Requirements for Progress in Understanding Solar Flare Energy Transport: The Gradual Phase

A white Paper in response to the ***Solar and Space Physics (Heliophysics) Decadal Survey***

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Summary:

Solar flares are a fundamental component of solar eruptive events (SEEs), along with solar energetic particles (SEPs) and coronal mass ejections (CMEs). Flare emission is the first component of a SEE to impact the Earth's atmosphere which can set the stage for the later arrival of the associated SEPs, CME, and space weather event. Magnetic reconnection drives SEEs by restructuring the solar coronal magnetic field, liberating a tremendous amount of energy which is partitioned into various physical manifestations: particle acceleration, mass and magnetic-field eruption, atmospheric heating, and the subsequent emission of radiation as solar flares. In this white paper we discuss the observational and theoretical advances required in order to make substantial progress in understanding the physical processes acting during the gradual phase of a flare. That is, the decay period, following the initial rapid release of energy during the impulsive phase (see our other white paper). In particular we want to address the *unknown processes that sustain the long decay phase of flares*, and identify the *unknown mechanism and magnitude of continued energy injection during the gradual phase*.

1 Overview

Solar flares are a fundamental component of solar eruptive events (SEEs; along with solar energetic particles, SEPs, and coronal mass ejections, CMEs). Flares are the first component of the SEE to impact our atmosphere, which can set the stage for the arrival of the associated SEPs and CME. Magnetic reconnection drives SEEs by restructuring the solar coronal magnetic field, liberating a tremendous amount of energy which is partitioned into various physical manifestations: particle acceleration, mass and magnetic-field eruption, atmospheric heating, and the subsequent emission of radiation as solar flares. To explain and ultimately predict these geoeffective events, the heliophysics community requires a comprehensive understanding of the processes that transform and distribute stored magnetic energy into other forms, including the broadband radiative enhancement that characterises flares.

SOLAR AND SPACE PHYSICS (HELIOPHYSICS) DECADAL SURVEY:
SOLAR FLARE ENERGY PARTITIONING AND TRANSPORT

MAIN RECOMMENDATIONS

- Continue and expand upon use of large scale collaborative efforts:
  - Commit significant amounts of research and analysis (R&A) funds to expand efforts similar to NASA DRIVE centers, that aim to bring together large groups of scientists to tackle major problems. This has proven to be successful in bringing together observers, modellers and theorists.
  - Encourage the use of both NASA and NSF assets in R&A solicitations within each body. It is important to be able to leverage both ground and space based observatories to tackle these problems, particularly in ground based observations fill gaps in space based coverage (and vice versa).
- Obtain simultaneous high-resolution (E)UV/Optical/IR, Hard X-ray, and γ observations:

Soft X-ray	(E)UV/Optical/IR	Other
1-12 keV (large temperature coverage, ~2 - > 25MK)	Spectra over large temperature range to track mass motions	Coronal magnetic field strengths
< 1s cadence	< 1s cadence	Chromospheric magnetic field strengths
<0.3 keV FWHM to resolve spectral lines	< 1 km/s spectral resolution	Use CMOS-detectors to avoid pixel bleeding if saturation does occur
Active region scale FOV	Short exposure times to avoid saturation (e.g. ms in EUV)	
Spatially resolved SXR sources (i.e. not Sun-as-a-Star)	<1″ resolution over active region scale FOV	

Figure 1: *Our main recommendations for tackling the problems of energy transport and partitioning during the gradual phase of solar flares.*

This white paper discusses energy transport during the gradual phase of flares. We discuss the impulsive phase in a related white paper.

The gradual phase follows the impulsive phase, which is the initial dramatic release and transport of flare energy, typically associated with the presence of hard X-rays (HXR). HXR emission is the signature of accelerated nonthermal electrons, produced mainly from their bombardment of the dense chromosphere. The precipitation of these accelerated nonthermal electrons is thought to be the primary vehicle by which flare energy is transported from the coronal release site throughout the Sun's atmosphere. This is followed by the longer duration gradual phase, during which SXR/(E)UV/optical/IR flare emission decays and there is a general absence of HXR emission (since nonthermal electron bombardment of the lower atmosphere has ceased). There may also be significant energy release and deposition during the gradual phase, but not transported via the nonthermal particles that we typically associate with flares.

