Multi-wavelength Analysis of Flare Energy Partitions using AF Psc

Abstract: This project team has been granted TESS Guest Investigator observations of the active flare star AF Psc during in TESS 20-second cadence mode during Cycle 4 along with ~65ksec of simultaneous high-cadence observations by Swift in the U-band and X-ray. The primary goal of this effort is to capture a rare multi-band observation of a stellar flare with high time resolution. Quasi-periodic pulsations (QPP) have previously been observed in high-cadence observations of flares on AF Psc, so a secondary objective is to attempt to capture a first-time multiband observation of an extrasolar QPP as a probe into the nature of these poorly-understood phenomena. The addition of time-resolved VLA Ku-band fluxes would significantly enhance this effort by probing the optically thin portion of the gyrosynchrotron spectrum.

<u>Scientific Background</u>

M dwarf stars are among the most likely places to find habitable planets in part because of their high number in close proximity to our Solar System. However, these highly active stars often host flare events that can have significant impacts on the exoplanet's atmosphere structure (Venot et al. 2018). Our current understanding of solar flares can be summarized in three parts. First, electron beams propagate through magnetized parts of the corona, producing radio/microwave (non-thermal) emission. Then, they deposit energy into the chromosphere, releasing hard X-ray and Near-ultraviolet/optical emissions. Finally, the pressure generated by the heating ablates chromospheric material into the corona, increasing the local temperature and density and releasing soft X-ray (thermal) emissions.

The applicability of this process to M dwarf flares is not well understood, as there are few constraints on particle acceleration in stellar flares and current studies suggest a disconnect between solar and stellar flares. Güdel 1996 showed that M dwarfs flares produce more radio emission relative to X-ray emission compared to solar flares. Kowalski et al. 2017 showed through modeling that much higher electron beam fluxes are needed to reproduce white light stellar flares compared to solar, and more modeling work guided by observations is needed to characterize the physical particle acceleration and subsequent radio response in such cases.

We propose to augment upcoming TESS and Swift observations of the active, flaring, mid-M dwarf star AF Psc with the VLA Ku-band. By combining simultaneous high time-resolution X-ray, optical, and radio observations, **we hope to measure the energy partition and temperature evolution of at least one flare across the electromagnetic regimes and compare them against a canonical partition model.** A canonical energy partition (Osten & Wolk 2015) is adopted for many stellar flare analyses, but there have been few direct observational tests using simultaneous multi-wavelength data due to observation coordination difficulties and flare unpredictabilities. Many prior multi-wavelength studies have also been restricted to minute-long cadences, limiting their use in understanding the time-domain behavior of flares, which can vary on timescales of seconds.

Even a single flare, observed across multiple bands 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 particle acceleration, 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 not known to be a binary, and there are no other bright sources within an arcminute listed in NVSS or FIRST at 1.4 GHz. Prior time-resolved observations of AF Psc suggest a high flare rate, giving us a very good chance of successfully making this measurement. 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 (Ramsay & Doyle 2014). 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. 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 (Welsh 2006; Doyle 2018). 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. To our knowledge, AF Psc has not been observed in radio bands before for the purpose of multi-wavelength flare analysis.

Justification for Timing: 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 (Kowalski et al. 2017). The broad, red-optical bandpass of TESS is a perfect complement to the UV/blue-optical bands on Swift. **Sector 42 (2021-08-20 to 2021-09-16) 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. The 2021A VLA semester between 2021-06-10 and 2021-09-06 coincides nicely with this.

Justification for DDT Observing with the VLA

Radio observations offer a direct probe of the accelerated particles in a stellar flare, as particles in a magnetic field produce gyrosynchrotron emission. Analysis on accelerated particles in solar flares is often done using hard X-ray observations, but these are sensitive in stellar flare observations. The Ku-band is chosen as it leans towards the optically thin part of the gyrosynchrotron spectrum while not needing as much calibration time as the other higher frequency bands available. Optically thin radio observations can be used with modeling to constrain the electron power-law index and total number density of accelerated electrons in the flares. This frequency would also help bridge the observational gap between optically thick 6 cm flares in literature and the more recent sub-mm flare detections using ALMA (MacGregor et al. 2020).

