Young Stars in Star Forming Regions with ZTF

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1. Abstract

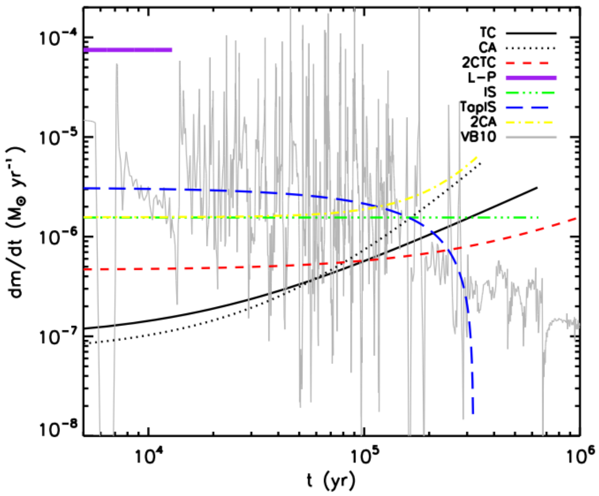
Variability in young pre-main sequence stars is driven by a combination of normal stellar phenomena (spot-modulated rotation, flares, binary eclipses) and circumstellar add-ons (accretion "burster" events, more standard magnetospheric accretion, and extinction-related "dipper" and "fader" events). The typical short-term behavior occurring on time scales of hours to months has now been fully sampled by CoRoT (in NGC 2264), MOST (for a few selected objects) and Kepler/K2 (in the Ophiuchus dark cloud, Upper Scorpius association, Taurus-Auriga star forming region, and M8 HII region). The longer term behavior that is associated primarily with circumstellar disk activity is still the domain of ground-based surveys, which have longer baselines, albeit lower precision photometry. PTF has provided steady cadence over 3-8 years on a few key star forming regions. ZTF will continue this legacy with better time sampling and sensitivity, and will provide definitive statistics on accretion events such as FU Ori and EX Lup outbursts – which appear critical for actually building up the final stellar mass.

2. Scientific Motivation

The paradigm of star formation now explicitly includes the concept of episodic accretion (see Figure 1), whereby stars accumulate some fraction of their final mass in the initial spherical infall stage, some fraction in early-stage disk accretion that is punctuated by elevated accretion rates of $\sim 10^{-5}$ to $10^{-4} M_{\odot}/yr$, and finally the last remaining ∼10% of their mass during the optically visible stage of pre-main sequence evolution, which is characterized by low disk accretion rates of $\sim 10^{-9}$ to $10^{-7} M_{\odot}/yr$, but also by infrequent bursts. The larger among these bursts, which last decades to perhaps centuries, are called FU Ori events, and involve a thermal or a (gravo-) magneto-rotational instability in the inner 0.1-few AU of the disk. Smaller amplitude and shorter duration (months to year-long) events, called EX Lup type bursts, may be related to instabilities associated with the interaction region between the disk and the stellar magnetosphere.

While there has been a significant amount of theoretical work on protostellar evolution, rigorous empirical constraints on the accretion history of young stars are nonexistent. Our basic framework is rooted in essentially back-of-the-envelope estimates of the outburst rates. Hillenbrand & Findeisen (2015) outlined the problem at hand, and the inability of past surveys to address it (see Figure 1). The implications for our understanding of how stars accrete their mass, and how they evolve in the HR diagram have become more mainstream questions as the PTF/iPTF era has unfolded.