While much of flare research concentrates on the impulsive phase, the gradual phase is also a topic of hot debate and scientific intrigue as it exhibits some serious discrepancies between models/theory and observations. Namely, the cooling times predicted by radiation-hydrodynamic codes during the gradual phase of flares are significantly shorter than flare observations suggest, by an order of magnitude or greater. We must ask, then, *what sustains the observed gradual phase, and what physical processes are missing from our models?* This is an important mystery to solve not only in order to obtain a fuller understanding of the energetics of solar flares, but due to geo-effective impacts of the gradual phase. The D-region of the Earth's ionosphere is significantly impacted by the excessive X-ray emission from solar flares which can result in radio blackouts, particularly at frequencies used in high-frequency radio communications. These blackouts can extend for several hours into the gradual phase of a flare, particularly during long-duration events when X-ray fluxes can consistently stay elevated (M- or even X-class levels) for several hours [e.g. 1].

Flare (radiation-)hydrodynamic simulations are usually driven by an intense, impulsive energy injection into an individual flux tube, the magnitudes and timescales of which are constrained by observations of, e.g., HXRs or optical/UV lightcurves. High-resolution spatiotemporal observations of optical/UV chromospheric flare sources indicate that this injection time is short, on the order of 10 – 20 s [e.g., 2, 3]. Following cessation of this energy input, the atmosphere should undergo rapid cooling due to large conductive heat fluxes exiting the flare-heated plasma [e.g., 4–6]. This occurs for both individual flare sources (that is, footpoints, or individual loops) and the large-scale flare arcade (integrated over the field-of-view, or summed over sub-regions). In contrast, during the observed flare gradual phase the coronal flare emission can be elevated for several tens of minutes to hours [7–11], compared to only a few minutes in simulations. In the dense chromosphere, observed UV and optical sources have cooling timescales on the order of several to tens of minutes [3, 12–14], compared to only several tens to ~hundred seconds in simulations. Likely related, the duration of chromospheric ablations and condensations exhibit a similar discrepancy, with observed mass flows (inferred from Doppler shifts of spectral lines) persisting significantly longer than models can reproduce [3–5]. Since both individual sources and the global flare exhibit longer-than-predicted cooling timescales, the resolution is unlikely to just be the activation of new loops along the flare arcade [e.g., 15].

It has been suggested that *energy release continues in the gradual phase, with magnitude comparable to that deposited in the impulsive phase* [e.g. 8, 9]. However, the origin and transport mechanism of this post-impulsive phase energy is largely unknown. In the next decade, we must aim to determine what sustains the flare gradual phase and what ingredients are missing in flare models. Specifically, efforts should aim

(1) **To determine the magnitude, source, and transport mechanisms of energy deposition during the gradual phase**;

(2) **To improve our modelling and observational constraints of the gradual phase, and our understanding of important plasma physical processes such as turbulence and nonlocal effects (which have far reaching applications beyond flares)**.

2 Post-Impulsive Phase Heating

Energy deposition and associated plasma heating during the gradual phase could be a significant fraction of the total energy released during flares, yet the character of this post-impulsive phase heating is poorly understood. Not accounting for this is a serious deficiency with our understanding of SEEs, so a concerted effort must be made to determine how much energy is required to sustain the gradual phase, and to identify the responsible mechanisms. This can be achieved through a combination of observations and modelling.

Recent work combining UV and EUV images of C class flares and 0D (loop averaged) EBTEL [16, 17] modelling have shown interesting results [8, 9]. Those studies assume that flare loops or threads formed by magnetic reconnection are magnetically line-tied during the flare, so heating events can be spatially resolved, to the extent limited by instrumental capabilities, at the lower-atmosphere footpoints of these loops. A technique called UV Footpoint Calorimeter [UFC; 18] is used to infer heating rates (magnitudes and temporal profiles) in flare loops from the brightness signatures – spatially resolved optical or UV light curves – in the chromosphere or transition region. Then individual flare loops are modelled, each energized with an intense impulsive heating episode, followed by a slow and weaker heating tail lasting several minutes, as manifested in the light curves of their footpoints. To account for the observed temporal evolution of the flare EUV emission at different temperatures, namely, the long-duration emission at 6-10 MK and the large delay of the 1-2 MK emission, 60% of flare energy had to be deposited in the short impulsive phase, with the remaining 40% deposited over a span of approximately 20 minutes.

