Automatic Detection of Accretion Bursts in Young Stellar Objects: a New Algorithm for Long–Term Sky Surveys

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Abstract
Young stellar objects in their pre-main sequence phase are characterized by irregular changes in brightness, generally attributed to an increase of the mass accretion rate due to various kinds of instabilities occurring in the circumstellar disk. In the era of large surveys aimed to monitor the sky, we present a pipeline to detect irregular bursts, in particular EXors-like (EX Lupi type eruptive variables), in the light curves. The procedure follows a heuristic approach and is tested against the light curves already collected for a few objects presently recognized as \textit{bona fide} or candidate EXors.

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1. Introduction
Young stellar objects (YSOs) of low mass (0.5–2 \(M_\odot\)) accumulate about 90\% of their final mass in about 10\(^5\) yr. After this stage, the mass accretion process continues for about 10\(^7\) yr at lower accretion rates (around 10\(^{-8}\)–10\(^{-7}\) \(M_\odot\) yr\(^{-1}\)) as typical T Tauri stars. According to a widely accepted picture, matter in accretion viscously migrates through the circumstellar disk toward
the inner edge from where it is intermittently channelled along the magnetic field lines to the central star; the fall onto the stellar surface produces a shock that cools by emitting a hot continuum (Shu et al., 1994).

Observationally, this kind of accretion manifests itself through sudden and intermittent bursts of luminosity as a consequence of the shock cooling, and produces a small and irregular photometric variability that typically ranges between $0.1-1$ mag.

However, some young sources display more powerful outbursts with amplitudes of several visual magnitudes. These objects, generally known as eruptive variables, are usually classified into two main classes (see also the review by Audard et al., 2014):

1. FUors (Hartmann & Kenyon, 1985) characterized by bursts ($\Delta m_V \gtrsim 4$ mag) of long duration (tens of years) with accretion rates of the order of $10^{-5} - 10^{-4}$ $M_\odot$ yr$^{-1}$ and spectra constituted by absorption lines;
2. EXors (Herbig, 1989) with shorter outbursts ($2 \lesssim \Delta m_V \lesssim 4$ mag, duration of months–one year) with a recurrence time of years, showing accretion rates of the order of $10^{-7} - 10^{-6}$ $M_\odot$ yr$^{-1}$, and characterized by emission line spectra (e.g. Herbig, 2008, Lorenzetti et al. 2009, Kospál et al. 2011, Sicilia-Aguilàr et al., 2012, Antoniucci et al., 2013).

Unfortunately, only a handful of objects are considered as genuine members of each class (Audard et al., 2014), although several efforts have been done so far either scrutinizing different catalogs (Giannini et al., 2009, Scholz et al., 2013, Antoniucci et al., 2014), or undertaking specific long-term monitoring programs (Grankin et al., 2007, 2008, Morales-Calderón et al., 2011, Hillenbrand et al., 2013, Giannini et al., 2017).

In the last decade, however, the situation has rapidly changed because multi-wavelength sky surveys have allowed to significantly increase the number of known or candidate eruptive variables. Among the ground-based surveys, which typically observe the optical and near-infrared sky with cadence of days or weeks, we underline the All-Sky Automated Survey for Supernovae (ASAS-SN), the Intermediate Palomar Transient Factory (iPTF), the Zwicky Transient Facility (ZTF), the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS) and the VISTA Variables in the Via Lactea (VVV).

Also, new eruptive variable candidates are identified almost every month by the Gaia Photometric Science Alerts Project (Hodgkin et al., 2021).

The new discoveries have significantly increased the number of potential FUor/EXor variables: only considering the Gaia alerts classified as young stellar sources one finds more than 200 cases and a fraction of these could well represent good FUor/EXor candidates. Although significant, these numbers are

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1. http://www.astronomy.ohio-state.edu/asassn/index.shtml
2. https://www.ptf.caltech.edu/iptf
3. https://www.ztf.caltech.edu/
4. https://panstarrs.stsci.edu/
5. https://vvvsurvey.org/
6. http://gsaweb.ast.cam.ac.uk/alerts
however too few to consider eruptive mass accretion as a common way through which stars accrete mass. Indeed, non-steady mass accretion has been proposed (Kenyon et al., 1990; Evans et al., 2009) as a way to solve the well-known luminosity problem: the typical observed luminosity of the YSOs is at least one order of magnitude lower than expected if accretion proceeds at rates predicted by the standard steady model (Shu, 1977).