However, the current census of FU Ori stars numbers less than 20 objects (!!), with an equal



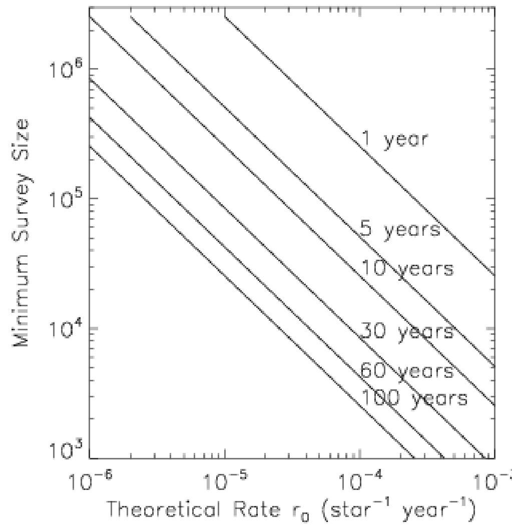


Fig. 1.— Left: Models for the evolution of accretion rate with time in the protostellar and early star/disk stages, from Dunham et al. (2014). Various colored lines indicate the predictions of standard, steady infall/accretion, models, while gray line indicates an episodic accretion model. Empirically constraining the burst frequencies in the later stages is a primary goal of our work with PTF → ZTF. Right: Survey size needed to have a 90% chance of detecting a factor of 2 deviation from a hypothetical outburst rate r_0 at 90% confidence, from Hillenbrand & Findeisen (2015). Table 1 shows that, altogether, we are surveying close to $5{\times}10^5$ stars, and thus will be placing meaningful limits on the outburst rates over the next several years, presuming an accurate denominator can be determined for the rate calculation.

though increasing number of EX Lup analogs, several of which are known to be repeating.

Work over the past decade has established that low-state accretion (i.e. that inbetween the bursts) in ∼1-10 Myr old stars, produces variability on time scales of typically 1-2 days and having amplitudes 2-20% (e.g. Findeisen, PhD thesis; Cody et al. 2014). Our PTF survey of star forming regions has provided the ability to identify new young stars via their varibility. The more limited in area, but much higher cadence and precision work done with CoRoT, MOST, K2, and Spitzer, however, has robustly characterized this "typical" low-state accretion variability – better than can be done from the ground.

Some exceptional PTF objects (e.g. PTF 10qpf, PTF 10nvg and PTF 15afq among others, and the sources in Findesen & Hillenbrand 2013; also see appendix) have been observed to burst for months to years at a time. These types of sources are almost uniquely in the domain of PTF/ZTF (since they are both rare and not readily identifiable in the short-duration space-based programs carried out to date). We aim to identify, characterize, and document the statistics of such bursting young stars, in order to assess the important of large-amplitude accretion variations. We also have been following several examples of very slowly, but systematically, brightening sources over the years of PTF data; based on our historical knowledge of FU Ori stars, these could be future outbursters that will be seen by ZTF or LSST, and for which PTF will contain the legacy data on their pre-outburst behavior.

2.1. Outline of Goals with ZTF

- continue PTF/iPTF legacy of young stars monitoring into the ZTF era
- accumulate the statistics needed in order to measure the rates of both FU Ori and EX Lup type disk accretion-driven outbursts.
- measure long term variability trends of well-known individual members of star forming regions

2.2. Competitiveness of ZTF

The players in young star "outburst" searches have been making use of data from PTF (Hillenbrand), PanSTARRS (Reipurth), ASAS (Herczeg), Gaia (Hodgkin), and small telescopes in eastern Europe (Munari, Kospal). The events are rare, but the target regions limited and known. Sky coverage is key, especially if events can be detected in the galactic plane.

PTF was a co-discoverer of the FU Ori star PTF 10qpf (Miller et al. 2010) and found the EX Lup star PTF 15afq (Miller et al. 2015), as well as observing a number of other interesting young star phenomena as reported in various refereed and e.g ATel articles involving the author. But PTF totally missed out on the detection of any of the several other young star FU Ori outbursts that have occurred over the past 9 years (specifically, V582 Aur found at Asiago in 2009, V2775 Ori found at REM / La Silla in 2011, V900 Mon found by an American amateur in 2011, and V960 Mon, found by a Japanese amateur in 2014). This was because of either: complete lack of coverage of the relevant positions by PTF, or lack of good photometry from existing images of the positions. While we have participated in the follow-up of these objects, e.g. notably by providing world-unique data from Keck/HIRES, we did not discover them.

