Towards a Physical Understanding of Tidal Disruption Events

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Final Report

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Abstract

Tidal Disruption Events (TDEs) have the potential to unlock physical understanding of many extreme astrophysical processes and the demographics of black holes. We are now entering the era of multi-mission all-sky monitoring in which we are detecting tens to (imminently) hundreds of TDEs per year, the accurate interpretation of which necessitates an overhaul of our modeling of TDEs. This is the motivation for our program.

Over our four week program we made significant progress in several areas: 1) observations of TDEs have now expanded into the radio and infrared, and new models that take advantage of this new wavelength regime were developed; 2) we explored the unexpected affinity of TDEs with post-starburst galaxies and several new collaborations formed to investigate this, 3) while TDEs were originally predicted to be X-ray bright, a population has been discovered in the optical and UV, and we discussed and revised current models for the origin of this emission; a new model for the ``plateau'' emission, which is built off the classic disc model for TDEs, was also discussed and implemented to explain the late-time emission from TDEs; 4) quasi-periodic eruptions, being an entirely new type of extragalactic and nuclear transient, were demonstrated to be directly linked to TDEs, which fostered extensive discussion of the theoretical modeling of these systems. We elaborate on the specifics of these advances below.

Additionally, we hosted and organized the annual KITP teacher's conference, at which two of the four program organizers delivered talks; based on a feedback survey it was well received by those in attendance. We also developed an action plan for a community-driven hosting service for TDE related data products and recruited new developers and beta testers. This effort is on track to have a preliminary version of the TDE data catalog ready by the end of 2024.

1. Program goals and progress toward those goals

The overarching goal of this program was to bring together theorists and observers to stimulate collaborations that lead to new research efforts, thereby improving our understanding of the physics of TDEs. The 4-week program began with a Scientific Conference devoted to the latest developments in TDE research. The conference included on the order of 100 participants, 46 of whom presented their work. This conference really set the scene for the remainder of the program as it brought all the program participants up to speed on the latest developments and provided the environment for developing new ideas that could be discussed at the program. Many of the observational highlights were completely new and catalyzed additional research

that continued throughout the remainder of the program (see additional details in Section 4 below).

On the Saturday of the first week we held a Teacher's Conference. The conference had roughly 50 high school and community college physics teachers and professors from around the country, who came to learn about the research being done at our program and the physics we implement to understand TDEs. Overall the teacher's conference was very well received according to feedback surveys.

Over the remaining 3 weeks of the program we held an active and well-attended schedule of talks and discussions. These focussed on key areas of TDE research. Key topics covered include (1) the optical and X-ray properties of TDEs, (2) radiation production mechanisms in TDEs, (3) numerical modeling of TDEs and associated errors, (4) new surveys for discovery of TDEs, (5) radio properties of TDEs, (6) the host galaxy puzzle of TDEs and the post-starburst galaxy preference, (7) the nature of super-Eddington accretion and (8) the progenitor systems for quasi-periodic eruptions (QPEs) and repeating nuclear transients (RNTs). These scheduled sessions served to kick start discussions amongst focussed groups of participants who were then well placed to make progress.

The original program goals, as envisioned by the coordinators during the conception of the program, were:

1. Developing quantitative predictions from theoretical models so that they can be directly confronted with observational data, e.g., predicting from simulation dynamics the optical lightcurve of the event rather than simply measuring the fallback rate.
2. Developing data analysis techniques that facilitate robust statistical comparison between multi-band lightcurves and theoretical predictions to allow a detailed understanding of the estimated parameters of each event and the errors associated with such estimations.
3. Using theoretical models and observed data to build a picture of TDE demographics, including black hole mass estimates, host galaxy properties, and stellar properties (mass, age, metallicity, rotation).
4. Creating and using theoretical predictions for TDE properties (e.g., optical and X-ray lightcurves) to revise current observing strategies (e.g., cadence requirements for accurate parameter estimation from the lightcurves) and inform future mission design.