Multi-threaded modelling of flare arcades [19] found that including effects of loop length and ribbon separation could recover some observed flare properties, including the duration of the gradual soft X-ray (SXR) emission. Follow-up simulations using EBTEL, which modelled energy deposition onto successive loops through the gradual phase with timescales guided by quasi-periodic pulsations (QPPs, see below), also successfully reproduced flare lifetimes and irradiance [6]. In that work the heating rate was agnostic to the energy-transport mechanism (i.e., electron beams were not modelled), with no distinction between impulsive and gradual phase energy-transport mechanisms. Since there is no observational evidence of hard X-ray emission (and thus accelerated particles) after the impulsive phase, we are still left with the question of what is depositing energy onto those new threads/loops during the gradual phase. If more reconnection occurs, into what forms is that energy converted and transported?

Progress on this topic demands an accurate measurement of the energetic requirements with models capable of simulating the injection and transport of flare energy via nonthermal particles and the subsequent radiative hydrodynamic evolution of the atmosphere, including nonlocal and turbulent suppression of conduction (see below). Moving away from the 0D approach will allow the spatial distribution of heating to be studied, with more realistic radiative and conductive cooling. The character (magnitude and temporal profile) of post-impulsive phase energy deposition can be ascertained from comparing those models with observations.

Whereas the UFC experiments took advantage of spatially resolved and multi-wavelength observations of flares to provide first-order estimates of flare heating rates, and revealed the necessity for prolonged heating, they cannot diagnose heating mechanisms. Learning from the UFC experiment, a successful advanced physical model would incorporate the physics of reconnection energy release and conversion, treat the corona and the lower atmosphere consistently and coherently, and be rigorously constrained by observations.

Reconnection Driven Current Filamentation [RDCF; 20] is a potential process for prolonged heating in flare arcades. RDCF occurs when multiple layers of steep magnetic-field gradients (current sheets) form between post-reconnection flux tubes, e.g., when plasmoids merge with the top of the flare arcade, or when the reconnection sites are distributed at random heights in the flare current sheet. This process could slowly heat the arcade into the gradual phase.

Observations indicate that reconnection at the flare current sheet often involves the formation of plasmoids. These plasmoids propagate to the ends of the sheet and are absorbed into either the flare arcade or the erupting CME. Magnetic energy is released during the absorption and heats the plasma. The entire process of propagation and absorption may happen quickly early in the impulsive phase. At later times, when the current sheet is longer and the forces that expel the plasmoids are weaker, the process may be considerably slower. This could contribute to gradual phase heating.

Following the effects of flare loop retraction, [8] suggested several other gradual phase heating mechanisms to investigate. Newly-reconnected loops release energy as they retract [21, 22], which has been modelled using the `DEFT` and `PREFT` codes [23, 24]. If retracting loops receive resistance from lower-lying loops, slow shocks can be generated, resulting in heating over longer timescales [25, 26]. If loops do not reach their lowest energy state following impulsive energy release, they may continue to release energy via Joule dissipation, undergoing slow reconnection. Finally, the generation of magnetohydrodynamic (MHD) waves and their damping might last several tens of minutes [27]. Recent work by [28] used the PREFT code to investigate the effects of turbulent Alfvén waves as they were generated along a drag-impeded retracting flux tube [29]. While the dissipation of MHD turbulence was able to produce prolonged heating on the order of tens of minutes for a single-flux tube, the model remains to be constrained by observation. Increased spectrographic capabilities across many high-temperature lines in the corona would be able to diagnose the non-thermal line broadenings due to turbulence, providing a critical constraint for models with turbulent transport and heating. These processes should continue to be modelled, and the energy released by each mechanism should be compared to the observed gradual-phase requirements. A full treatment will require going beyond 1D in hydrodynamic models, and will require 2D/3D flare MHD codes.

To derive effective observational constraints on these models, we need unsaturated, high cadence, high spatial resolution images covering a broad temperature range of flare sources, measurements of loop length (and ideally loop geometry), and the timescale between successive loop activations. During the impulsive phase, chromospheric material that flows up into the corona (chromospheric ablation) can be diagnosed by spectroscopic observations. For example, the Doppler shifts of the Fe XXI 1354.1 Å line (forming at ~ 11 MK) from thousands of pixels in a single flare were found to be remarkably consistent: the narrow distribution slowed from peak shift back to rest over several minutes [2]. When modelled, however, this Doppler shift persists only as long as energy is injected, so there is no gradual-phase Doppler shift within each pixel [4]. The mechanism(s) by which continued energy deposition takes place must be able to reproduce such observations.

