exceed the Schwarzschild radius, also known as a black hole's event horizon. The Schwarzschild radius is given as:

$$r_s = 2GM_M/c^2$$

where G is the gravitational constant and c is the speed of light. Inside the Roche limit, orbiting material experiences spaghettification and disperses and forms rings, whereas outside the limit, material tends to coalesce. When a star becomes tidally disrupted by a black hole, it creates an accretion disk around the black hole. An accretion disk is a structure formed by diffuse material in orbital motion around a massive central body. When a portion of the star's mass is captured into an accretion disk around the black hole, there is a temporary flare of electromagnetic 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 gamma-rays(Bloom et al., 2011), as matter in the disk is consumed by the black hole. In 1990, that the first TDE-compliant candidates were detected through the "All Sky" X-ray survey of DLR's and NASA's ROSAT satellite. Subsequent observations are still being made today, with at least 56 TDE candidates reported in literature (Gezari, 2021).

It is important to study TDEs because they allow us to study black holes and accretion physics. Characteristics of black holes such as mass and size can be deduced from studying the emission spectra of these events. Also, since majority of the star’s contents becomes an accretion disk, observers can study the complex processes that take place in accretion physics. In addition, 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.

In addition to being a TDE, the specific case of AT2018fyk has displayed some unique properties. On Sept. 8, 2018, the All-Sky Automated Survey for Supernovae (ASASSN) spotted a flare in the nucleus of a distant galaxy 893 million light-years away and it was cataloged as AT2018fyk. Various X-ray telescopes, including NASA's Swift, Europe's XMM-Newton, the NICER instrument mounted to the International Space Station, and Germany's eROSITA, observed the black hole brightening dramatically. Ordinarily, TDEs exhibit a smooth decline in brightness over several years, but about 600 days after it had first been noticed, the X-rays had quickly vanished. Then, about 600 days after that, the black hole suddenly flared up again. Thomas Wevers, an astronomer at the European Southern Observatory, found that the repeated flares were the signature of a star that had survived a TDE and completed another orbit to experience a second TDE, and defined this as a repeating partial TDE (Wevers et al., 2023).

In this work, we seek to provide an analysis of the transient AT2018fyk's light curve over time, using data that was accessed through the digitized sky survey. 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 AT2018fyk's magnitude curve, we will seek to model AT2018FYK's light curve and compare it with the relevant literature.

Methods:

The optical data of AT2018fyk, 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 - 5/23/25), we were able to get the apparent magnitudes of AT2018fyk, 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 AT2018fyk, 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 (SN) computed by Astroart. With this signal to noise ratio, the resulting error in the images was calculated using,

$N=1/SN$, (3)

where N is the uncertainty.

Table 2:

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

After observing the overall plot, we observed something that looked like a sudden brightening and the gradual dimming over the period of a few months, so we plotted those data points while setting the brightest point as day 0. The natural log of the acquired magnitudes were plotted over the natural log of time, such that the resulting plot can be fitted by a linear function. I then used the linfitxy function in MATLAB (see code in Appendix A) to find the parameters on the function:

$M(t)=M_0t^a$ (4)

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

$M=-2.5\log_{10}(f)$ (5)

where f is the flux from AT2018fyk. Solving this equation for f, we find

$f=10^{-.4M}$ (6)

Using the flux-luminosity relation, given by

$L=4\pi r^2 f$ (7)

Where r=274 Mpc is the distance to AT2018fyk as found by Wevers et al. (2023), we can find the luminosity of AT2018fyk. We are then able to find luminosity as a function of time based on our observations. Based on this derivation the luminosity of AT2018fyk as a function of time will have the form of a power law.