During the short program we made significant progress towards these goals, and have continued to make progress afterwards via new collaborations that were forged at the program. TDEs are a fast paced topic with regular injections of impetus from new and confounding observational results. A major theme that has arisen between our first discussions of the idea for a program and the time at which the program took place is the idea of repeating partial TDEs and the possibility that they are responsible for producing the QPEs and RNTs that we now observe alongside standard TDEs. We therefore took the opportunity to exploit the flexibility of KITP programs to include this aspect as a key part of the program. In this context we detail a representative subset of topics and the progress made towards each at the program:

Host galaxies of TDEs

Recent studies of the host galaxies of TDEs have found different trends for TDEs identified in different wavelengths. We had several stimulating presentations at the conference and program describing new results in this space. During program discussions, it has become clear that there is not a simple explanation for this difference from dust in the host galaxy, contamination from AGN, or other selection biases. We discussed useful follow-up observations that will address these questions, especially detailed follow-up of radio-selected TDEs and dust modeling of host galaxies. In attempting to complete the census of TDEs, it has become clear that properly accounting for TDEs in systems with persistent or pre-existing gas accretion disks (AGN) will be necessary. Program discussions led to collaborative work on Seyfert activity and extended emission line regions from past AGN activity in TDE and QPE hosts.

Radio observations of TDEs

Both the scientific conference and the program illustrated the dramatic progress in radio studies of TDEs that has been made in the past few years, with numerous conference talks and one discussion session during the program exclusively dedicated to radio observations and their interpretation. Additional program discussion sessions also incorporated this topic. The recent discovery that some TDEs can power brightening radio emission ~years post-disruption was a point of particular interest; several new theories to explain this phenomenon were discussed, ranging from off-axis jets to a variable density profile around the host supermassive black hole. The possible connections between state changes in the accretion flow and the launch of radio-producing outflows were also discussed and analogies were considered to accretion transitions observed around the stellar mass black holes that power X-ray binaries. The conference also enabled new discussions and coordinations between previously separate groups studying TDEs in the radio; new connections were forged between scientists focused on blindly detecting radio TDEs in wide-field radio surveys and those focused on following up TDEs detected at other wavelengths.

Disc formation and accretion

One of the most challenging aspects of modeling TDEs is the process of disc formation. This is challenging because the returning stream is both extremely thin and elongated, meaning that hydrodynamical models require very high spatial resolution. A long-standing ingredient in the disc formation process is the concept of “nozzle shocks” which are purported to dissipate kinetic energy in the stream as it passes through pericentre. Through repeated pericentre passages with such dissipation the stream could in principle release enough energy to circularize into a disc. However, during the meeting there was significant discussion of the role of numerical viscosity in driving this dissipation in the simulations reported in the literature to date. Comparisons were made with analytical models that show very little dissipation in comparison to the numerical models. These discussions have prompted several collaborations that aim to determine exactly how important the nozzle shocks are, and whether or not they affect the stream orbit significantly before stream-stream collisions occur. Another major question in TDE physics is whether the energy released from the event originates from collisions by the stream (with either itself or the disc) or whether the energy is predominantly accretion energy released once a disc has formed. High resolution general relativistic simulations were presented that

strongly favor the accretion energy scenario, and provided a good fit to the optical properties of TDE lightcurves. These theoretical discussions led to collaborations among various groups to further investigate the nature of disc formation at even higher resolution, and features of the simulated lightcurves yielded observables that are testable by current and future observations; a number of collaborations were formed to enact these tests.

QPEs and repeating partial disruptions

Quasi-periodic eruptions are intense (>~ 1-2 orders of magnitude above background) bursts of soft (~ 0.1-1 keV) and thermal X-ray emission from the nuclei of galaxies that repeat on timescales of hours to ~ days (duty cycle ~ 10%). These eruptions have no observable emission at other wavelengths, and there have now been a handful (5-10) of such systems observed and characterized. There have also been much longer (both in duration and recurrence timescale) and repeating electromagnetic outbursts from galactic nuclei, the individual outbursts of which resemble TDEs (i.e., they possess at least optical emission that rises and fades on timescales of ~ weeks). The latter have been termed repeating nuclear transients, and there are only a few such events known.

These systems were discovered between the time we submitted the application for our program and its start, and were discussed extensively during the conference; perhaps the most exciting result was the indisputable demonstration of the link between TDEs and QPEs, as the transient AT2019qiz – a standard optical/UV-bright TDE – was found to undergo QPE outbursts ~ years after the original detection. There was also work presented on AT2022dbl, which was a standard optical/UV TDE that brightened a second time – with an almost identical flare – roughly 700 days following the first outburst. These detections sparked significant and detailed discussions on the modeling of both of these types of systems, with many new collaborations fostered and papers written and submitted (see Section 2 below).