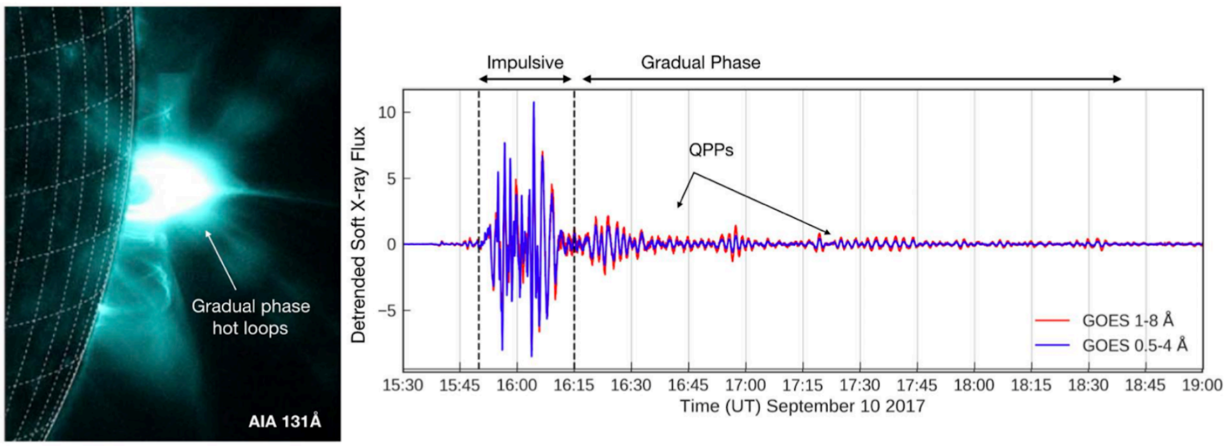

Figure 2: *An example of QPPs in the gradual phase of a solar flare. The image shows SDO/AIA 131Å emission, where hot ($T \sim 10$ MK) flare loops are present in the gradual phase. During the gradual phase QPPs persist for many hours, shown for the GOES soft X-ray channels. Adapted from [30].*

The presence of QPPs in the emission from flares provides crucial information regarding energy-release timescales and heating processes [31]. While QPPs are most often prominently identified during the impulsive phase in emission associated with nonthermal particle acceleration, small-amplitude SXR QPPs associated with the hot thermal phase can extend late into the gradual phase [32], continuing for a significant period of time after the last detectable signatures of particle acceleration [30]. Figure 2 illustrates the presence of QPPs in the gradual phase of a long-duration flare persisting for hours after the impulsive phase. The underlying mechanism of QPPs is debated, but it is generally agreed that they are driven by either MHD waves or repetitive (or bursty) reconnection [31, 33]. Both mechanisms depend on properties of the flare reconnection region and the acceleration sites, and thus are directly associated with flare energy-release processes. Following the recent identification of gradual-phase QPPs, many questions arise about the nature of these pulsations, their relation to their impulsive-phase counterparts, and whether they are signatures of extended energy release and heating, given that they are prominently identified in the hottest EUV channels and SXR observations. To use the observational signatures (amplitude and period) of gradual-phase QPPs to identify the energy release process, we must identify and locate the mechanism(s) responsible. These small-amplitude QPPs need to be spatially and temporally resolved in SXR and EUV images with high time cadence, on the order of seconds. Crucially, in order to identify pixel locations of the QPPs, which occur in the brightest regions, these images must not be saturated. What is required to identify the locations of the QPPs, and hence the potential heating locations, are EUV and SXR imaging instruments that are specifically flare-designed with rapid cadence and short exposure, and an exposure control that does not vary much over the flare.

3 Turbulence and Suppressing Thermal Conduction

Flare loops cool primarily through radiation and conduction. To properly assess the need for energy deposition in the gradual phase, we must ensure that important plasma physics effects are included in our models, and that detailed observations are used to estimate the magnitude of their impact. For example, the suppression of thermal conduction via nonlocal effects and turbulent scattering would slow the conductive cooling substantially, lengthening the gradual phase in simulations.

Classical Spitzer-Härm conduction is essentially a collisional process. When the collisional mean free path (MFP) for the electrons responsible for carrying the heat flux is long compared to the scale of the temperature gradient, then nonlocal heat transport can be important [34]. During solar flares steep temperature gradients routinely form through the corona and in shocks in the chromosphere. Turbulence is also present (potentially from Alfvén waves produced during magnetic reconnection, as discussed above), leading to turbulent scattering and a further reduction of the heat flux [35, 36]. Accounting for both effects [36–40] was found to produce a heat flux significantly smaller that than predicted by Spitzer-Härm conduction. Experiments using the `EBTEL` code to model flaring coronal loops [40] showed that reducing the heat flux resulted in cooling timescales more consistent with observations. Given the significant impacts that nonlocal effects and turbulent scattering will have on both the impulsive- and gradual-phase dynamics, these effects should be incorporated into state-of-the-art flare radiation-hydrodynamic models to properly account for nonlocal effects (and in MHD models that include thermodynamics). A convenient method to incorporate both nonlocal and turbulent effects was introduced recently by [36].

