Detection and Analyses of stellar flares using Kepler

Aashish Gupta[1,2*] and Jeewan C. Pandey[2]

1. PDPM Indian Institute of Information Technology, Design and Manufacturing, Jabalpur
2. Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital

Abstract:
Manual identification of flares is done in the case of single-target month-long time-series by visual inspection but it is a very difficult task for years-long observations and nearly impossible for several hundred targets; which is essential for a comprehensive study. We present a pipeline for automatic detection and analyses of flares, using the times series data from the Kepler Mission. We developed layers of detrending to remove various astrophysical and systematic variations, using a variable-degree polynomial function, an ingenious iterative Fourier detrending method, and trend estimation by spline-fitted Hodrick Prescott filter. Data was lightly filtered using an original algorithm to flatten noisy variations, accompanied by a Wiener filter. Flares were detected using sigma clipping algorithm with a 2.5-sigma threshold. Detected flares were further analysed in order to get various flare parameters like flare duration, flare energy, etc.

1. Introduction

Flares are energetic eruptions that form as the result of violent magnetic reconnection events and are ultimately a byproduct of the stellar magnetic dynamo. They give a direct insight into the stellar magnetic activity and thus, into the stellar structure and evolutionary phase of a star. We need continuous observations over a long baseline and an excellent photometric accuracy to study them. Kepler, a space observatory launched by NASA to discover exoplanets, provides observations for a few million targets, with an unprecedented precision and continuous for a long time, making it a great basis for studying stellar flares. Although these data sets can be visually inspected for the flare signature, it is a very tedious and time taking task. To comprehensively study flares, we need a robust and efficient pipeline. Davenport (2016) developed a similar pipeline and was later improved over by Vida et al. (2018). These pipelines still have a lot of scope for improvement, especially in the detection of more frequent, low energy flares.

2. Data

For our purpose, we used short (1-minute) cadence data available in Kepler archive. Kepler light curves contain Simple Aperture Photometry (SAP) data and Pre-search Data Conditioning (PDC) de-trended data. The PDC module tries to remove signatures of long-term systematic variations. The corrections applied can affect only long-term astrophysical variations, therefore, we use PDC detrended data for our study.