Looking forward, ZTF wins in terms of cadence and depth, though it must cover "the right" fields in order to participate in this science. Seemingly there is full-sky coverage, including the Gould's Belt ring of local star formation, and the plane. The challenge for ZTF will be in producing good photometry in semi-crowded and sometimes nebulous fields. PTF field 4588, for example, has been imaged 1315 times over 8 years (Table 1) in PTF/iPTF; this is a unique data stream in young star research! However, for the majority of the field, photometry has not been reported since 2013 for reasons that are currently unknown (see Appendix).

2.3. Figures of Merit

The main figure of merit by which this project can be judged is the fraction of known young stars in a given star forming region, for which the pipelines produce usable lightcurves. The highest level science goal we have, relies on not only detecting the interesting events, but also, critically, on understanding the denominator, i.e. for how many young stars in a given region could we have seen an event of a certain type, given the survey areal coverage, cadence, and depth?

After this, the bar to reach will be establishing ZTF as the leading discovery telescope for northern hemisphere FU Ori events.

2.4. Real Time Activities

The project does require human attention, since many types of stars – and all young stars – are variable at the sensitivity level of ZTF. Our experience with PTF gives us the know-how for conducting the scanning, though we have relied to date entirely on the existing PTF infrastructure within the "marshals" (both transient and galactic) and the "treasures portal," in order to identify and store objects of interest. The main decisions and actions, in order, will be:

1. Is object located towards a known star forming region? To date, we have implemented this simply as: Is object in one of the specified PTF Star Forming Regions fields? For ZTF, more specific spatial queries will need to be designed.
2. Does object trigger standard PTF → ZTF alarm bells, based on its relative brightness changes, and accompanying r/b vetting?
3. Is object a known young star?
4. Is object associated with infrared excess, as assessed via Spitzer/WISE?
5. Is the variability interesting enough to "save" the object with a ZTF name?
6. Is the variability interesting enough to request an immediate spectrum?

7a. Does the spectrum indicate an FU Ori type event (absorption lines; wind signatures)? If so, write ATel, follow up at higher spectral resolution, and with an infrared spectrum. Produce a thorough, proper journal paper, ASAP.

7b. Does the spectrum indicate an EX Lup type event (emission line dominated)? If so, write ATel. Follow up with proper journal paper.

3. Proposed Observations

Unlike many other ZTF programs, this one cares about *specific* areas of sky. The standard ZTF observation plan should provide sufficient coverage of the fields of interest, assuming that the middle-galactic latitudes are included in the general survey. There are the local regions of star formation that are located up to ±20 deg from the galactic plane, so not in the GPS, as well as the more distant 1 and 2 kpc star forming regions that are in the spiral arms, so indeed covered in the GPS. The PTF star forming regions fields observed over the past 3-8 years are illustrated in Figure 2. If the standard ZTF 3-day cadence does not apply at all latitudes, we would be interested in specifying fields to be allocated as ZTF star forming regions fields, that would receive such cadence.

The proposed survey depth and cadence are prefectly acceptable to this program. Young star science will be in the high S/N regime of data taken in the standard ZTF surveys to 20.5 mag.

The primary filter of interest is the r'-band, with g'-band less useful given the very red color of the targetted stellar population. If there is a trade to be made between cadence and color information, cadence in r' is definitely preferred over split r' and g' observations.

Observations for this program can be carried out all year, with some concentration of fields in summer and winter RA ranges, but nearly full-year accessibility of one particular field of interest: the galactic plane North America Nebula region (PTF Field ID 4588).