Recently [41] implemented suppression of thermal conduction by nonlocal effects and turbulence into the RADYN radiation-hydrodynamics code, and performed a parameter study in which the suppression factor was varied. They found that simulations with reduced heat flux predicted slow bulk flows, less intense lines spectral emission, and longer cooling times. [41] found that a suppression factor between 0.3-0.5 was required to produce a temperature vs velocity stratification consistent with the observational results of [42, 43]. They also use the inferred turbulent mean free path to broaden spectral lines, again finding more consistent results when comparing with [42, 43]. This latter point suggests that the observed nonthermal widths from spectral lines forming at different temperatures can place constraints on the turbulence mean free path, and thus on the amount of heat flux suppression that is present.

Numerical experiments that cover the relevant parameter space of turbulent MFP length and spectral index should be performed, building upon the efforts of [40] and [41]. The aim is to determine the most likely values of those parameters and the magnitude of suppression of conduction, with predicted peak temperatures and cooling times compared to observations of those quantities. An estimate of the turbulent mean free path length was calculated using observations of the variation of hard X-ray source size with energy [44], and the kinetic energy of turbulent motions (but not its spectrum) has been estimated using a combination of X-ray and EUV spectroscopy [35]. Future observations should aim to determine both the turbulent MFP and the turbulence spectrum of fluctuations of the magnetic field present in flares, ideally simultaneously. These quantities should be measured from multiple heights spanning chromosphere to corona (thus spanning multiple temperature regimes), and will require simultaneous high spatial resolution hard X-ray observations and (E)UV (arcsecond or better), and high spectral resolution (E)UV spectroscopy (a few mÅ or better) to observe nonthermal line widths [e.g., 45]. Estimating the magnitude of suppression from observations is also possible [46]. There, slow-mode waves were observed in a flaring coronal loop, and the phase shift between perturbations of temperature and electron density was obtained. From the values measured, it was suggested that thermal conduction was reduced from the classical value, and that this effect grew with temperature. In concert with observations, serious efforts should be spent developing self-consistent models of flares that include MHD turbulence (or other sources of) and their effects on plasma dynamics.

Through resolving the serious problem of the gradual-phase energy budget, we will also learn about turbulence in the solar atmosphere at a range of scales. Thus we can probe fundamental plasma physics processes at work in the Sun that will also be at play (on different scales) throughout the heliosphere, with far-reaching consequences beyond governing the flare gradual phase. Turbulence, for example, could play a role in the heating of the corona and acceleration of the solar wind [47]. The ubiquitous conversion of magnetic and kinetic energy to heating in the solar atmosphere is undoubtedly impacted by turbulence. Nonlocal heat transport also affects the formation of the transition region, and the flow of mass and energy between the chromosphere to corona.

