Using AF Psc to test of flare energy partitions with TESS and Swift

Introduction

We propose to observe the active, flaring, mid-M dwarf star AF Psc at 20-second cadence with TESS during Sector 42. Combined with simultaneous X-ray and ultraviolet observations at high cadence with Swift (this proposal) and simultaneous observations in the radio with the VLA (in a Director's Discretionary proposal we will submit if selected here), **we will measure the energy partition and temperature evolution of at least one flare across four electromagnetic regimes and compare against a canonical partition model.** A canonical energy partition [1] is adopted for many stellar flare analyses, but there have been precious few direct observational tests using simultaneous data in many different wavebands. This is primarily due to the difficulty of coordinating such observations across observatories. Many prior multi-band studies of flaring stars have also been restricted to observational cadences of minutes, limiting their use in understanding the time-domain behavior of flares which are known to vary on timescales of seconds. **Even a single flare, observed across the radio, X-ray, ultraviolet, and optical with time resolution at sub-minute cadence will be a significant addition** to the available observational constraints of flare energy partitions, models of flare time evolution, and quasi-periodic pulsation (QPP) formation mechanisms.

Target selection: AF Psc

AF Psc is an M4.5 dwarf 35 pc from the Sun that is known to produce frequent and large flare events. The star is fairly bright (TESS mag ~11.3) but not bright enough to trigger safety thresholds for observing with Swift XRT or UVOT (except in the clear filter), even from a significant increase in brightness due to a large flare. The star is not known to be a binary, and there are no nearby objects of comparable brightness (the closest is more than 8 TESS pixels away), thus all flare events can be assigned to AF Psc, even with the large pixel size of TESS. The star was observed by the K2 mission during its engineering campaign with 30-minute cadence over nine days: 14 flares were detected with energies of 10^31-10^32 ergs in the Kepler bandpass [2]. The star was also observed in long and short cadence during K2 Campaigns 12 and 19, and visual inspection shows a comparable flare/day rate. The resulting estimate of ~1.5 +/- 0.5 flares/day from the K2 data is a lower limit on the number of flares we'll detect in this proposal, because the shorter cadence of TESS and the improved contrast of Swift in the UV can find shorter duration flares that K2 is not sensitive to.

AF Psc was also observed by GALEX for a total of ~1 hour as part of a GI program, and despite the short time on target, a large flare was observed during one of the 30-minute visits, further evidence of the high flare rate from this star. Thanks to the time-tagged nature of the GALEX detectors, the flare shape was able to be resolved in fine detail, and a quasi-period pulsation (QPP) of ~30 seconds was detected during the flare in both the FUV and NUV bands of GALEX [3,4]. AF Psc thus makes an attractive target for a simultaneous, high-cadence, multi-wavelength campaign to study its flares. Based on the star's flare history from K2, we expect to observe at least one large flare over ~18 hours of observation, and likely a few shorter-duration flares. High time resolution of even a single flare on AF Psc will allow for a detailed breakdown of the energy partition, a measurement of the time evolution of the flare's temperature profile, and the first detailed, multi-wavelength observational constraint on the formation mechanism of a QPP, should one be present.

Justification for TESS 20-second cadence

With the availability of the 20-second mode on TESS, for the first time there is now an opportunity to get continuous observations of flare stars at the seconds-level in radio, X-ray, ultraviolet, and optical. Most stellar flares are observed to have blackbody equivalent temperatures of ~10,000 K and thus a peak flux contribution in the near-UV. However, departures from a blackbody fit during the decay phase of a flare in the red-optical can be a key distinguisher for flare formation mechanisms. [5] The broad, red-optical bandpass of TESS is a perfect complement to the UV/blue-optical bands on Swift. While the main goal of this proposal is to study at least one flare with simultaneous coverage from three different observatories, with four different wavelength regimes, the month-long baseline of a full TESS Sector will allow for an estimate of the flare frequency distribution for this specific target across a wide range of flare durations and energies, including flare durations that were not detected even with the short-cadence K2 observations in Campaigns 12 and 19. **TESS has not observed this intriguing flare star before at any cadence**, Sector 42 will be the first and **only time** AF Psc will be observed in Cycles 1-4 by TESS, according to the TESS Web Viewing Tool**.**