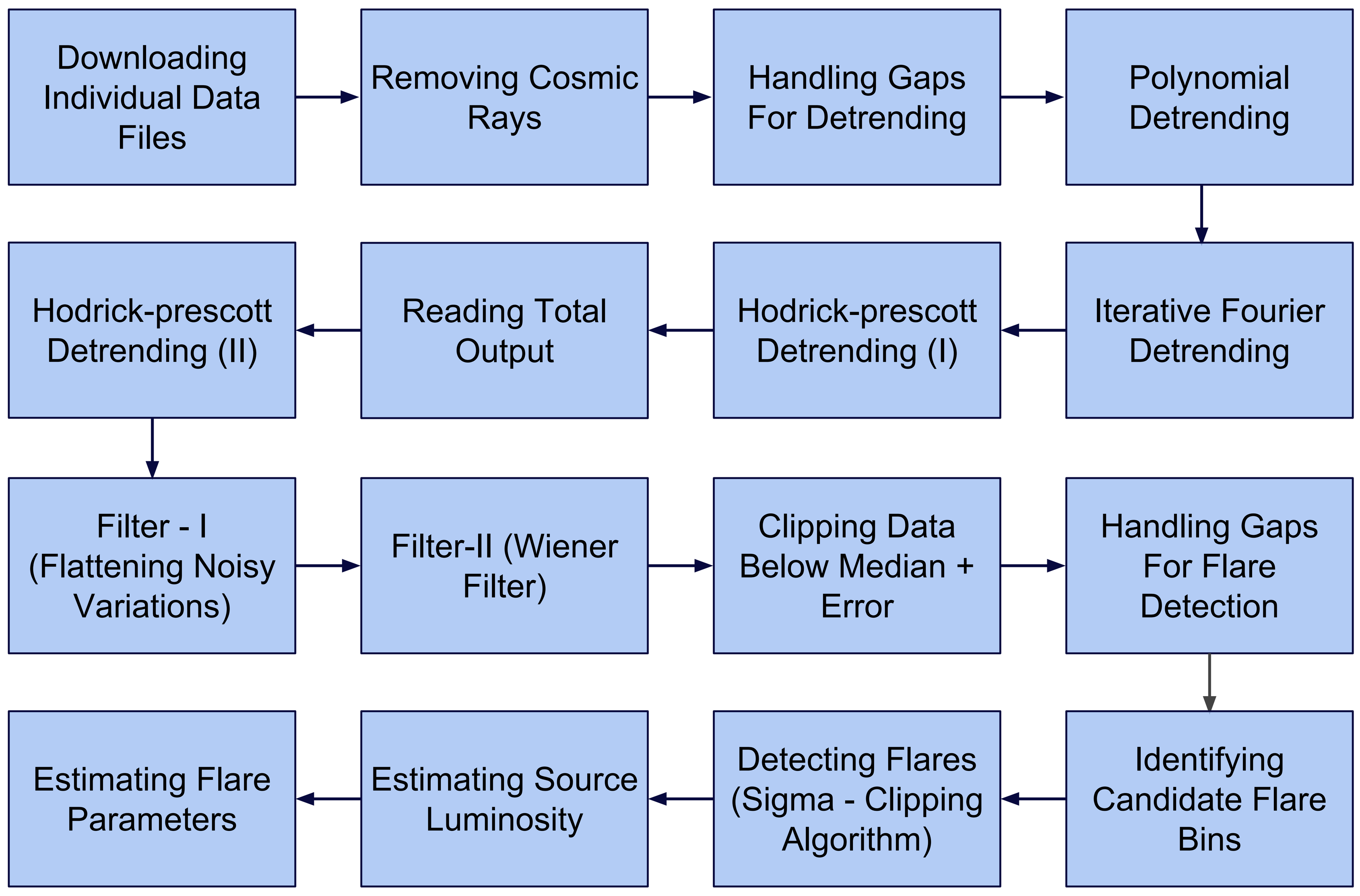

Fig.1. Flow-Chart of the pipeline

3. Flare Detection Technique

Figure 1. shows the flow chart of our method. *The whole detection process is divided into three major subtasks: i) detrending data, ii) filtering data, and iii) detecting flares (see figures 2-7 for KIC-6791060).*

3.1. Detrending Data

Data is detrended in 3 steps:

1. Input lightcurve was to be corrected for some systematic variation characteristic to Kepler satellite. A polynomial, with degree up to 3, is fitted and subtracted from the lightcurve.
2. Any possible periodic trends from the data which can be of astrophysical origin are eliminated by iteratively fitting a Fourier series in small bins of 5 times the prominent period. The order of Fourier series is decided by the number of significant peaks in Lomb-Scargle Periodogram of the data. Goodness-of-fit is checked by R-squared value.
3. In order to remove the low amplitude variations in the Fourier detrended data the Hodrick Prescott filter[3] is used. Values for the rest of the points are interpolated by fitting a spline in this estimated trend.

3.2. Filtering Data

Data is filtered in 2 steps:

1. An ingenious filter was designed and implemented which used the median of photometric errors of all data points to remove noisy fluctuations. All local minima are found out and if the maximum variation between them is less than the 1.5 times the median photometric errors, in between flux values are replaced by the mean of that fluctuation.
2. Even after step 1, unwanted fluctuations are left over. These fluctuations cannot be directly distinguished from real flare events. To overcome this, we have used a more sophisticated filter named Wiener filter[4]. Wiener filter is used with its window length equal to 2 data points.

3.3. Detecting Flares

It is known that flaring event is a sudden increment in a flux, it should be between two local minima in a lightcurve. These minima will be candidates for the beginning and ending of that particular flare. We tactically identify minima and essentially get bins which are potential flares.

Then we used a modified sigma-clipping algorithm for Flare detection. In an iteration, a threshold (for maximum flux value) was calculated as 2.5 times the standard deviation. The number of data points in the bin, flux values adjacent to maximum flux, and total duration are also checked to minimise false detections. Bins satisfying all the conditions are classified as flares. The points above the threshold value are removed and then a new threshold value is calculated. If the new threshold value is nearly the same as the previous one, iterations are stopped.