Overall, it is our impression that this program has both propelled the field forwards in terms of its ability to understand TDEs and take advantage of the incoming volume of data in this area, and led to a large number of new collaborations formed between participants who – partially due to the era of restricted travel due to Covid and the fact that this is a relatively new field with an anomalously young community of researchers – had never previously met or discussed research together. For example, one of our participants commented that the program meant that the community was “able to revitalize the TDE working group for Rubin Observatory’s upcoming LSST survey, which I and several others joined during the meeting. We are planning additional telecons to get this work up and running, which is very timely given the imminent start of the survey.”

One of the participants commented that “The number, variety and depth of open questions in the field, together with the progress being made, made clear to me during the program, have convinced me to submit my next ERC grant proposal on TDEs.” This is one of several people who mentioned that they will prepare and submit ERC grant proposals based on discussions and ideas developed at this meeting.

We are grateful to one of the participants for the following comment: “Let me conclude by saying that this was by far the “youngest” program I have attended, since the coordinators as well as the speakers and attendees of both program and conference were mostly under 40 years old. This is great, and it reflects the energy of this new field, still the organisers should still be praised for prioritising talk slots at the conference for PhD students and young postdocs. Gender balance was also the best I have seen so far at a KITP program. Hence again this should be seen as a great achievement of the organisers, really well done! I am organising a workshop on astrophysical black holes next Spring in the Alps, with a couple of senior colleagues who were at this program, and I can only say that we will struggle to match the standard set forth by this program.”

The full impact of this cross-fertilisation of ideas shared during the program is yet to be realized, but based on the community feedback and individual participant reports we know this program was a great success both scientifically and for the careers of many junior colleagues.

Finally, we want to express our gratitude to the KITP, its staff, and its funders, for the opportunity to lead this program in such a world-class and well-run environment. It will stand out as a career highlight for so many, and the online resources created by the program will serve as a fantastic launching point for new entrants into this field.

2. Projects, collaborations, and manuscripts that resulted from the program

Following the program our participants completed reports on their time at KITP. Many of the participants mentioned either submitting or planning to submit future funding bids on this topic. Several participants (Coughlin, Nicholl, Mockler, and Hammerstein) worked on and submitted a chapter to the Encyclopedia of Astrophysics on tidal disruption events, which is a formalized collection of scientific ``snippets'' designed to educate newcomers on the fundamentals of astronomical subfields. The participants also detailed a large number of new collaborations and submitted papers that were facilitated by the program. We list these here:

New projects / collaborations

- New collaboration on the dynamics of TDE debris streams by Zack Andalman, Eliot Quataert, Eric Coughlin and Chris Nixon
- One of our participants “organized an informal session the second week which focused on updating the woeful Wikipedia articles on TDEs, which were completely rehauled and updated by the experts in the field present.”
- Yvette Cendes and Tatsuya Matsumoto worked on a paper that is to be submitted on the TDE AT2018hyz
- Rob Eyles-Ferris worked on a paper in collaboration with Chris Nixon and Eric Coughlin on an unusual TDE LSXPS J0956
- Graduate student Nick Earl worked with Decker French, Wenbin Lu, Megan Masterson and Erin Kara on disk interpretations of photometry and new data on a concurrent IR flare to the observed optical flare