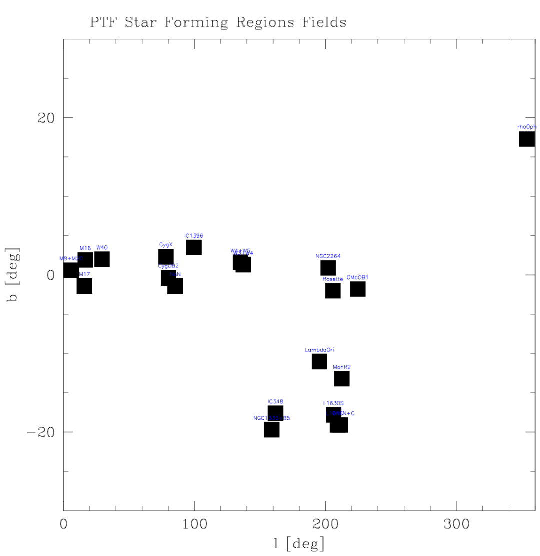


Table 1. PTF Star Forming Regions Program – 3° × 2° Fields

Star Forming Region	Estimated # Young Stars	Observed l,b	Start of Monitoring	Epochs to Date[1]	PTF Field ID
– Summer Fields –					
ρ Oph / L1688	1×10^3	353.8, +17.3	2013	161	1638
M8 and M20	1×10^4	5.9, +0.6	2013	167	11644
M16	5×10^3	16.7, +1.9	2013	198	22045
M17	5×10^3	16.0, -1.4	2013	193	21944
W40	3×10^3	29.4, +2.0	2013	226	22568
Cyg X	2×10^5	78.2, +2.3	2013	287	24430
Cyg OB2	3×10^4	80.1, -0.4	2013	282	24431
IC 1396	5×10^3	99.5, +3.5	2013	260	14984
North America Nebula	7×10^3	85.3, -1.4	*2009*	*1315*	4588
W3 and W4	5×10^4	137.3, +1.3	2013	249	24996
W4 and W5	5×10^4	135.1, +1.6	2013	272	5049
– Winter Fields –					
IC 348	1×10^3	161.8, -17.6	2014	179	24024
B5 and NGC 1333	1×10^3	159.0, -19.7	2014	171	24023
Lambda Ori	1×10^3	195.4, -11.0	2014	156	3141
L1641-north/central	2×10^3	211.2, -19.1	*2010*	*284*	110021
L1630-south	1×10^3	206.1, -17.8	2014	148	22511
ONC	1×10^4	209.2, -19.1	2011?	781+60	101003
Monr R2	1×10^3	212.5, -13.2	2014	145	2408
NGC 2264	1×10^4	202.0, +0.9	2014	178	3145
Rosette Nebula	3×10^4	205.6, -2.0	2014	149	2935
CMa OB1	2×10^3	224.6, -1.8	2014	134	22100

[1]numbers current to 2017 January

Fig. 2.— Information regarding the PTF Star Forming Regions Program carried out to date.

4. Supporting Observations

Spectroscopic follow-up of the rare variability events is required. Palomar is suitable for initial reconnaissance, and infrared spectra from e.g. IRTF would be the next step. Keck/HIRES is also highly desirable as soon as it can be arranged. If there is not spectroscopic time immediately available within the ZTF collaboration, community interest in young star outburst phenomena will make special requests definitely serviceable, and will readily lead to the necessary spectra.

There are groups with small telescopes in eastern Europe who have performed multi-color, long timescale follow-up of the recent FU Ori outbursts (as well as other notable young stars undergoing unusual behaviors). So the colors aspect of the science is not necessary to lead from within the ZTF collaboration. That said, were 60" time available for early stage follow-up, all the better for us.

The total time needed for supporting observations for this program is negligible, in the grand scheme of ZTF follow-up. The program can always provide spectroscopic targets, but truly time-critical spectra would be limited to fewer than a few objects per year. Continuum S/N >30 at $R > 2000$ is desired, e.g. DBSP or NGS; SEDM resolution is not suitable.