Such a fundamental question will be hopefully answered in the next years thanks to the Legacy Survey of Space and Time (LSST7), which will be performed with the Vera Rubin Observatory (VRO). This survey will monitor the southern sky in six bands (u, g, r, i, z, y) at a 5σ, single exposure, sensitivity varying between 23.3 and 25.0 magnitudes8.

This, coupled with an optimal monitoring cadence of a few days, will allow us to perform for the first time statistical studies of eruptive variables based on large samples.

Given the huge number of detected variables expected to be alerted each night, it is mandatory to have in place an algorithm capable of both identifying the candidate eruptive variables and distinguishing them from other phenomena of stellar variability (e.g. extinction-driven, long-period Mira-type, variability induced by magnetic activity, hot/cold spots, or flares). In this paper we describe the algorithm we have implemented to identify brightening episodes in generic light curves, which has been optimised and tested with a sample of known EXor-type objects, whose typical variability timescales are compatible with the measurement cadence and mission lifetime of the LSST.

Our approach relies on the data collected by the public databases cited above (Shappee et al., 2014; Jayasinghe et al., 2018; 2019a,b; Gaia collaboration, 2018; Law et al., 2009; Chambers & Pan-STARRS Team, 2016), which allow unbiased searches for EXor candidates at complementary levels of sensitivity in the optical band, where the intrinsic fluctuation of the EXor brightness has the maximum amplitude (Lorenzetti et al., 2007).

However, even if the light curves considered in the present work are typically sampled in days or months, it is important to note that the algorithm presented here is independent of the involved time scales because it simply takes into account the ordered sequence of photometric points. While on one side this means that the detection of a given feature in the light curve is separated from its physical interpretation in terms of the involved time scale, on the other allows a more extensive use of the procedure to other kind of light curves.

In the following sections we will present some typical light curves (Section 2) and describe the algorithm devised to capture their most relevant features (Section 3). The implemented procedure is detailed in Section 3.1 and the results of its application to typical well sampled cases of known or candidate EXors are presented in Section 4. Our final remarks are given in Section 5.

7https://www.lsst.org/
8https://www.lsst.org/scientists/keynumbers
2. Light Curves

In the previous section, we have provided a brief description of the main photometric and spectroscopic features that characterize the two classes of young eruptive variables, namely the FUors and EXors. This classification dates back to some decades ago, when very few objects had been discovered. Although this picture is in general still valid, the increasing number of discoveries that occurred in the subsequent years has revealed that indeed eruptive variables may exhibit light curves very different (e.g. in duration, cadence, amplitude, rising time/decline) from each other. These different properties cannot easily be ascribed to one of the two classes. Examples are V1647 Ori (Reipurth & Aspin, 2004) and V2493 Cyg (Semkov et al., 2010), whose photometric behavior in terms of outburst amplitude and duration is intermediate between those typical of EXors and FUors (e.g. Audard et al., 2014). More generally, the photometric surveys cited in the previous section, together with long-term monitoring of specific sources (e.g. Hillenbrand et al., 2013; Giannini et al., 2017) and archival searches of observations of the last century (Jurdana-Sepic et al., 2017, 2018), have revealed not only that the light curves of eruptive variables can significantly vary from object to object, but also that the same source can be subject to very different outburst episodes for the duration, intensity, and speed of brightness increase (Giannini et al., 2020).

It is also worth noting that, in addition to eruptive variables, another kind of young variables exists. In these sources, identified as UXor variables, the brightness fluctuations are (although not only) caused by periodic decreases of luminosity due to the transit of an obstacle along the line of sight (e.g. planets, dust clumps, irregularities in the circumstellar disks), which causes an enhancement of the circumstellar extinction and brightness variations of similar amplitude and cadence as those of accretion-driven variables. However, UXors often show a periodicity in the light curve, while accretion bursts are episodic events with an apparently stochastic recurrence.