Data:

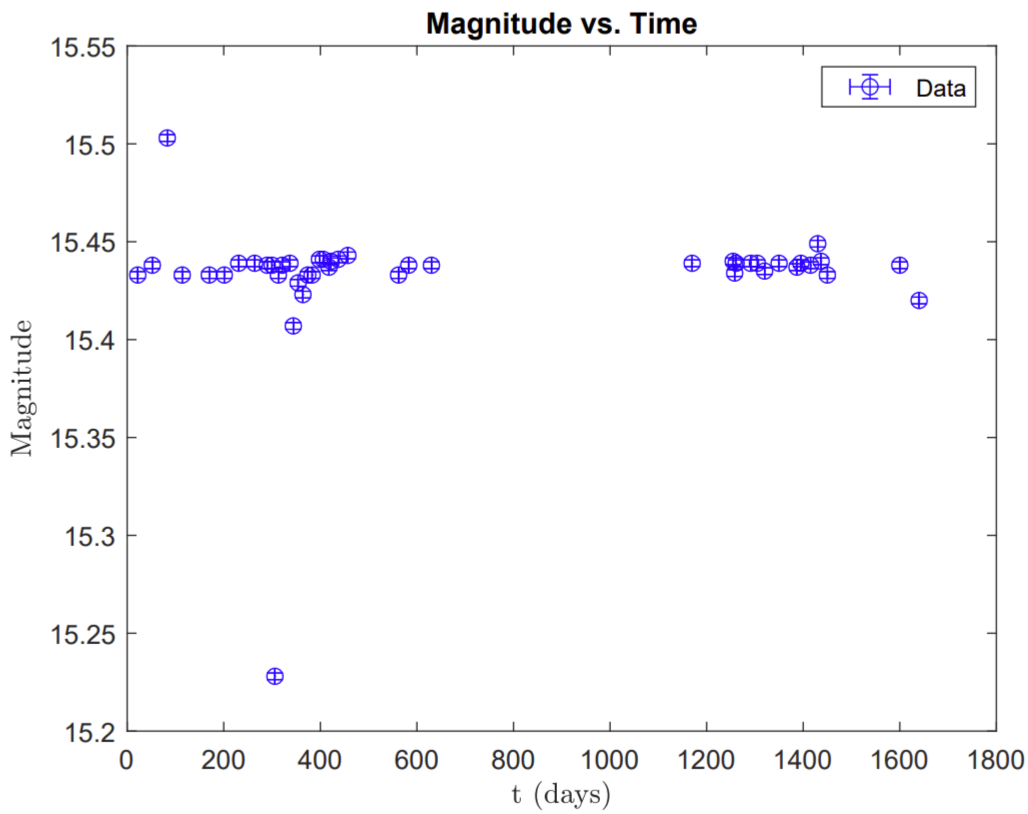
t (date) (year/month/date)	Apparent Magnitude	Apparent Magnitude Uncertainty	Luminosity	Luminosity Uncertainty

180922	15.433	0.001709401709	0.5874859614	0.0004016998027
181022	15.438	0.001711742554	0.5847867086	0.0004004017176
181123	15.503	0.001735508504	0.550804517	0.0003823703693
181224	15.433	0.001709401709	0.5874859614	0.0004016998027
190320	15.433	0.001709401709	0.5874859614	0.0004016998027
190421	15.433	0.001709401709	0.5874859614	0.0004016998027
190529	15.439	0.001712328767	0.5842483481	0.0004001701014
190624	15.439	0.001712328767	0.5842483481	0.0004001701014
190720	15.438	0.001712328767	0.5847867086	0.0004005388415
190801	15.438	0.00171203561	0.5847867086	0.0004004702678
190807	15.228	0.001708233686	0.7095736721	0.0004848470599
190814	15.433	0.001709401709	0.5874859614	0.0004016998027
190821	15.438	0.001712328767	0.5847867086	0.0004005388415
190907	15.439	0.001712328767	0.5842483481	0.0004001701014
190914	15.407	0.001712328767	0.6017242207	0.0004121398772
190924	15.429	0.00171203561	0.5896543315	0.0004038036853
191003	15.423	0.00171203561	0.5929219021	0.0004060413642
191013	15.433	0.001709401709	0.5874859614	0.0004016998027
191023	15.433	0.001709401709	0.5874859614	0.0004016998027
191108	15.441	0.00171203561	0.5831731135	0.0003993652549