5. Expertise to Undertake Project

Young star expertise is abundant in 218 Cahill; other ZTF collaborators are welcome to join the team. The author has worked primarily with Adam Miller on PTF data in this science area. Interaction with the rest of the ZTF team, especially the data processing experts, is highly desirable.

Beyond expertise, what is needed for progress is attention and time devoted to: 1) the global set of (P/Z TF) young stars observations, both existing and future; 2) paper production on intermediate and final products of survey, i.e. beyond the outbursts.

6. Manpower and Timeline

This would be an excellent thesis project, should a Ph.D. student materialize with interests in the area of young star variability. Otherwise, I have had various SURF students looking at the data from the PTF Star Forming Regions program, following the Ph.D. thesis work of K. Findeisen a few years ago.

7. Appendix: Example PTF/iPTF Light Curves

The following example lightcurves are provided as an illustration of some of the individual products to date, of the PTF star-forming regions survey.

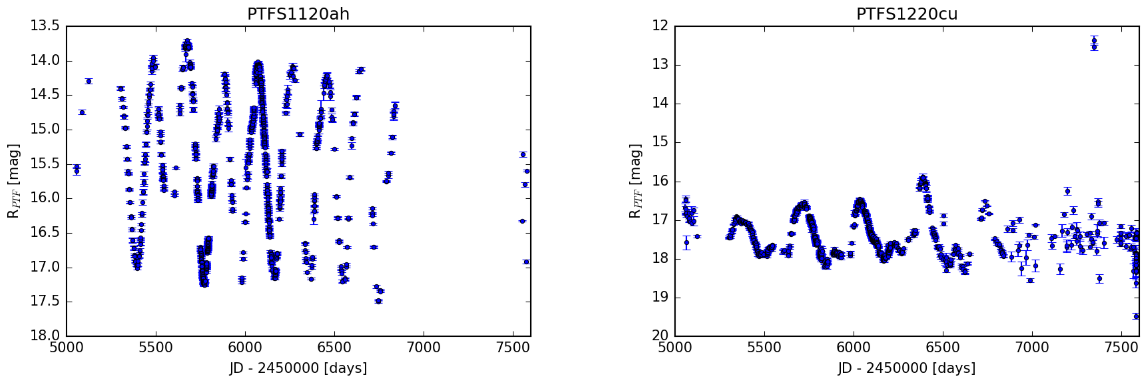


Fig. 3.— These are semi-regular pulsating giants, not young stars (though perhaps interesting to someone else). The lightcurves are shown to illustrate the several years of either totally missing, or extremely poor quality, photometry in the existing data stream for PTF field 4588; the images exist, but something went wrong with their processing.

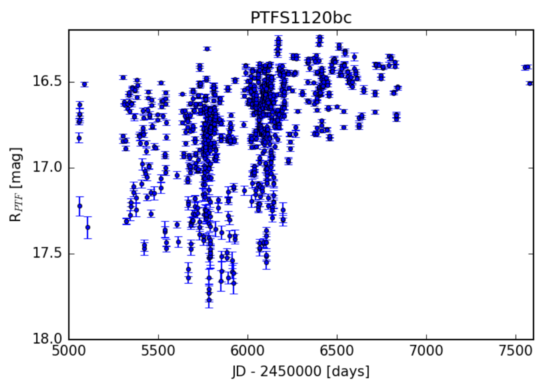


Fig. 4.— Typical "stochastic" behavior for an accreting young star, though larger amplitude than most examples.