In Fig. 1 we show some light curves to exemplify the different behaviors described above. All the data have been retrieved from the ASAS-SN (V-band), the ZTF (g-band), or the Gaia (G-band) databases, with the exception of V1118 Ori whose data (V-band) are also taken from the literature (Giannini et al., 2020). The time coverage of the photometry depends on the source, spanning in the range from ~5 years (e.g. PV Cep) to ~30 years (V1118 Ori), and is shown in Table 1 along with other information on these objects.

Since the light curves are shown here only for illustrative purposes, we did not apply any photometric correction to convert the data points to a unique

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9The Gaia Alerts G magnitudes are derived from a preliminary calibration of the Gaia unfiltered (white light) photometry. The Gaia “G” band is defined by the instrument response only and covers a broad wavelength range, from the near ultraviolet (~330 nm) to the near infrared (~1050 nm).
band. This procedure, despite rough, allows us to obtain a broader view of the photometric behavior of these objects. In particular this is the case for XZ Tau and V1184 Tau, where the available ASASSN observations obtained in V band (central wavelength \(\sim\)5500 Å) have been complemented with Gaia G (\(\sim\)5800 Å) data, and for ASASSN-13db whose light curve has been supplemented with ZTF g (\(\sim\)4800 Å) photometry approximately covering the last two years.

In the first three panels, we show the light curves of three classical EXors: V1118 Ori, XZ Tau, and VY Tau. The first two objects show a similar, although not identical, behavior, with stochastic brightness increases of about 3 magnitudes, typically lasting several months that are interspersed by periods of quiescence during which a certain level of activity is however still recognizable. Conversely, VY Tau presents a well-defined level of quiescence around \(V = 13.7\) mag interrupted by sudden and very short episodes of significant brightness increase. The fourth panel shows how the light curve of PV Cep passed from the quiescence to the outburst phase very slowly (about 3 magnitudes in 3 yr) then started declining again after 2017. In the fifth and sixth panels are depicted the light curves of two sources, iPTF15afq and ASASSN-13db, that show rapid brightness increase (\(\sim\)3 mag in a few months) followed by a comparatively rapid decrease. In particular ASASSN-13db is reminiscent of both the behaviors observed in V1118 Ori and in PV Cep: it has undergone a first outburst of short duration and high speed in both the rising and declining phases, followed by a second outburst of higher intensity and much longer duration.

In the next three panels of Fig. 1 the light curves of some objects usually classified as UXors are presented: GM Cep, V1184 Tau, and V2492 Cyg. Out of these, GM Cep shows an almost stable high-level state with roughly periodical dimmings, while V1184 Tau presents a slowly increasing and then decreasing light curve with superimposed lower amplitude variations that could be ascribed to accretion events ([Giannini et al.] 2016). V2492 Cyg also shows periodical, semi-regular variations that are likely due to either extinction or accretion phenomena ([Hillenbrand et al.] 2013).

Finally, in the last three panels, there is the light curve of V2493 Cyg, a source whose behavior is intermediate between an EXor and a FUor, followed by two examples of YSO variables recently discovered by Gaia. The first (Gaia19ajj) looks like PVCep or V2492Cyg, increasing of about 5 mag in five years between 2015 and 2019 and rapidly decreasing to the presumably quiescent state in one year, while the second (Gaia18dvy) has undergone a slow, monotonical increase between 2016 and 2019, passing from G \(\sim\)19 to G \(\sim\)15. Since 2019, this source is fading again, but at an even lower rate.

Given the variety of light curves exhibited by young eruptive variables, we have decided to devise a recognition algorithm based on the observational data of V1118 Ori, which is one of the very few objects for which the light curve has been frequently sampled and monitored for tens of years. Therefore, our procedure follows two main steps: 1) implementation of an algorithm able to recognize all the bursts observed in V1118 Ori; 2) validation of this algorithm to recover the accretion outbursts observed in the light curves of other objects.
Figure 1: Examples of light curves illustrating the wide variety of photometric behaviors exhibited by eruptive young stars. The additional tick marks at the bottom of each panel correspond to the beginning of the indicated years in the light curves. For each object, the photometric band of the observations is shown in the upper right corner. The light curve of V1118 Ori in the V band has been collected from the literature, while for XZ Tau, ASASSN-13db, and V1184 Tau the photometry has been assembled by using two input catalogs (see text).
Table 1: Characteristics of the sources\textsuperscript{a} in Fig. 1.