The relative timing of the TESS and VLA GI programs in relation to the observation window for AF Psc by TESS did not allow for us to propose these VLA observations through the normal program. The approval for the TESS observations came after the prior submission window---and the justification for VLA is poor without the coordinating observations of TESS and Swift---and the observations will take place before the next VLA GI round. We are therefore requesting use of Director's Discretionary Time for this request.

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.

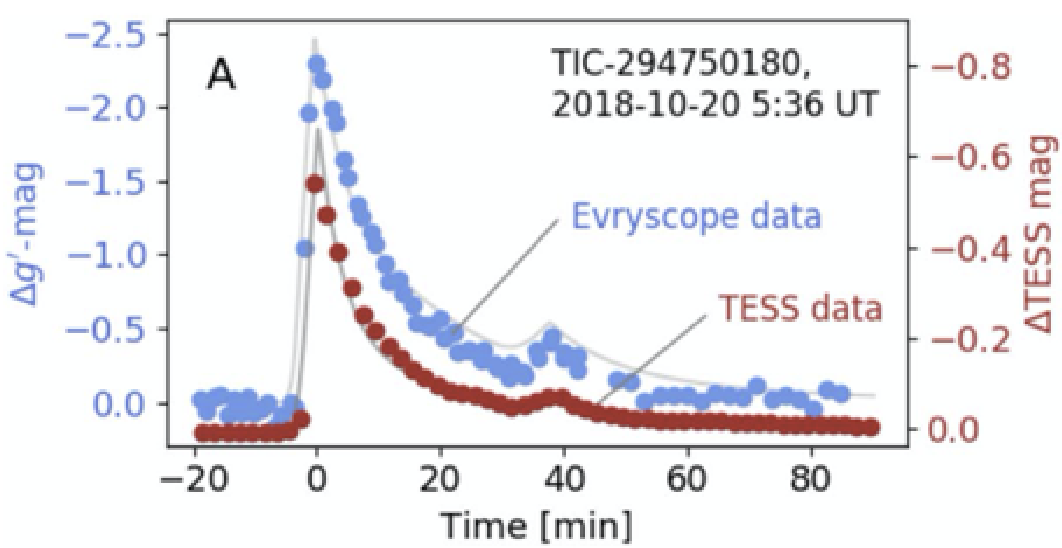

Fig.1: Evryscope (blue-optical) and TESS simultaneous data of a flare. When converted from delta mag to flux, the temperature evolution of the flare is determined. This proposal will perform

a similar task, but with up to four bandpasses spanning the radio, X-ray, and optical. This figure is adopted from Figure 1 in Howard et al. 2020.

Risk Mitigation

We have no specific time slot requests nor minimum request for time-on-target from VLA, but the maximum useful duration is the ~65ksec allocated to Swift by the TESS GI program. Because flares occur randomly in time and typically last <1 hour, VLA observations do not need to be continuous or back-to-back. Swift can take a maximum of about three 30-minute U-band observations per day due to on-board data limits, so longer daily time blocks will not be necessary. We have confirmed with the Swift team that simultaneous observations can be scheduled with a week of advanced notice from the VLA team. As we are interested in flux densities for a point source, the specific configuration of VLA does not matter should time beyond the 2021A semester be available. Special care will be taken to address how the configuration change affects extraneous source removal and data calibration in this case.

The canonical energy partition of flares from Osten & Wolk (2015) 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 from Solar data and multi-wavelength observations of a single flare star (AD Leo; Hawley & Pettersen 1991; Hawley 1995). Thus, observing even a single flare from AF Psc in time-tag mode with Swift UVOT and XRT, red-optical fluxes from TESS, and VLA Ku-band, at the same high-cadence sampling, will allow for one of the most detailed energy partition studies of a stellar flare to-date.

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