- A new collaboration between Decker French, Jean Somalwar and Vikram Ravi on age-dating TDE host galaxies using archival and new host galaxy data will likely result in publications led by Jean Somalwar and graduate student Margaret Shepherd.
- Decker French, Chris Nixon and Ann Zabludoff began a collaboration on TDE rates in Seyfert galaxies, and during the program Decker was able to compile archival data to test the significance of TDE overrepresentation in Seyfert II galaxies, broken down by host galaxy type.
- A new collaboration between Decker French, Ben Shappee and Jason Hinkle, will likely result in a publication using UV photometry of likely TDE host galaxies to constrain the maximum duration of the UV-bright disk phase.
- A new collaboration between Decker French, Chris Nixon and Eric Coughlin on using host galaxy observations of jetted TDEs to constrain likely disrupted star masses. They will propose for new observations that will hopefully lead to a paper.
- Adelle Goodwin finalised a manuscript on the TDE AT2022dsb, including an optical lightcurve contributed by one of the program participants.
- Adelle Goodwin began a paper presenting observations of a second radio flare from the TDE AT2020vwl in collaboration with theorists at the program who provided 3 theoretical scenarios that could explain the flare.
- Kimitake Hayasaki has a paper in preparation and in collaboration with Daniel Price, Fangyi Hu, and Adelle Goodwin, that focuses on modeling the radio-emitting region by Smoothed Particle Hydrodynamics (SPH) simulations, aiming to enhance the theoretical framework and predictive models for these radio TDEs.
- Kimitake Hayasaki has another paper, currently in preparation, that details the findings presented in his talk, "Non-relativistic disk-wind-driven expanding radio-emitting shell in tidal disruption events." This paper will comprehensively analyze the mechanisms driving the observed radio emissions and their implications for radio TDEs by incorporating thermal energy and SMBH gravity.
- Kimitake Hayasaki began working with Andrew Mummery on a project examining the black hole mass observable through TDEs. Another exciting collaboration with Lucio Mayer explores the tidal disruption of stars by SMBH binaries, which could reveal new insights into the dynamics of binary black hole systems and their observational signatures.
- Itai Linial revised his upcoming paper titled “Tidal Disruption of a Star on a Nearly Circular Orbit” based on discussions at the program.
- Lucio Mayer and Adelle Goodwin started a collaboration to submit a proposal for observations of TDEs in galaxy mergers, to complement simulations.
- Lucio Mayer, Chris Nixon and Eric Coughlin began discussing a collaboration using the new Exascale SPH-EXA code, which Lucio presented at the program, to evolve at much higher resolution the early-stage simulations of TDEs.
- Lucio Mayer and Clement Bonnerot discussed a collaboration to demonstrate convergence in the nozzle shock properties in TDE simulations.
- Brian Metzger, Sjoert van Velzen and Andrew Mummery plan to measure the total (i.e., time-integrated) optical/UV output of TDEs at early times, along with the dependence of this quantity on SMBH mass, to constrain the emission model.

- Matt Nicholl led the development of a new strategy to determine the possible range of repetition periods in TDE-QPEs, and will lead applications to get X-ray observations covering all possible periods for all known TDEs. He also designed a Hubble program to test for variability in the UV, which will be submitted at the next mid-cycle deadline.
- Matt Nicholl plans to lead a broad community proposal for the Hubble Space Telescope to address key questions related to host galaxies of TDEs. Feedback received from colleagues at the program will greatly improve the proposal and the chances of it being awarded time.
- Daniel Price and Sara Rastello began a collaboration to implement binary star collisions in the smoothed particle hydrodynamics code PHANTOM.
- Daniel Price, Chris Nixon and Alessia Franchini began work to implement code functionality and setup needed in PHANTOM for simulating stars interacting with AGN discs for simulating quasi-periodic eruptions.
- Daniel Price, Fitz Hu, Adelle Goodwin, Kimi Hayasaki and Re'em Sari worked on a forthcoming paper on radio emission from TDEs
- Daniel Price, Jing-Ze Ma and Selma de Mink discussed a code comparison on convection in stars.
- Daniel Price and Kimitake Hayasaki began discussions on a possible project on radiation hydro effects in tidal disruption event simulations.
- Daniel Price and Chris Nixon began a collaboration to optimize the shock capturing methodology in SPH.
- Eliot Quataert discussed with Itai Linial, Eric Coughlin, and Chris Nixon the breakthrough that, over the last few years, there has been the discovery of very slowly evolving late-time optical-UV emission in nearly every TDE that likely marks the formation of a slowly spreading accretion disk. Previous theoretical work on this problem has not realistically accounted for the transition in disk physics during different phases of this evolution, and it is likely that they will pursue calculations along these lines.
- Sara Rastello has been invited by Prof. Lodato to visit him in Milan to give a talk and continue their collaboration (alongside Elena Rossi) on hydrodynamically simulating micro-TDEs and gravitational-wave emission.
- Sara Rastello will work with Matthew Nicholl and Brenna Mockler on the possible detection of micro-TDEs and the modeling of the TDE light curves.
- Nathan Roth will follow up with Lars Bildsten about what tools are available for obtaining multi-group opacities for rad-hydro calculations related to stellar evolution
- Greg Salvesen intends to work with Elena Rossi & Eric Coughlin on individual S stars orbiting the supermassive black hole in the Galactic center, and assuming their origin is the Hills mechanism, they plan to constrain the progenitor binary systems.
- Greg Salvesen plans to investigate with Andy Mummery the disk-continuum model degeneracy between plunging region emission and black hole spin in the X-ray binary M33 X–7.
- Greg Salvesen discussed with Selma de Mink & Ruggero Valli incorporating observationally informed constraints on supernova kicks and spin-orbit misalignments into binary stellar evolution models to (in)validate individual sub-models. The specific systems they have in mind are the Gaia BHs and MAXI J1820+070.