| Name        | VarType | Ref\textsuperscript{b} | Simbad class | photometry source | time coverage (yr) | bursts detected |
|-------------|---------|-------------------------|--------------|-------------------|--------------------|-----------------|
| XZ Tau      | EXor ?  | 1 Orion                 | ASASSN+ZTF   | 8.3               | 2                  |
| VY Tau      | EXor    | 1 Orion                 | ASASSN       | 15.1              | 0\textsuperscript{c}|
| ASASSN-13db | EXor    | 2 transient             | ASASSN+Gaia  | 7.0               | 2                  |
| V1118 Ori   | EXor    | 1 Orion                 | Giannini et al. (2020) | 31 | 6      |
| V1184 Tau   | UXor/EXor | 1 Orion              | ASASSN+ZTF   | 12.2              | 1                  |
| iPTF15afq   | EXor ?  | 3 YSO                   | Gaia         | 5.9               | 2                  |
| Gaia19ajj   | EXor ?  | 4 YSO                   | Gaia         | 6.3               | 1                  |
| Gaia18dvy   | EXor    | 5 Orion                 | Gaia         | 6.1               | 1                  |
| PV Cep      | EXor ?  | 1 Orion                 | ASASSN       | 6.3               | 1                  |
| V2492 Cyg   | EXor ?  | 1 Orion                 | ASASSN       | 10.4              | 3                  |
| V2493 Cyg   | EXor/UFur | 6 Orion              | ASASSN       | 26.5              | 1                  |
| GM Cep      | UXor    | 7 Orion                 | ASASSN       | 13.1              | 1\textsuperscript{d}|

\textsuperscript{a}ordered in increasing Right Ascension.

\textsuperscript{b} (1) Audard et al. (2014); (2) Holoi et al. (2014); (3) Miller et al. (2015); (4) Hillenbrand et al. (2019); (5) Szegedi-Elek et al. (2020); (6) Köspal et al. (2011); (7) Semkov et al. (2010).

\textsuperscript{c} while bumps are recognizable, they are not detected as bursts because $\Delta m < 2$ mag.

\textsuperscript{d} probably fictitious because the source resembles the UXor type, showing fadings more than bursts.

also to test its capabilities and limitations.

3. Adopted Method

We are interested in the detection of EXor-like candidate events because the light curves of this kind of sources are known for only a handful of well sampled cases. In this context, statistical approaches, including advanced light curve analysis for transients, cannot be reasonably trained and validated before to be used.

We have developed an “ad hoc” procedure to detect potentially interesting cases, namely sources exhibiting brightenings of the kind expected for candidate EXors. Indeed, here we focus our attention on the detection of bursts in a light curve, leaving the classification of the sources to further considerations (as burst duration, recurrence, rising or declining speed, etc.) that are out of the scope of this work.

Here the approach is in fact both simple and empirical, meaning that the sequence of steps implemented in our procedure closely resembles what a trained eye would suggest in classifying a given sequence of photometric points that progressively build up the light curve.

The method is based on the recognition of a reference observation, hereinafter called “reference point” which can play the role of the \textit{bona fide} quiescence level of the source. An important characteristic of this point is that it remains a fixed point until a new observation is identified which is deemed to be more representative of a quiescent state. In such a case the reference point is updated by correspondingly assigning the reference status to the new recognized position in the light curve.
In practice, the first observation of a light curve is adopted as the initial reference point. The analysis then proceeds point by point, until the subsequent photometric behavior of the light curve suggests that the reached brightness can represent a better estimate of the quiescence level. In this latter case the reference status is assigned to the newly deemed quiescent point. This algorithm essentially compares the magnitude of each new point in the light curve with the magnitude at quiescence and, if the difference exceeds a given threshold, the source is considered to be in a higher brightness state.

These basic considerations have been implemented in an IDL procedure, hereinafter called pipeline, aimed to take into account several possible behaviors empirically chosen in the final tail of the light curve.

The pipeline goes sequentially through the photometric series, evaluating each point with respect to the characteristics of the previous light curve for the purpose of detecting specific behaviors. To this aim a sequence of steps have been devised in such a way that, when a given condition is fulfilled, an appropriate flag is assigned to the point and the analysis moves on to consider the next photometric point.