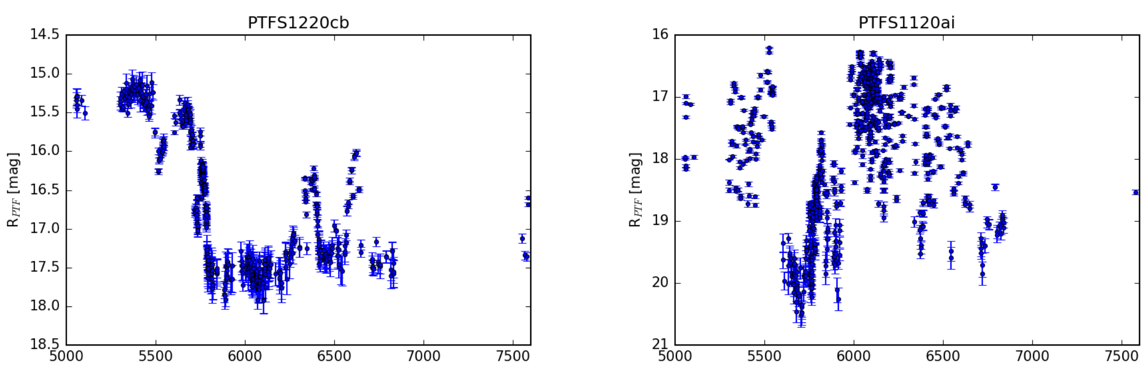


Fig. 5.— Examples of long-term (year to multi-year) fading sources.

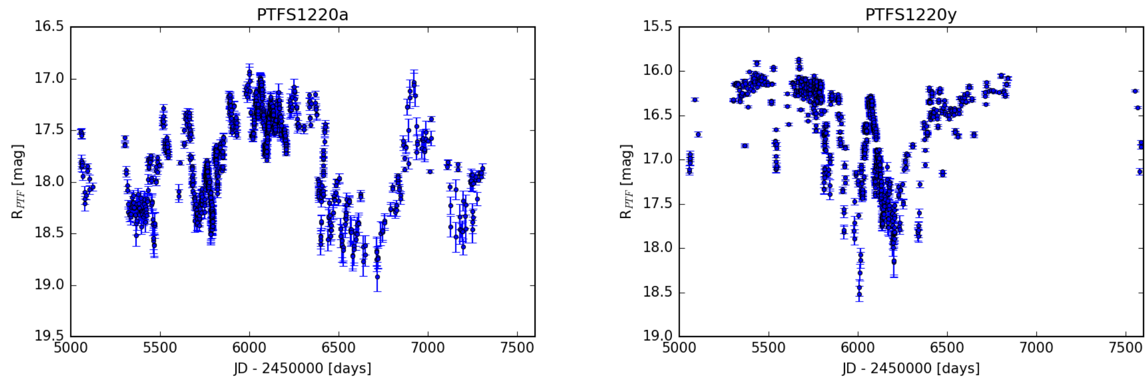


Fig. 6.— More faders.

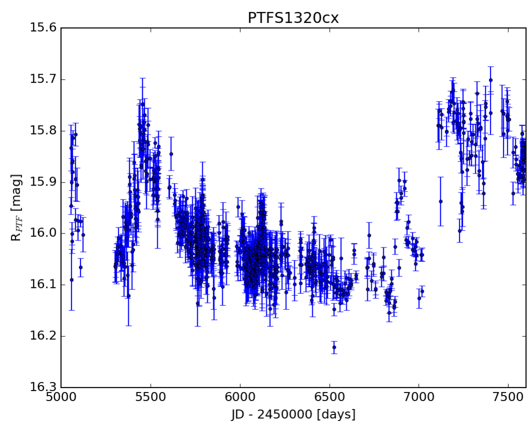


Fig. 7.— Ambiguous case. Is this several year-long bursts, or a multi-year duration fade?

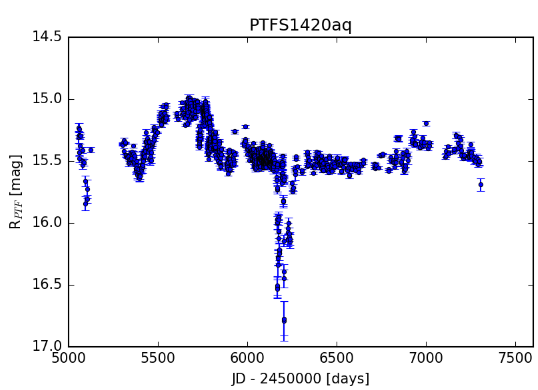


Fig. 8.— This source exhibits both a multi-month bursting behavior and a few week fading event.