- Greg Salvesen intends to work with DJ Pasham on very bright and obscured sources that can have a dust-scattered emission component in their X-ray spectrum, on top of the disk continuum component. They discussed trying to determine if these two components (dust vs disk) can be distinguished from their spectra alone. This is important for interpreting NICER observations of such sources because NICER is not an imaging telescope, so cannot detect the usual signature of dust as extended X-ray emission.
- Greg Salvesen worked with Alessia Franchini, who wants to fit her precession model to QPE light curves, with the complication of big gaps in the data. Salvesen has experience with Bayesian inference for parameter estimation and plans to contribute this to the project.
- Greg Salvesen discussed with Nathan Ross an ambition to apply codes developed at their respective national labs (LANL and LLNL) to black hole accretion disk problems. Specifically, they are interested in leveraging their world-leading capabilities in radiation transfer and opacities. They are both hoping to pursue this independently in the near term and possibly as a joint-lab effort in the long term.
- Thomas Wevers worked on a paper in preparation on HST photometry of a QPE and related disk modeling with Muryel Guolo and Andrew Mummery. Future work and collaborations were also initiated, including: an observing proposal submitted with French, Zabludoff and others following discussions described earlier, related to maximising TDE identification in the LSST era; an HST observing proposal in preparation for UV photometry of a QPE (with Nicholl et al.); and an HST observing proposal in preparation for late-time UV photometry of a TDE (with Pasham et al.)
- Kate Alexander and Hannah Dykaar began a collaboration on the TDE AT2022dbl, which will lead to a first-author paper by Hannah.

Submitted papers:

- Wevers & French 2024, in press, https://arxiv.org/abs/2406.02674, “Extended emission line regions in post-starburst galaxies hosting tidal disruption events”.
- Wevers, French, Zabludoff et al. 2024, submitted to ApJ, https://arxiv.org/abs/2406.02678 “Quasi-periodic X- ray eruptions and tidal disruption events prefer similar host galaxies”.
- Metzger, Hui, Cantiello 2024 https://arxiv.org/abs/2407.07955 “Fragmentation in Gravitationally-Unstable Collapsar Disks and Sub-Solar Neutron Star Mergers”
- Nicholl et al. 2024 submitted a Nature paper on the quasi-periodic X-ray eruptions in the TDE AT2019qiz
- Makrygianni, Arcavi, Newsome, Bandopadhyay, Coughlin, Linial, Mockler, Quataert, Nixon et al. submitted to Nature, “The partial tidal disruption of a star on a 700-day orbit around a supermassive black hole”
- Newsome, Arcavi et al. 2024 submitted to ApJ a paper on extreme coronal line emitters
- Price, Liptai, Mandel, Shepherd, Lodato & Levin 2024 https://arxiv.org/abs/2404.09381 “Eddington envelopes: The fate of stars on parabolic orbits tidally disrupted by supermassive black holes”

- Bandopadhyay, Coughlin, Nixon & Pasham https://arxiv.org/abs/2406.03675 “Repeating nuclear transients from repeating partial tidal disruption events: reproducing ASASSN-14ko and AT2020vdq”
- Pasham, Coughlin, Guolo, Wevers, Nixon, Hinkle & Bandopadhyay 2024 https://arxiv.org/abs/2406.18124 “A Potential Second Shutoff from AT2018fyk: An updated Orbital Ephemeris of the Surviving Star under the Repeating Partial Tidal Disruption Event Paradigm”