3.1. Pipeline description

To assist the description of the steps involved in the pipeline, in Fig. 2 we show an artificial light curve simulating typical photometric behaviors we expect to find in eruptive variable sources. Even if the sampling interval adopted in this simulated curve is of the order of the days, the evaluation of the state of the source will be based merely on the observational sequence of points, leaving any consideration on the timescales involved to a subsequent physical interpretation of the brightness variations. Because of this we shall focus our attention on the simple detection of some interesting characteristics of the light curves:

a) a reference point representing a plausible baseline (quiescence level);

b) short-term magnitude changes of a duration less than the sampling interval (e.g. a spike);

c) long-term magnitude changes extending over multiple observations (bursts or fadings);

d) drifts in the brightness of the baseline.

A web interface for our pipeline is accessible at https://exorlc.le.infn.it.

3.1.1. Pipeline details

Here the implementation details are described and since this section is quite technical it can be skipped without compromising the comprehension of the subsequent sections.

The light curve analysis is carried out in a loop that sequentially examines all the observations through a series of steps. In our approach an important
role is assigned to what we call “reference point” that represents our best guess, given the available data in the evolving light curve, of the source quiescent state. Consequently, an essential part of the pipeline is oriented to the identification of this point that stands for the reference magnitude against which the algorithm evaluates the brightness changes. However, because even in quiescence our sources are typically characterized by some more or less important brightness fluctuations, we introduce a tolerance parameter quantifying the amplitude of such intrinsic variations. This can then be used to adapt the detection algorithm to the kind of light curve analyzed.

In the following we describe the considerations we adopted to empirically classify a given point $i$ in one of the possible states, namely: reference (estimated quiescence), high, drop, spike, generic. The implementation of the pipeline begins by defining the starting observation in the light curve as the first reference point, and then skipping a few subsequent points whose status is difficult to estimate on the basis of a still too short light curve. The procedure then follows a sequence of steps aimed to evaluate at each point the corresponding status, according to these considerations:

1- **Reference point sliding toward the local minimum of brightness.** If the current point $i$ is immediately preceded by an already defined reference point in $i-1$ and if the source in $i$ is fainter than in $i-1$, then it is chosen as the new reference. In Fig. 2 this case produces the two green asterisks at $x=32$ and $x=88$ which mark points that, satisfying this criterion, relocate the previous reference point and ensure that the estimated quiescent level actually corresponds to a local minimum.
2- **Reference point before a relevant brightening.** In this case the sequence of the four last points $i-3, i-2, i-1, i$ is considered. If they show a monotonically increasing brightness and the accumulated magnitude difference is larger than a given threshold, $m_{i-3} - m_i > \Delta m_{th}$, then the reference is updated if in the point $i-3$ the source is fainter (within a given tolerance) than in the preceding reference point. Such a case is illustrated in Fig. [2] by the green asterisk just before the brightening at $x=22$.

3- **A plateau in the light curve suggests a quiescent state and then a new reference.** When the magnitude of the point $i$ is consistent with the mean magnitude of a reasonable number of immediately preceding points (here we adopt 7 points) whose standard deviation is less than 0.1 mag, then the point is considered on a plateau of the light curve. In this case, if the magnitude of the preceding reference point is larger than (within the tolerance) the plateau mean magnitude, the point $i$ is considered as the new reference point. This is the case illustrated in Fig [2] by the green asterisk at $x\sim 50$.

4- **A minimum in a descending branch could represent a reference point.** If the sequence of points $i-3, i-2, i-1$ exhibits a continuously decreasing brightness, while the point $i$ shows instead an increase, then a reference status is assigned to the point $i-1$ if $m_{i-1} > m_{\text{ref}}$, even considering the tolerance, as exemplified in Fig. [2] at position $x=95$;

5- **Detection of spikes.** A “spike” is flagged when in a sequence of five points the magnitude of the midpoint differs more than a predefined threshold from the linear fit to the 4 adjacent points $i-4, i-3, i-1, i$. This definition captures single points significantly deviating from the neighborhood and includes both upward and downward brightness changes. Should the midpoint $i-2$ have been previously assigned to another status (e.g. reference or high), then this assignment is removed and the point is flagged as a spike. In the case the previous assignment was a reference, the immediately preceding reference point is recovered for the subsequent analysis. Two spikes are visible in the simulated light curve at the positions $x=8$ and 75

