Observing Application

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Proposal ID:	GBT/23A-273
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PI:	Kate Alexander
Type:	Regular
Category:	Gravitational Waves and Energetic Transients
Total time:	17.5

Monitoring the Exceptional Jetted Tidal Disruption Event AT2022cmc

Abstract:

Transient accretion onto a supermassive black hole through the tidal disruption of a stray star offers a unique opportunity to probe the environment around quiescent galactic nuclei and to map the lifecycle of relativistic jets and outflows. In 2011, radio and millimeter observations of the tidal disruption event (TDE) Swift J1644+57 revealed that these dramatic events can power luminous relativistic jets. Nevertheless, observations have revealed that powerful jets in TDEs are extremely rare; despite over a decade of searching, Swift J1644+57 remained the only well-studied jetted TDE until 2022. In this proposal we request continued MUSTANG2 monitoring of the recently discovered transient AT2022cmc, the first TDE observed to launch a powerful relativistic jet in 11 years. The observations proposed here will measure a possible jet break, track the peak of the spectral energy distribution (SED) as it evolves to lower frequencies, and determine the spectral index of the optically thin portion of the SED, uniquely determining the outflow kinetic energy, jet collimation, and the density profile around the SMBH.

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Related Proposals:

GBT22A-459, VLA20B-377

Joint:

Not a Joint Proposal.

Observing type(s):

Continuum, Single Pointing(s), Monitoring

GBT Resources

Name	Group	Frontend & Backend	Setup
m90GHz (Shared Risk)	Monitor_90GHz	Mustang 2 Mustang 2	Number of Banks: 0

Sources

Name	Position		Velocity		Group
AT2022cmc	**Coordinate system**	Equatorial	**Convention**	Radio	Jetted TDE
	Equinox	J2000			
	Right Ascension	13:34:43.207 00:00:00.0	**Ref. frame**	LSRK	
	Declination	+33:13:00.54 00:00:00.0	**Velocity**	0.00	
	Calibrator	No			

Sessions:

Name	Session time (hours)	Repeat	Separation	LST minimum	LST maximum	Elevation minimum
Monitor_TDE	1.75	10	30 day	08:31:07	18:38:19	30

Session Constraints:

Name	Scheduling constraints	Comments
Monitor_TDE	We request observations ~monthly throughout semester 2023A, as permitted by weather and instrument availability. Our cadence is chosen to roughly align with our approved VLA monitoring of this target (but observations can be taken up to 1-2 weeks apart, so no special coordination is required). We also request to avoid observations above 77 degrees elevation (see technical justification).	When possible, we will combine our observations with MUSTANG2 observations from other active programs to minimize overheads.

Session Source/Resource Pairs:

Session name	Source	Resource	Time
Monitor_TDE	AT2022cmc	m90GHz (Shared Risk)	1.75 hour

Plan of dissertation: no

Technical Justification:

Dates:

We request observations seperated by approximently one month. Exact timing is not critical.

Observing time:

We will use the standard MUSTANG2 daisy scans with a radius of 2.5' which is optimal for small sources such as this TDE.

Mapping:

To ensure detection we require a senstivity of 0.1mJy per beam. With the above scanning, MUSTANG2 reaches 56uK per beam in one hour (see https://greenbankobservatory.org/science/gbt-observers/mustang-2/). When rounded up to the nearest 15 minutes (the minimum allocation of GBT time) we will require half an hour on source to reach our sensitivity goal. Absolute calibration will also be very important and past experience indicates this will require an extra half hour.

RFI considerations:

RFI is not a problem at 90GHz

Overhead:

In addition to time for calibration we request 45 minutes in order to get MUSTANG2 setup (receiver change, focusing / OOF, detector bias etc). This is typical of all MUSTANG2 projects. If our observations can follow other MUSTANG2 projects we can give up this time. This time is typical of MUSTANG2 projects.