Original plots (1-month baseline):

Zoomed-in plots (1-day baseline):

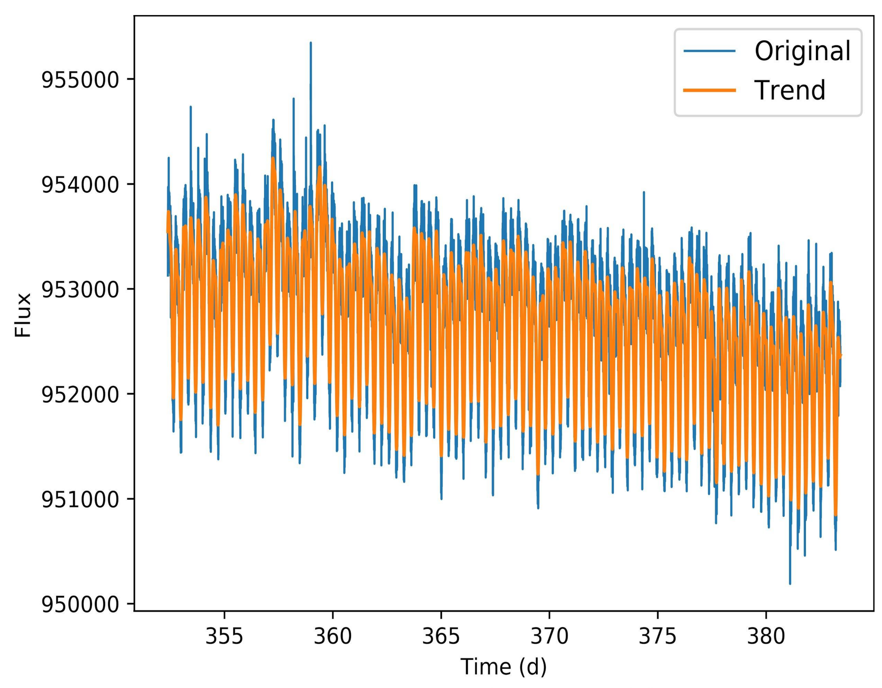

Fig. 2. Trend estimated for KIC-6791060

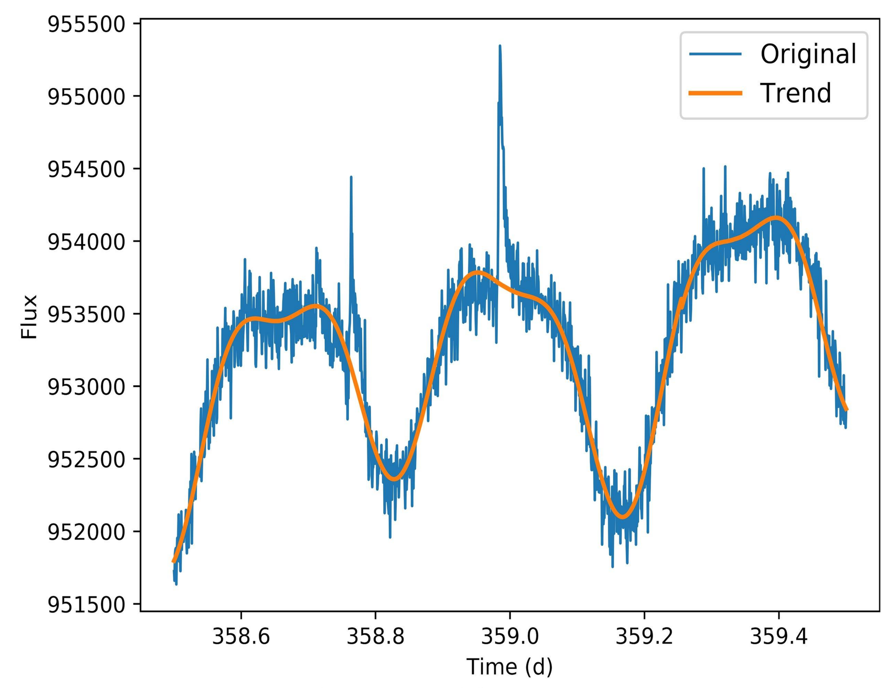

Fig. 3. Trend estimated for KIC-6791060 (358.5-359.5)