6- **Sudden brightness drop and update of the reference point.** If the magnitude in the last two points, $i-1$ and $i$, is larger than in the reference and the difference $m_i - m_{\text{ref}}$ is larger than a predefined threshold, the point $i$ is highlighted as a “drop” due to the sensible fading of the source. These cases are shown as upside-down red triangles ($x=6, 12, 95$). Furthermore the point is also taken as a reference point if one of these conditions is satisfied:

i) the magnitude in $i-3, i-2, i-1, i$ grows monotonically and the magnitude difference $m_i - m_{i-3}$ is larger than the tolerance (e.g. at $x=95$);
ii) the last five points of the light curve are cradle-shaped, free from 
spikes, and the magnitude difference \( m_{i-2} - m_i \) is larger than the 
tolerance. If this condition is not satisfied, a further point \( i - 5 \) is 
considered to verify if its magnitude is coherent with the cradle-shaped 
trend and the difference \( m_{i-2} - m_{i-5} \) is larger than the tolerance.

In the same line a point is similarly highlighted as a drop when the se-
quence of points \( i - 3, i - 2, i - 1, i \) shows a monotonically descending 
brightness, so that the accumulated difference in magnitude is larger than 
a threshold (e.g. at \( x = 29, 41, 67 \)). Even in cases of non-monotonic fad-
ing, the point is anyway considered as a drop if the magnitude difference 
between the points \( i \) and \( i - 4 \) is larger than the threshold.

7- Assign the “high” status to the point. In the opposite case in which the 
magnitude at both \( i - 1 \) and \( i \) points is significantly lower than in the last 
reference point and the difference \( m_{\text{ref}} - m_i \) is larger than a predefined 
threshold, the point \( i \) is flagged to represent a high state and is shown 
in Fig. 2 as a red point. If instead the points \( i - 1 \) and \( i \) fall below 
the threshold, the behavior of the light curve is further analyzed and a 
reference point is assigned if one of these conditions is verified:

- the source in the last points is continuously and significantly fading,
  with the last point falling, within the tolerance, near the magnitude 
of the last reference point;
- the sequence of the last five points is cradle-shaped with the lower 
brightness midpoint beyond the tolerance from the magnitude of the 
last reference point. An example of this being the reference point 
marked in \( x = 117 \).

3.2. Tests on a known source

To illustrate the results obtained by experimenting the pipeline on an actual 
light curve, we used the data collected for V1118 Ori, probably the best observed 
EXor source, whose light curve is shown in the upper panel of Fig. 3, encom-
passing about 30 years from \( t_{\text{ini}} \approx 1989 \) to \( t_{\text{fin}} \approx 2020 \). In this figure red filled 
circles are used to emphasize the high state phase of the source, corresponding 
to a brightening of \( \Delta m > 2 \) mag with respect to the estimated quiescent state 
(see Section 3.1), the latter represented by the preceding green asterisk. A blue 
triangle is used to mark a spike that here corresponds to a jump of \( \Delta m = \pm 1 \) 
mag.

Since the light curve analysis begins by considering the initial observation as 
the first reference point, it is necessary to ensure that the results of the pipeline 
are reasonably independent of the particular state of the source at the beginning 
of the observations.

To this aim we modified the light curve by moving the initial point at \( t_{\text{ini}} + \Delta t \), 
artificially appending all the skipped data points after the last observation 
at \( t_{\text{fin}} \), namely at the end of the original curve. In this way we obtained a
number of artificial light curves that, once submitted to the pipeline, always show the same points recognized as high state, except in the very initial part of the curve where the results depend on the stochastic position chosen for the starting point that, in turn, defines the first reference point.

This is illustrated by the remaining two other panels in Fig. 3 that essentially show a replica of the same light curve, but with the initial point assumed in two different dates corresponding to an active and a quiescent state, respectively.

In the middle panel a shift of $\Delta t=6002$ JD brings the peak of the 2005/06 bump in the first position and consequently the bump itself remains unrecognized due to the lack of a previous reliable reference point actually associated to a quiescent state. This is progressively better devised in the subsequent descending phase of the brightness, until the bottom of the curve is reached where a new reference point is assigned, representing more faithfully the quiescence.