References

[1] Redmon, R. J., et al. 2018, Space Weather, 16, 1190, doi:10.1029/2018SW001897
[2] Graham, D. R. & Cauzzi, G. 2015, ApJL, 807, L22, doi:10.1088/2041-8205/807/2/L22
[3] Graham, D. R., et al. 2020, ApJ, 895, 6, doi:10.3847/1538-4357/ab88ad
[4] Kerr, G. S., et al. 2020, ApJ, 900, 18, doi:10.3847/1538-4357/abaa46
[5] Reep, J. W., et al. 2018, ApJ, 856, 149, doi:10.3847/1538-4357/aab273
[6] Reep, J. W., et al. 2020, ApJ, 895, 30, doi:10.3847/1538-4357/ab89a0
[7] Russell, A. J. B. & Fletcher, L. 2013, ApJ, 765, 81, doi:10.1088/0004-637X/765/2/81
[8] Qiu, J. & Longcope, D. W. 2016, ApJ, 820, 14, doi:10.3847/0004-637X/820/1/14
[9] Zhu, C., et al. 2018, ApJ, 856, 27, doi:10.3847/1538-4357/aaad10
[10] Ryan, D. F., et al. 2012, ApJS, 202, 11, doi:10.1088/0067-0049/202/2/11
[11] Ryan, D. F., et al. 2013, ApJ, 778, 68, doi:10.1088/0004-637X/778/1/68
[12] Cheng, J. X., et al. 2012, ApJ, 744, 48, doi:10.1088/0004-637X/744/1/48
[13] Qiu, J., et al. 2010, ApJ, 725, 319, doi:10.1088/0004-637X/725/1/319
[14] Kawate, T., et al. 2016, ApJ, 833, 50, doi:10.3847/1538-4357/833/1/50
[15] Dere, K. P. & Cook, J. W. 1979, ApJ, 229, 772, doi:10.1086/157013
[16] Klimchuk, J. A., et al. 2008, ApJ, 682, 1351, doi:10.1086/589426
[17] Cargill, P. J., et al. 2012, ApJ, 752, 161, doi:10.1088/0004-637X/752/2/161
[18] Qiu, J. 2021, ApJ, 909, 99, doi:10.3847/1538-4357/abe0b3
[19] Reep, J. W. & Toriumi, S. 2017, ApJ, 851, 4, doi:10.3847/1538-4357/aa96fe
[20] Karpen, J. T., et al. 1996, ApJL, 460, L73, doi:10.1086/309965
[21] Longcope, D. W., et al. 2009, ApJL, 690, L18, doi:10.1088/0004-637X/690/1/L18
[22] Forbes, T. G. & Acton, L. W. 1996, ApJ, 459, 330, doi:10.1086/176896
[23] Guidoni, S. E. & Longcope, D. W. 2010, ApJ, 718, 1476, doi:10.1088/0004-637X/718/2/1476
[24] Longcope, D. W. & Klimchuk, J. A. 2015, ApJ, 813, 131, doi:10.1088/0004-637X/813/2/131
[25] Cargill, P. J. & Priest, E. R. 1982, Sol. Phys., 76, 357, doi:10.1007/BF00170991
[26] Cargill, P. J. & Priest, E. R. 1983, ApJ, 266, 383, doi:10.1086/160786
[27] Wang, T. 2011, Space Science Rev., 158, 397, doi:10.1007/s11214-010-9716-1
[28] Ashfield IV, W. & Longcope, D. 2022, *In preparation*
[29] Unverferth, J. & Longcope, D. 2021, ApJ, 923, 248, doi:10.3847/1538-4357/ac312e
[30] Hayes, L. A., et al. 2019, ApJ, 875, 33
[31] Nakariakov, V. M. & Melnikov, V. F. 2009, Space Science Rev., 149, 119, doi:10.1007/s11214-009-9536-3
[32] Dennis, B. R., et al. 2017, ApJ, 836, 84
[33] McLaughlin, J. A., et al. 2018, Space Science Rev., 214, 45, doi:10.1007/s11214-018-0478-5
[34] Karpen, J. T. & DeVore, C. R. 1987, ApJ, 320, 904, doi:10.1086/165608
[35] Kontar, E. P., et al. 2017, Phys. Rev. Letters, 118, 155101, doi:10.1103/PhysRevLett.118.155101
[36] Emslie, A. G. & Bian, N. H. 2018, ApJ, 865, 67, doi:10.3847/1538-4357/aad961
[37] Bian, N. H., et al. 2016, ApJ, 824, 78, doi:10.3847/0004-637X/824/2/78
[38] Bian, N. H., et al. 2016, ApJ, 833, 76, doi:10.3847/1538-4357/833/1/76
[39] Bian, N. H., et al. 2017, ApJ, 835, 262, doi:10.3847/1538-4357/835/2/262
[40] Bian, N., et al. 2018, ApJ, 852, 127, doi:10.3847/1538-4357/aa9f29
[41] Allred, J. C., et al. 2022, ApJ, 931, 60, doi:10.3847/1538-4357/ac69e8
[42] Milligan, R. O. & Dennis, B. R. 2009, ApJ, 699, 968, doi:10.1088/0004-637X/699/2/968

[43] Milligan, R. O. 2011, ApJ, 740, 70, doi:10.1088/0004-637X/740/2/70
[44] Kontar, E. P., et al. 2014, ApJ, 780, 176, doi:10.1088/0004-637X/780/2/176
[45] Jeffrey, N. L. S., et al. 2018, Science Advances, 4, 2794, doi:10.1126/sciadv.aav2794
[46] Wang, T., et al. 2015, ApJL, 811, L13, doi:10.1088/2041-8205/811/1/L13
[47] Cranmer, S. R., et al. 2015, Phil. Trans. of the Royal Soc. Lon. A, 373, 20140148, doi:10.1098/rsta.2014.0148