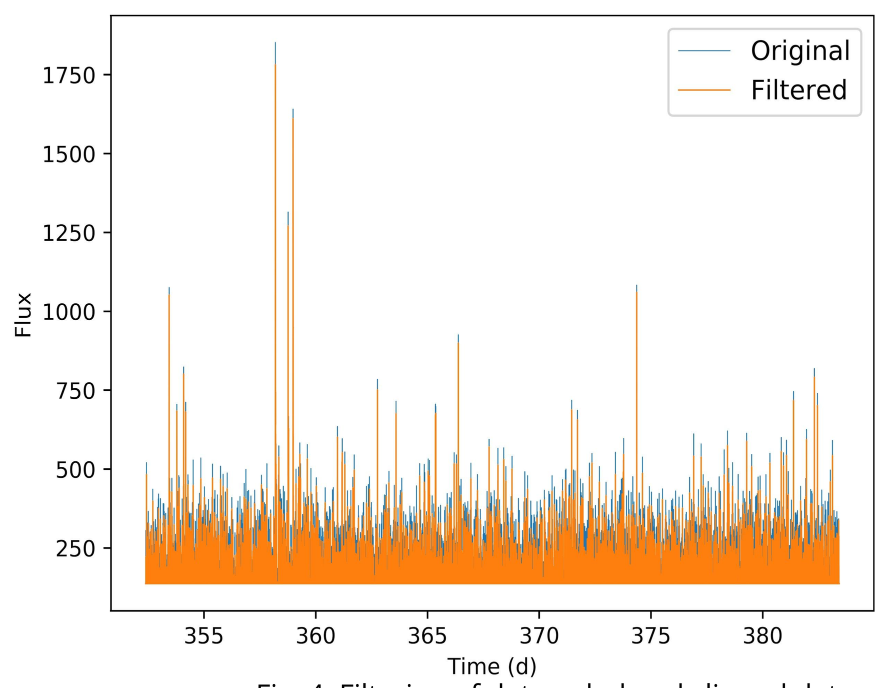

Fig. 4. Filtering of detrended and clipped data

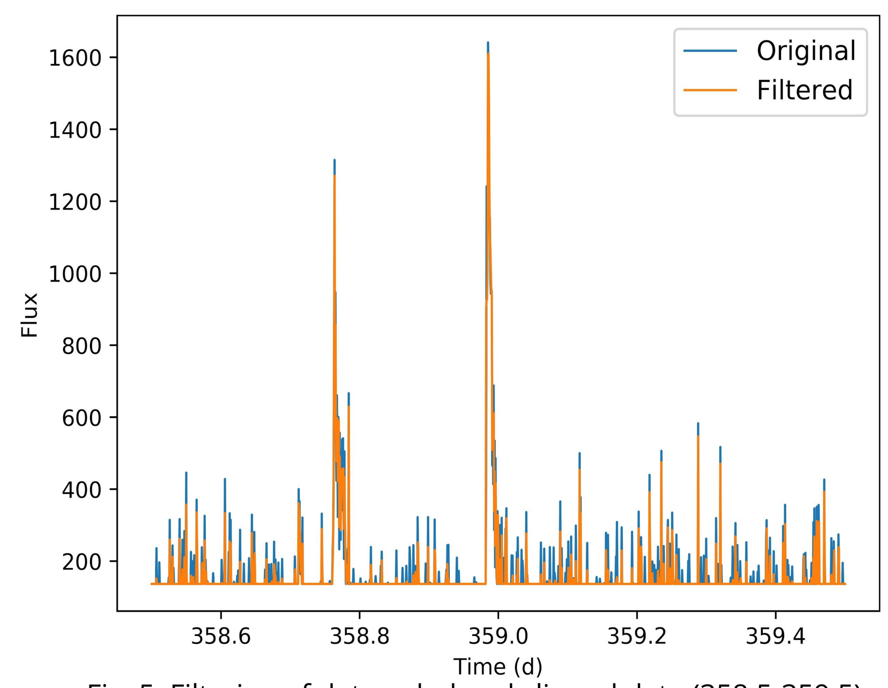

Fig. 5. Filtering of detrended and clipped data (358.5-359.5)