Clearly, from this position onward, the analysis of the light curve closely follows the results obtained for the original curve in the top panel.
The last panel at the bottom shows the same light curve, but shifted by \( \Delta t = 8433 \) JD so that the starting point of the observations falls now in a low activity region of the original curve. Because of this, the assumed first observation is already near a quiescent phase of the source so that all the subsequent points are classified similarly to the original curve.

Whatever the shift we adopt, after a transitory initial phase needed to estimate a representative quiescent level, the analysis always detects the same high states making us confident on the capability of the pipeline to reasonably find the high state episodes of the source. This also means that an alert can be appropriately issued, should the increase in brightness with respect to the reference point exceed a given threshold. Indeed, repeating this kind of test with a random initial point, the results are invariably very similar once the reference point has reached a reliable quiescent state, with the result that all the bursts reported in the literature for this source are always detected. The exception is clearly the case in which the beginning of the light curve falls on a burst that, in this way, is missed as illustrated in the 2nd panel of Fig. 3.

4. Application to case examples

With the aim of testing the procedure against other photometric behaviors, we submitted the light curves in Fig. 1 to our pipeline, obtaining the results shown in Fig. 4a and 4b. In these figures the threshold in the magnitude difference required for a point \( i \) to be considered as “high state” has been set to \( \Delta m = m_{\text{ref}} - m_i > 2 \) mag, quite typical of EXor sources. The tolerance has been taken at 0.2 mag to account for the small brightness fluctuations considered as intrinsic to the quiescence state. For simplicity, here we adopt the same value for all the analyzed sources even if, in principle, this parameter could be tuned on specific values tailored on the small fluctuations actually present in the light curve of each source (see Section 3.1). Finally, the threshold for a spike has been set to 1 mag.

In Fig. 4a, the upper left panel is taken from Fig. 3 and is reported here for ease of comparison with the other sources. Note that at the beginning of the year 1990 there is a notable fading in brightness that is marked as both reference point (green asterisk) and drop (red upside-down triangle, overplotted), the latter introduced to highlight rapid brightness decreases (see Section 3.1 point 6). Similar cases are also found in iPTF15afq in the descending branch at the end of the light curve and in ASASSN-13db in the rapid fading at the end of 2016. In Fig. 4b the subsequent two other cases are also evidenced: V2492 Cyg whose brightness decreased \(~5\) mag in 2018, and Gaia19ajj that experienced a flux drop of \(~3\) mag toward the end of 2020.

In the case of XZ Tau the fluctuations of the light curve are always within the adopted 2 mag threshold, with the exception of three isolated points, two of which located around the small brightening peak seen between the end of 2014 and the beginning of 2015, and the other high point being more isolated. Despite the latter could resemble a spike, this is not recognized as such by the
Figure 4a: The light curves of the first six sources in Fig. 1 with superimposed the reference (green), spike (blue), and high state (red) points established by using the pipeline described in Section 3.1. In each panel, the spectral band of the observations is shown with a letter in the upper right corner, two letters being used to indicate the use of two different bands (see text). The threshold in magnitude and the tolerance have been set to 2 and 0.2 mag, respectively.
pipeline because of its position is compatible with the ordered sequence of the immediately preceding and following points. A spike is instead highlighted (see Section 3.1 point 5) at the end of 2020, shown as a blue triangle.

The next source, VY Tau, shows an approximately constant baseline at \( \sim 13.7 \) mag, interrupted by three small and sharp peaks suggesting that this object suffers rapid and isolated jumps in brightness of the order of 1 mag. Their amplitude is however too small with respect to the adopted threshold, so that they are not highlighted by the pipeline. There is also a point marked as a spike that, given its brightness and time of occurrence, could be interpreted as a fourth rapid brightening belonging to the same series of episodes. However, due to its isolation with respect to the adjacent points, it has been formally marked as a spike.

The light curve of PV Cep shows instead an almost monotonic rise (years 2013–2015) until the high state phase is reached lasting \( \sim 2 \) years (2015–2016). The subsequent decline appears much more bumpy and without peculiar points as spikes or drops.