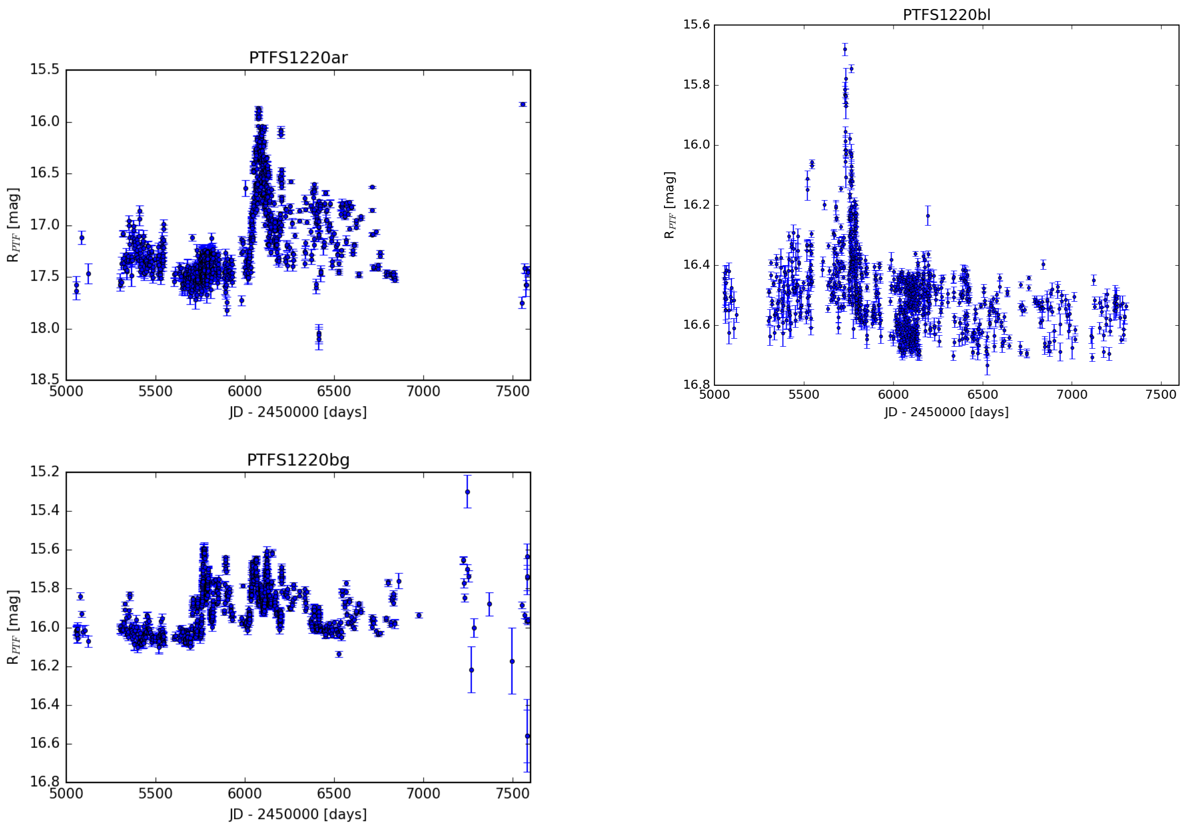


Fig. 9.— Minorly bursting type sources, two larger amplitude and singular events, the other smaller amplitude and repeating.