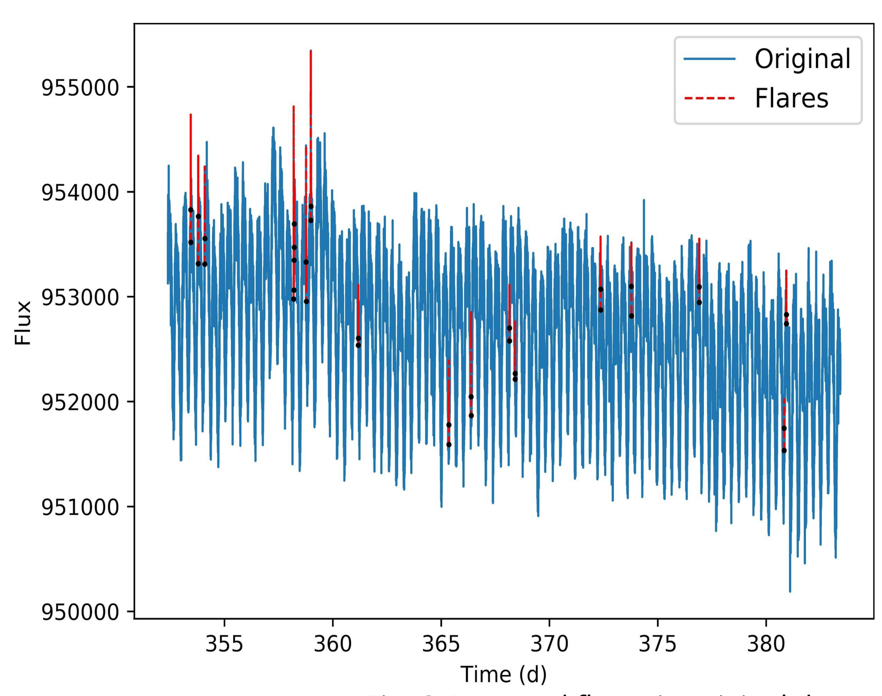

Fig. 6. Detected flares in original data

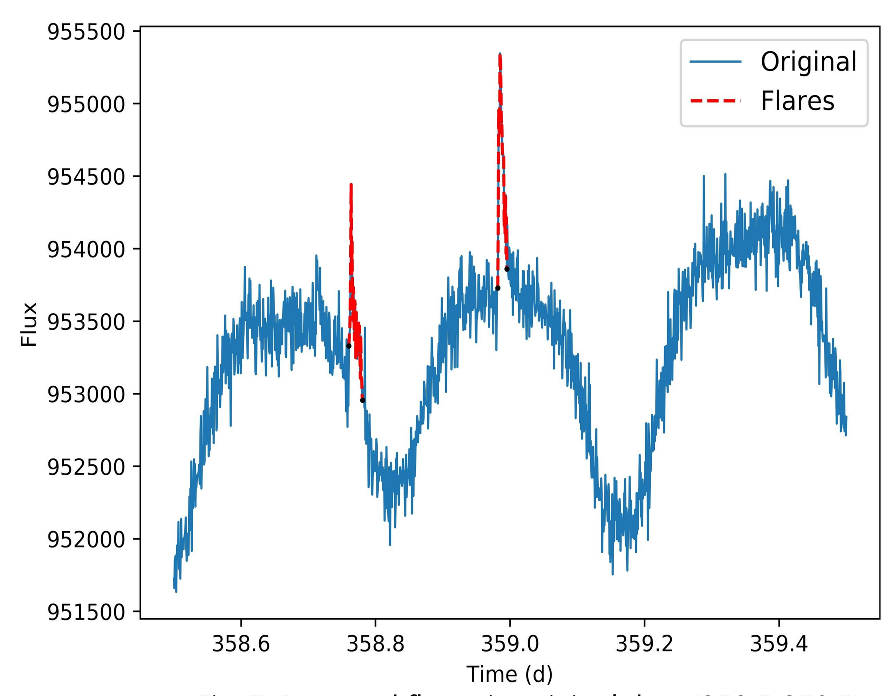

Fig. 7. Detected flares in original data (358.5-359.5)

4. Flare Analysis and Results

The morphologies of detected flares are then analysed to estimate various parameters like energy, duration, etc. The flares rise and decay times are estimated by exponential fittings as shown in Figure 8. Equivalent durations are calculated using trapezoidal integration of relative flux value over the flare duration, where relative flux is ratio of increased flux to the local-quiescent-state flux. These can be multiplied to object local-quiescent-state luminosity to estimate flare energies. To estimate luminosity, we use distances from Gaia mission. Other parameters like flare duration, flare amplitude, and the phase of minimum are also derived. In the object KIC-6791060, we detected 18 flares in the only available short-cadence dataset of one month. We found a strong correlation between flare energies, flare durations, flare amplitudes, and flare decay times for this source as shown in Figure 9.