Need for joint Swift observations

The Swift telescope allows for simultaneous observations in X-ray (via the XRT spectrometer, able to measure fluxes in both the "soft" and "hard" X-ray regimes) and the UV/optical via the UVOT instrument in time-tag mode. UVOT has three UV filters spanning the near-UV, as well as U-, B-, and V-band optical filters. We will observe in the U-band since the throughput is higher than the UVW1 filter, allowing us to match the 20-second cadence of TESS and still be close to the peak of the flare continuum emission for a 10,000 K flare. **We will be able to model the flare mechanisms in detail by directly comparing the UVOT and TESS fluxes at high cadence.** When searching for a QPP during the flare, having the signal present in two bands from two completely different telescopes and reduction pipelines mitigates false positives due to systematic errors, while also testing that the strength of the QPP signal does not scale with signal-to-noise in each band (a test that the QPP signal is wavelength independent). By design, Swift can observe with both the XRT and UVOT instruments at the same time. We have confirmed with Swift operations staff that AF Psc is safely observable during TESS Sector 42.

Risk Mitigation

Because flares occur randomly in time and typically last <1 hour, the Swift observations needn't be contiguous or back-to-back. We have requested the amount of Swift coverage that we think will provide a very, very high chance of observing a flare simultaneously with both missions. However, less Swift coverage is viable, but at the expense of increased risk of not capturing a dual-band observation of a flare.

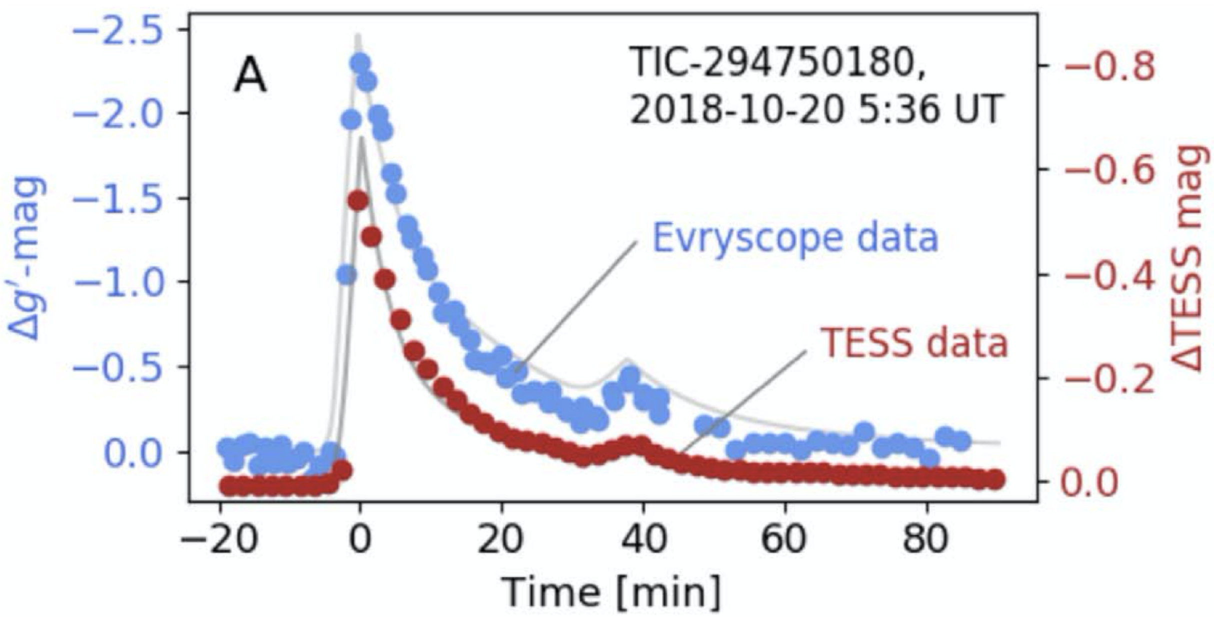

Fig.1: Evryscope (blue-optical) and TESS simultaneous data of a flare. When converted from delta mag to flux, the temperature evolution of the flare is determined. This proposal will perform a similar task, but with up to four bandpasses spanning the radio, X-ray, and optical. This figure is adopted from Figure 1 in [11].