As in the case of VY Tau, even the light curve of iPTF15afq shows an almost stable baseline (mag \( \sim 18 \)) in the years 2015–2019 with only two adjacent points highlighted by the pipeline. At the end of 2019 the brightening was \( \sim 4 \) mag and lasted a few months, while in the year 2020 a larger and rapid fading (\( \sim 5 \) mag) has been observed lasting approximately one year and followed by a comparatively slower decline. A sequence of red upside-down triangles marks a series of drop in brightness that has now reached \( \sim 20 \) mag.

In the last panel the ASASSN-13db light curve begins at the end of 2013 with a 100 days bump, with the brightness rapidly rising in 20 days at a rate of \( \sim 0.1 \) mag/day and then falling at \( \sim 0.025 \) mag/day to the previous level of \( \sim 16 \) mag. Then, after a one year gap in the observations, the source is found again in a high state at \( \sim 14 \) mag, remaining bright for more than two years until January 2017 when brightness falls at a rate of 0.1 mag/day reaching a plateau at \( \sim 18 \) mag. At the end of this rapidly descending phase a red triangle marks the point as a “drop” indicating a sensible decrease in brightness with respect to the preceding observations (see Section 3.1 point 6).

The results obtained in the remaining six example cases are shown in Fig. 4b. In the upper left panel the light curve of GM Cep is presented with some points highlighted toward the end of the curve. Their magnitude difference from the preceding reference point is actually larger than the threshold but, should the reference point represents more an extinction variation than a quiescent level, the high state points could be more apparent than due to a genuine activity of the source.

The next case, V1184 Tau, appears dominated by a global trend encompass-
Figure 4b: As in Fig. 4a but for the last six sources of Fig. 1.
ing more than ~10 years. In the first part of the light curve the brightness increases slowly for more than 2 mag, albeit with large fluctuations, surpassing the adopted threshold ($\Delta m = 2$ mag) in 2013 and then, after ~2 years, begins to decline reaching ~18 mag. In this evolution, spikes are detected in 2009, 2013, and 2019, and a drop, more recently, at the end of 2020.

The two subsequent light curves show very different behaviors. V2492 Cyg appears irregularly variable and the pipeline, besides highlighting the high states, finds several spikes and drops in brightness. On the contrary, V2493 Cyg maintains a quite constant brightness in the years preceding 2010, jumping of ~5 mag in six months and then remaining in a high state till now.

The last two cases analyzed are Gaia sources, both showing an increase in brightness of ~5 mag in three years. However, Gaia19aij has the light growing phase accompanied by large fluctuations of ~1 mag and, after reaching a high state, in 2020 rapidly decreases as indicated by the red upside-down triangle. On the contrary, Gaia18dvy grows in brightness much more regularly so that no peculiar points are detected, until the magnitude difference with the reference point exceeds the adopted threshold and the object is considered in high state.

A summary is given in Table 1 that, besides showing the time intervals covered by the light curves analyzed, also reports the number of detected bursts, namely clusters of connected points recognizable as a single brightening episode with amplitude $\Delta m > 2$ mag.

However, we underline that using this algorithm is clearly not enough to pick-up a specific kind of object because our procedure only represents a first step, aimed to select candidate sources to be subsequently scrutinized with additional criteria (e.g., burst time scale, rising and declining slope, repetition) specialized on the observational characteristics of the specific class of objects.

5. Conclusions

Nowadays large number of well-sampled light curves are being collected. The trend will grow as the next generation of survey telescopes, both ground and space-borne, come into operation.

This new opportunity is ideally suited to answer in an unbiased way important questions about the evolution of the pre-main sequence stars, and in particular of their disks which are in the planet forming phase. With the aim to have a tool suitable to scrutinize large amounts of light curves, we have developed a simple software capable of searching for rapid brightening and fading in light curves, particularly for the detection of the EXor phenomena to shed light on their sporadic accretion processes as the origin of stellar masses.

The pipeline has been tested on a few well-sampled light curves of recognized or candidate EXors with encouraging results. For our tests we adopted a
threshold of $\Delta m = 2$ mag to detect a burst in brightness, a typical value characterizing the PMS stars classified as EXors. Finally we emphasize that this work is devoted to the simple detection of bursts in light curves, leaving the problem of the source classification to subsequent analysis.

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