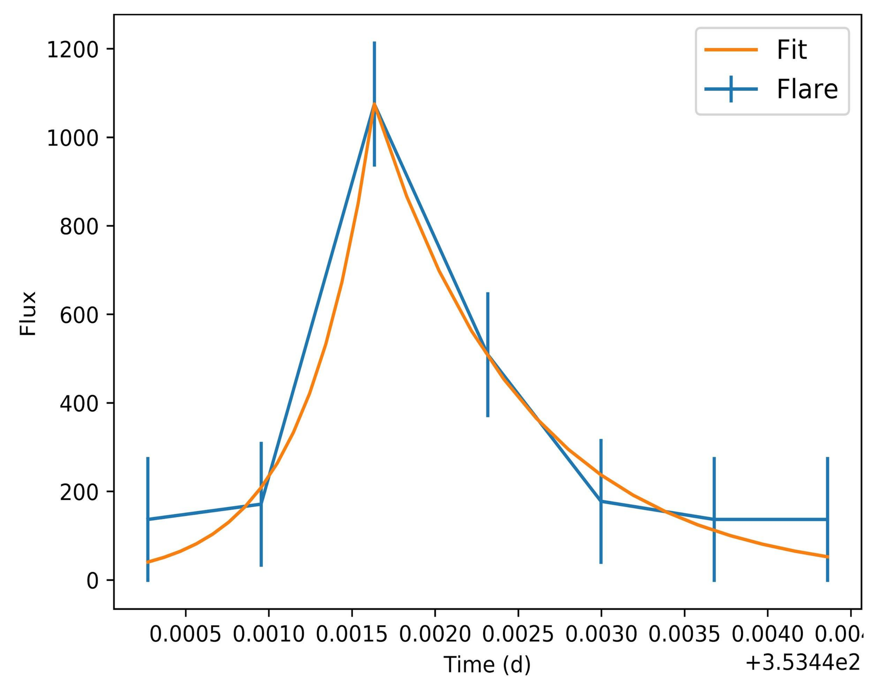

Fig. 8. Exponential fit for a flare

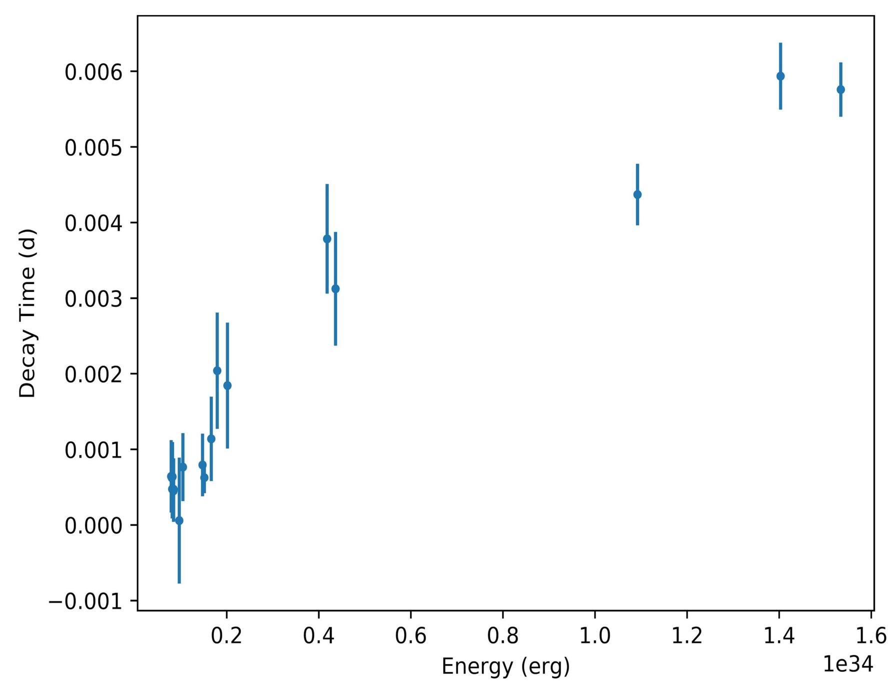

Fig. 9. Energy v/s Decay times graph for KIC-6791060

5. References:

1. Davenport, J. R. A., 2016, ApJ, 829, 23
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3. Hodrick, R.J and Prescott E. C., 1980, Post-war U.S. business cycles: an empirical investigation, Mimeo (Carnegie-Mellon University, Pittsburgh, PA).
4. Wiener N, 1942, The interpolation, extrapolation and smoothing of stationary time series

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** Contact details: +91-9479318979/+91-7206093790, aashishgupta3008@gmail.com*