The canonical energy partition of flares from [1] identifies the two major contributors to a flare's total bolometric energy: a UV/optical component arising from the photosphere / chromosphere that contributes ~60-70% of the bolometric energy, and high energy emission from the corona that can be measured in X-ray fluxes, and contributes the bulk of the remaining 30-40%. This energy partition is constrained observationally in [1] from Solar data and multi-wavelength observations **of a single flare star** (AD Leo [6,7]). Thus, observing even a single flare from AF Psc in time-tag mode with Swift UVOT and XRT, **combined with the red-optical fluxes from TESS** at the same high-cadence sampling, will allow for one of the most detailed, high-cadence energy partition studies of a flare to-date, other than the Sun, and will serve as a significant contribution to flares with simultaneous multi-wavelength observations.

<u>Completing the Picture: VLA Radio Observations</u>

We will submit a DDT proposal to the VLA, if this proposal is selected, to observe AF Psc at 2 cm (Ku band, JVLA) in the C configuration over the same period of time as the Swift observations. This frequency is more likely to be in the optically thin part of the gyrosynchrotron spectrum, and can help to constrain the power-law index and total number of accelerated electrons in the flares. VLA and Swift have a joint observing program for this type of project. We must submit a DDT because, unfortunately, AF Psc's TESS observations in Sector 42 end right before the start of the 2021B Semester (begins 22 Sept.), and thus we can not propose for joint observations in the upcoming NRAO 2021B call for proposals. The VLA schedulers are aware of our plan and have assured us they will be able to accommodate this arrangement should our VLA DDT proposal be accepted. Through communications with the VLA schedulers we have found that directly buying guaranteed VLA time using the funds set aside for ground observing in the TESS Cycle 4 call is precluded,d because such arrangements are unusual and take a long time to arrange. We note that while the simultaneous radio observations will enable the most complete flare modeling and characterization, all of our proposed science objectives (the energy budget test, study of flare temperature evolution, and a QPP search and analysis) can be completed without the radio data using only the TESS and Swift joint observations.

Data Reduction and Analysis Strategy

Swift data will be processed using the available Swift software and standard methods detailed in the XRT/UVOT User Guides. This project team also has extensive prior experience working with GALEX data, which has similar detector hardware as UVOT. VLA data will be reduced using standard methods in AIPS. For all lightcurves, an iterative Savitzky-Golay filter smoothing algorithm will be used to remove stellar and systematic noise, enabling flares to be found by inspection. For TESS light curves, we will further test this against open-source TESS-focused de-trending and/or flare finding routines, such as lightkurve [8] and stella [9].

Flare temperatures will be derived using X-ray flare spectra, adapting previous methodologies [10, 12] used for late-type M dwarf stars. This will include fitting modeled bremsstrahlung continua, line luminosity ratios, and Doppler shifts to observed spectra. The 1D radiative-hydrodynamic RADYN flare code [13, 14], along with supplements using the new FP code [15], will be used to construct synthetic flares to match our analyzed responses from flares across observed regions. Energies from the different responses will be estimated based on these models and compared to the canonical partition model. RADYN will also allow us to determine the heating mechanisms, and therefore underlying physics, needed to generate the responses observed. We believe that this is the first time TESS data will be used for this kind of multi-band modeling analysis of a flare.

Work Plan

At a total effort of 100 hours (0.05 FTE), the project PI will take primary responsibility for the scientific direction of work and ensure that project objectives are met within time and budget constraints. The PI will oversee one undergraduate student who will conduct the majority of the data reduction and flare characterization at a total effort of 520 hours (0.25 FTE). We expect that the student will be an advanced undergraduate; the project has been scoped as a ~10 week summer research effort (~0.2 FTE) for Summer 2022. Our expectation is that the student will then lead preparation and submission of a peer-reviewed publication of the work as first-author (with an additional ~0.05 FTE), focusing on presenting the high time-resolution light curves and initial analysis of flare morphologies across bands. Three unfunded Co-Is are included to provide expertise, at de minimis effort, on TESS data, radio data, and flare modeling / physics respectively. Contingent on the outcome of the main work effort, the Co-Is may prepare additional papers at no cost to this project.

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