3. Efforts to achieve participation by underrepresented groups

Our efforts to achieve participation by underrepresented groups started early in the planning process, when choosing a list of key program participants. We were able to invite a balanced number of men and women to participate, as well as a diversity in career stage and science type (observer vs theorist, TDE specialist vs specialist in a related topic). When advertising the program and the conference, we also made efforts to expand beyond our standard networks – in addition to posting the advertisements to institutional mailing lists and slack workspaces, we advertised on the AAS and HEAD mailing lists and on social media (e.g. the facebook group for professional astronomers, which currently has 9.3k members worldwide). This was successful, with participants from 4 continents ultimately participating in the program. Remote participation also facilitated broader participation; three of our junior presenters (two graduate students from India and Australia, one postdoc from Europe who couldn’t get a visa) were able to give well-received conference presentations only thanks to this remote option. The recorded online talks will continue to facilitate the long-lasting global impact of this program and conference.

The TDEs field is overall a very young field, thus, we readily achieved a good balance in career stage for presenters at both the conference and the program sessions held in the weeks afterwards. Many of the most exciting recent discoveries have been made by graduate students and postdocs, so it required very little active management to encourage these younger folks to participate actively after arriving at KITP. Our code of conduct was well-adhered to, providing a comfortable environment for everyone to participate. The organizers are not aware of any conduct violations that occurred during the program.

4. Scientific and programmatic impact of the conference

The first week of our KITP program, April 23 -- 26, was dedicated to a conference, ``Anticipating the Rising Tide of Tidal Disruption Events: Theory and Observations.'' The overall goals of the conference were to set the stage for the coming program, establish our agenda, and get everyone ``up to speed'' on the latest developments in the field, specifically by 1) enabling program participants to present their latest observational and theoretical findings on tidal disruption events (TDEs), and 2) providing non-program-participants (because the program was only 4 weeks we had a very limited number of spots) a means to present their research. The latter served to widen the impact of the program while simultaneously broadening the scientific

content presented at the conference, and also gave junior scientists an opportunity to speak, thus adding to the inclusivity of the KITP.

The conference was an overwhelming success in its implementation and execution, with a total of 120 applicants, 89 of whom attended (i.e., after excluding cancellations). The highlights that served to guide the program and that had substantial impact on the field were: 1) the discovery of commonplace late-time radio emission from TDEs, suggesting either delayed engine activity and/or the interaction of ejecta with the circumnuclear medium of the black hole, 2) the association between TDEs and coronal line-emitter active galactic nuclei, indicating that this type of rare AGN could be seeded by TDE activity, 3) the spectacular affirmation of the connection between quasi-periodic eruptions (QPEs) -- an entirely new phenomenon discovered only in the last ~ 5 years -- and TDEs through the direct detection of QPEs following the TDE AT2019qiz, and 4) the detection of a new class of ``repeating'' TDE, detailed modeling of which could enable distinct insights into black hole properties.

The impact of the conference on the program was as-intended: the observational and theoretical highlights focused our discussion and scientific emphasis for the ensuing three weeks, and enabled more rapid progress to be made in these very timely and exciting areas of time-domain astronomy. The impact on the field was also immediate: the research described in many of the talks have subsequently been submitted for publication in high-impact journals, and the interactions between program participants expedited this process and fostered new collaborations.

5. Suggestions for future programs

Many of the most impactful publications in this field have been led by junior career scientists, especially senior grad students. We had a large number of grad students attend as affiliates, who positively contributed to the workshop and are leading many new projects that emerged from the workshop. However, the process to select affiliates could be smoother, and some miscommunications on the requirements led to one grad student leaving for LA for a week after the conference because of the dates his advisor was available. Future workshops could best allow for the participation of junior career researchers by making the affiliate application process more transparent, and making it clear to outsiders that collaborators (not necessarily the students' advisors) are welcome to be the affiliate's contact while they are at KITP.

We found the KITP program structure to be a good mix of structured discussions/talks and time to work on new projects. Several organizers were new to KITP, having not been to a previous workshop, and it would be helpful to have a cheat sheet with sample program schedules and ideas on how to structure the time well in advance of the program, to help plan. Our speakers and discussion leaders did well, but we would have liked to give participants more time in advance of the program to prepare.