191116	15.441	0.001712328767	0.5831731135	0.0003994336394
191128	15.437	0.00171203561	0.5853255652	0.0004008392845
191202	15.44	0.001712328767	0.5837104832	0.0003998017008
191217	15.441	0.001709401709	0.5831731135	0.0003987508468
200107	15.443	0.001714383679	0.5820998577	0.0003991769983
200422	15.433	0.001709401709	0.5874859614	0.0004016998027
200513	15.438	0.001711742554	0.5847867086	0.0004004017176
200701	15.438	0.001712328767	0.5847867086	0.0004005388415
220106	15.439	0.001712328767	0.5842483481	0.0004001701014
220325	15.44	0.001712622024	0.5837104832	0.0003998701718
220328	15.434	0.001709401709	0.5869451159	0.0004013299938
220331	15.439	0.001711742554	0.5842483481	0.0004000331038
220430	15.439	0.001712328767	0.5842483481	0.0004001701014
220514	15.439	0.001712328767	0.5842483481	0.0004001701014
220603	15.435	0.001709693965	0.5864047684	0.0004010290774
220704	15.439	0.001712328767	0.5842483481	0.0004001701014
220807	15.437	0.001712328767	0.5853255652	0.0004009079214
220815	15.439	0.001712328767	0.5842483481	0.0004001701014
221004	15.438	0.001709109554	0.5847867086	0.0003997858203
221022	15.449	0.001715265866	0.578891927	0.0003971814251

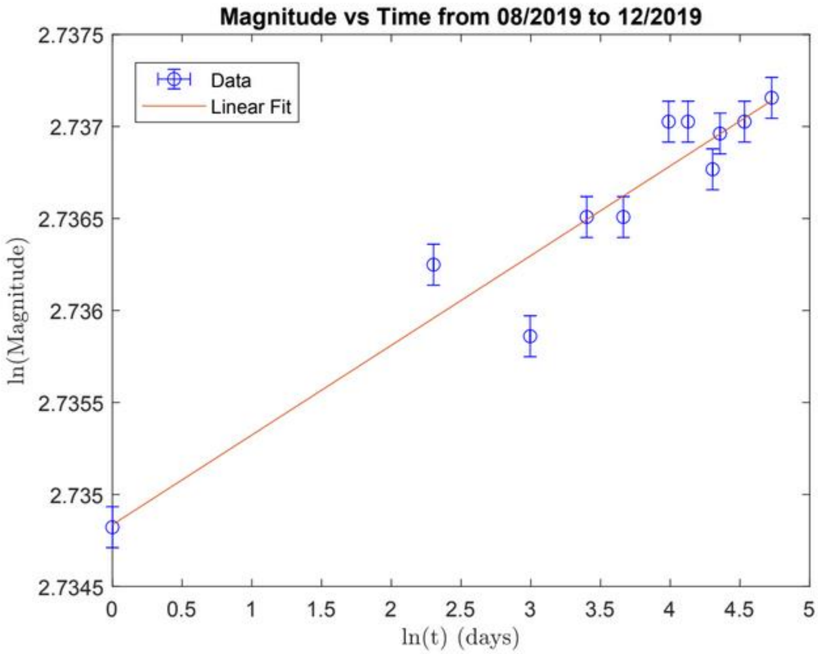
221029	15.44	0.001711156742	0.5837104832	0.0003995280515
221112	15.433	0.001709401709	0.5874859614	0.0004016998027
230414	15.438	0.00171203561	0.5847867086	0.0004004702678
230525	15.42	0.001712622024	0.5945624713	0.0004073043133

Figure 1:



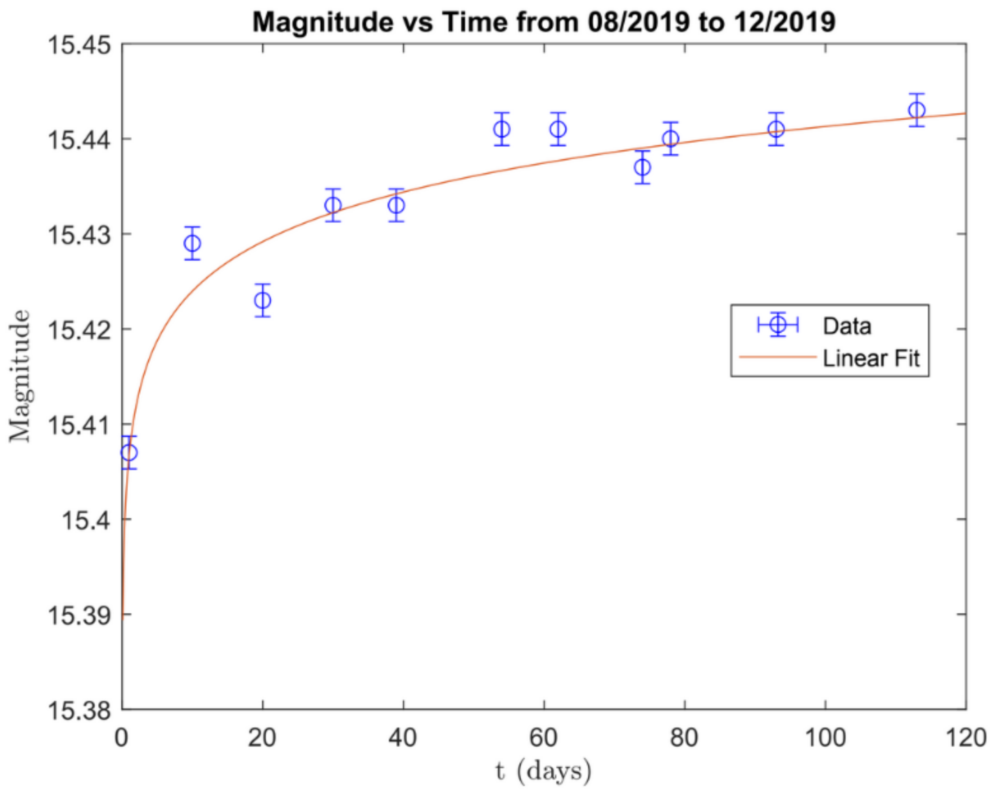
A graph of all measured magnitudes over a time period of 2018 and 2023. From August to December of 2019, we can see a gradual change in the magnitude, so we will focus on those data points when analyzing our data.

Figure 2:



A graph of the measured magnitudes over the time period of August 2019 to December 2019. This displayed the natural log values for time (in days) and magnitude, which allows us to perform a linear fit, giving us a resulting equation of $\ln(M(t))=(0.00048745 \pm 2.578e\text{-}5)\ln(t) + 2.7348 \pm 9.604e\text{-}5$. This fit has a chi squared of 3.6903.

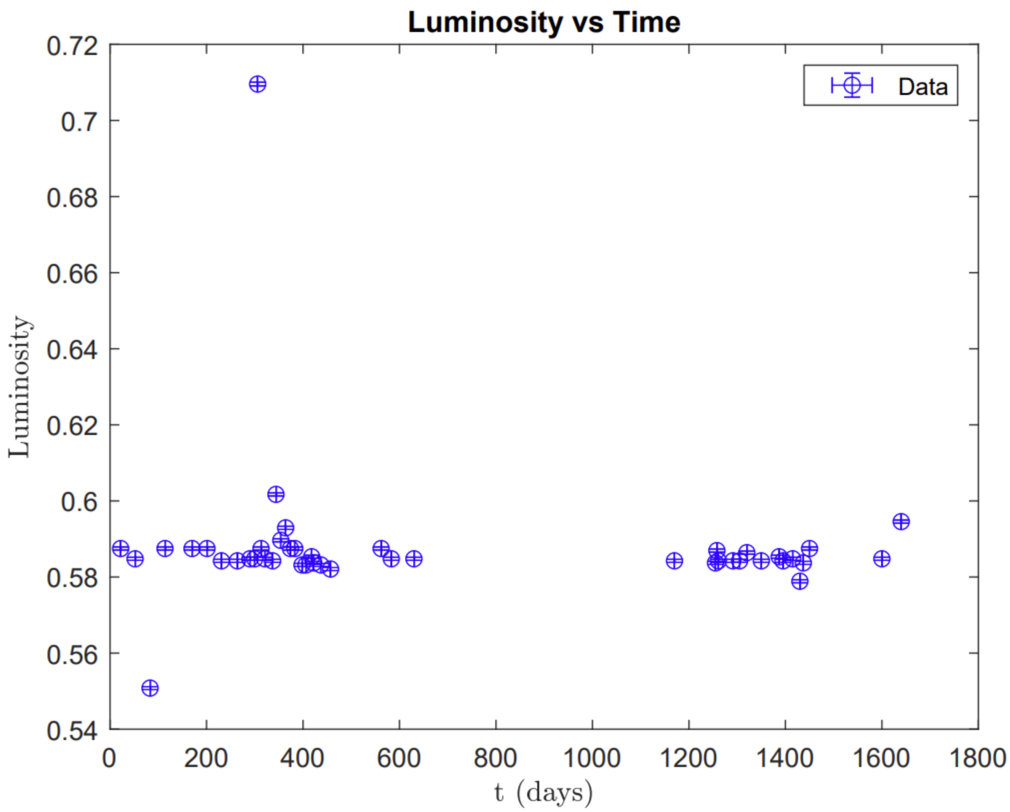
Figure 3:



A graph of the measured magnitudes over the time period of August 2019 to December 2019. This displayed the values for time (in days) and magnitude. It also displayed the line of best fit, which is $M(t) = (15.4067 \pm .0014)t^{(0.00048745 \pm 2.578e\text{-}5)}$.

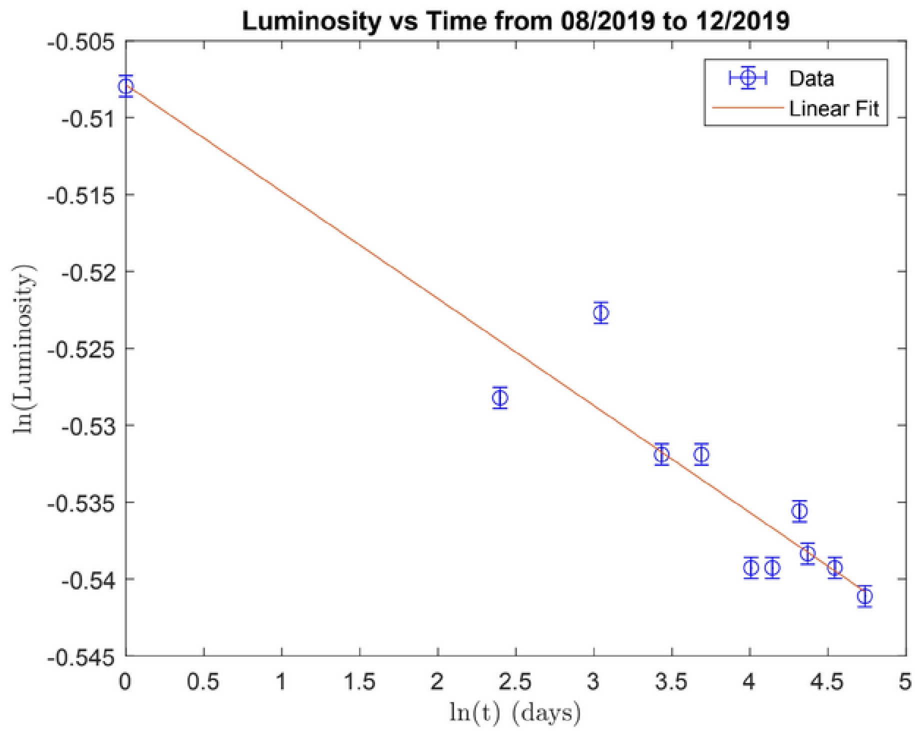
Using equations (6) and (7), we can convert the observed magnitudes into luminosity, seen in Figure 4. Then, we followed a similar procedure to plot find the luminosity vs time function.