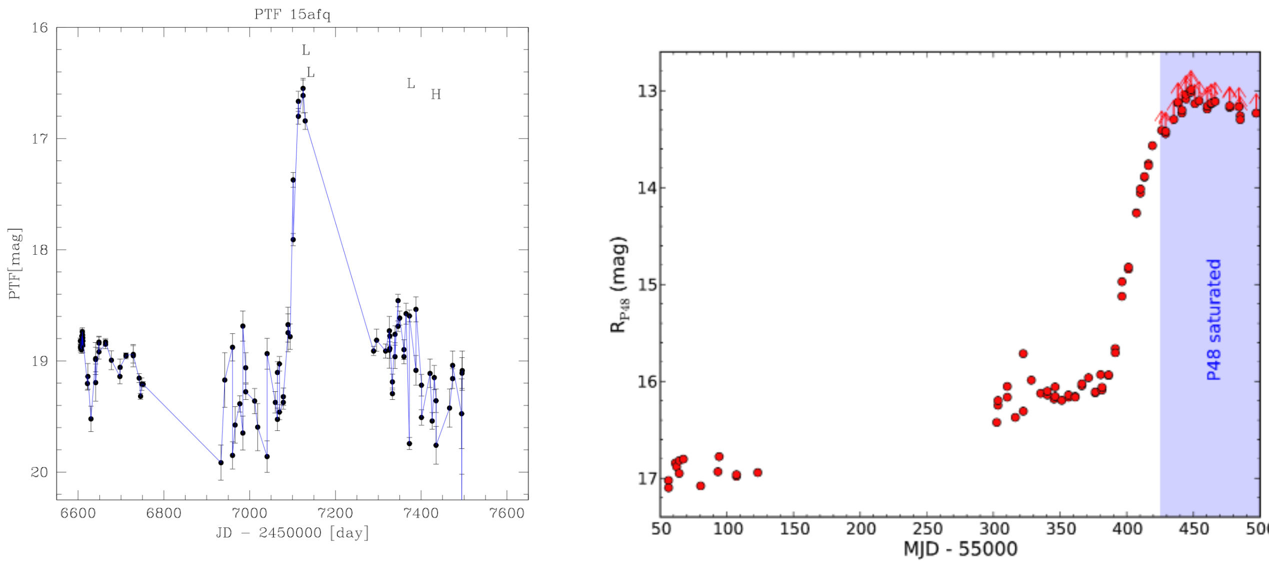


Fig. 10.— Spectroscopically confirmed (left) EX Lup type burst, and (right) the one FU Ori event caught by PTF-classic, PTF 10qpf, a.k.a LkHα 188-G4 or HBC 722.

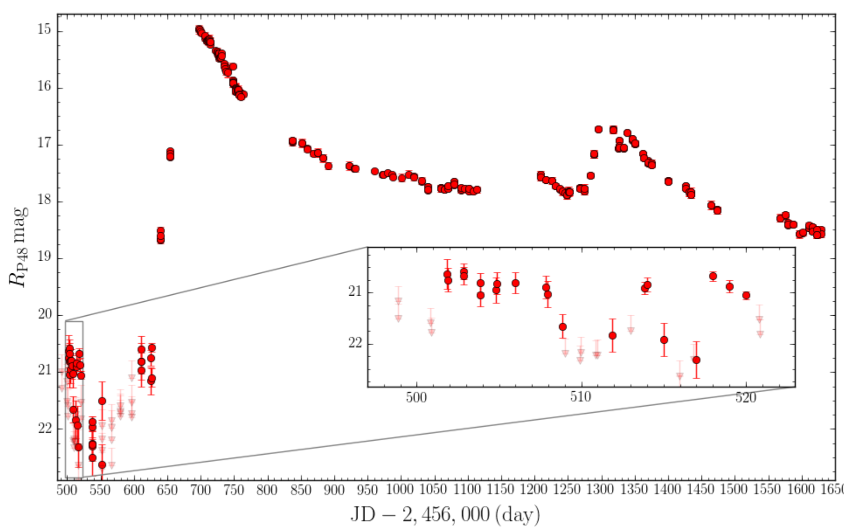


Fig. 11.— Mystery object that is an unusual FU Ori candidate, based on its spectrum; however, no alternate explanation has emerged.