Figure 4:



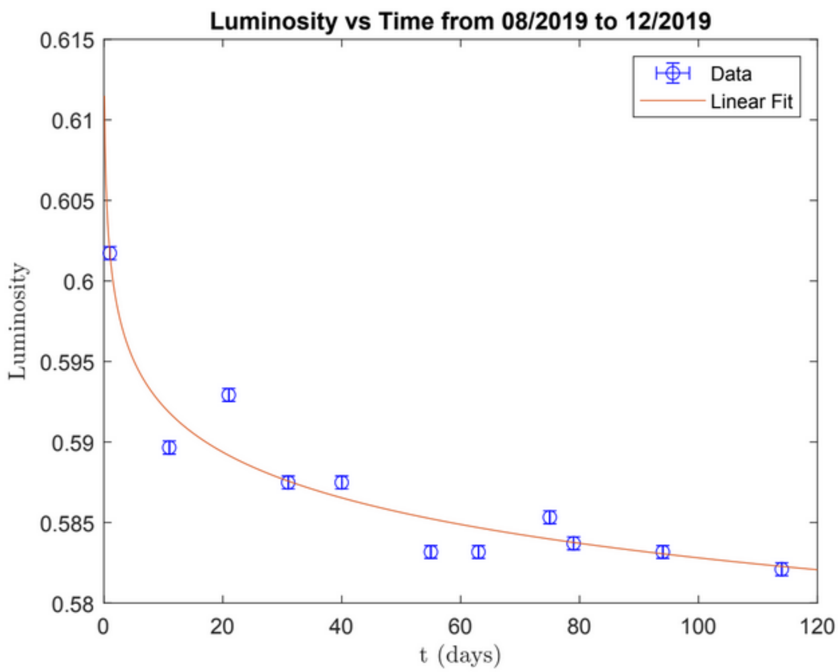
A graph of all measured luminosity over a time period of 2018 and 2023. From August to December of 2019, we can see a gradual change in the luminosity, so we will focus on those data points when analyzing our data.

Figure 5:



A graph of the measured magnitudes over the time period of August 2019 to December 2019. This displayed the natural log values for time (in days) and luminosity, which allows us to perform a linear fit, giving us a resulting equation of ln(L(t))=(-.0069571±(1.5958e-4))ln(t) + -0.50786±(5.9795e-4). This fit has a chi squared of 19.221.

Figure 6:



A graph of the measured luminosity over the time period of August 2019 to December 2019. This displayed the values for time (in days) and luminosity. It also displayed the line of best fit, which is $L(t) = (0.6018 \pm .0003)t^{(-0.0069571 \pm 1.5958e-4)}$.

Analysis:

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 at all. There are a few reasons why this may be the case. The first is that (6) and (7) may be incorrect. These equations assume 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. We also assume that AT2018fyk radiates equally in all wavelengths, which is incorrect. Some articles suggest that at different wavelengths, the dimming/brightening of AT2018fyk are more noticeable by factors of >6000(Wevers et al., 2023), and the brightness itself also may behave differently (Wevers et al., 2019). Another reason why our value might vary as much as it does from theory could be the fact that AT2018fyk is a repeating partial TDE. Not much has been studied about this special case of TDEs, but recently there has been a lot more study into this (Malyali et al., 2021; Liu et al., 2023; Payne et al., 2021). There is not yet a consensus on the form of the light curve for repeating partial TDEs, therefore its not unreasonable that we would observe a different value that the current theory.

Additionally, the chi-squared values for the linear fits of the magnitude and the luminosity are 3.69 and 19.221 respectively, which may indicate a problem when converting from magnitude to luminosity. Since the chi-squared value is a measure of how well the fit matches the data points, with 1 being a perfect fit, it could be assumed that a t^a function might not even be the best function to describe the relation between luminosity and time based on the data. It might be an issue stemming from the use of apparent magnitude vs absolute magnitude. By not using the absolute magnitude of AT2018fyk, 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.

For future analysis of AT2018fyk'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 AT2018fyk'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 AT2018fyk 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. AT2018fyk 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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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.

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Appendix A:

```
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;
%%to use linfitxy open it Matlab, right click on its tab in code editor and
%%choose ADD "location" to Search Path. If you don't do this Matlab won't
%%know where to look for the file linfitxy
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 %%instructs matlab to hold displaying the plot
%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")
```