Joint considerations:

This is not a joint proposal, but our MUSTANG2 observations will be combined with VLA data from our approved monitoring program VLA20B-377 to model AT2022cmc's full spectral energy distribution. Observations taken within 1-2 weeks are sufficient for our science, so we do not require any special coordination between the two observatories.

Novel considerations:

Standard MUSTANG2 data reduction will be used.

Pulsar considerations:

NA

LST Range Justification:

We request our observations be above 30 degrees elevation for atomspheric opacity resons and below 77 degrees elevation due to the poor and rapidly changing beam shapes typically seen above this elevation (which makes calibration problematic).

Monitoring the Exceptional Jetted Tidal Disruption Event AT2022cmc

Summary

Transient accretion onto a supermassive black hole through the tidal disruption of a stray star offers a unique opportunity to probe the environment around quiescent galactic nuclei and to map the lifecycle of relativistic jets and outflows. In 2011, radio and millimeter observations of the tidal disruption event (TDE) Swift J1644+57 revealed that these dramatic events can power luminous relativistic jets [1]. Nevertheless, observations have revealed that powerful jets in TDEs are extremely rare, despite over a decade of searching. Until 2022, Swift J1644+57 remained the *only* well-studied jetted TDE to date. In this proposal we request continued MUSTANG2 monitoring of the recently discovered transient AT2022cmc, the first TDE observed to launch a powerful relativistic jet in 11 years. The observations proposed here will measure a possible jet break, track the peak of the spectral energy distribution (SED) as it evolves to lower frequencies, and determine the spectral index of the optically thin portion of the SED, uniquely determining the outflow kinetic energy, jet collimation, and the density profile around the SMBH.

1. Radio/millimeter Emission in TDEs

When a star passes close to a supermassive black hole (SMBH), tidal forces can overcome the gravitational energy holding the star together. Such tidal disruptions result in some fraction of a star's material being accreted onto the SMBH, temporarily raising the accretion rate by orders of magnitude [2]. The maximum mass fallback rate onto the SMBH can exceed the Eddington limit, potentially launching transient, relativistic (Lorentz factor, $\Gamma \gtrsim 5$) jets or fast ($v \approx 0.1c$) winds [3]. The interaction of these outflows with the ambient environment produces luminous synchrotron emission [4]. Studying the outflows launched during this phase by capturing this synchrotron radiation can provide important insight into the processes by which SMBHs grow and shape the galaxies in which they are embedded [5]. In addition to revealing the energetics of the jets and outflows themselves, radio and millimeter observations allow us to probe the environments near SMBHs at sub-parsec scales, which are otherwise unresolvable for all but the nearest galaxies using other observational techniques [6].

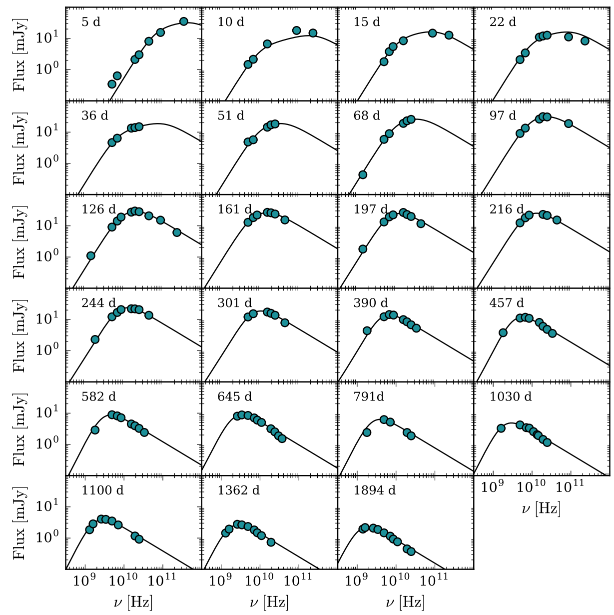

Figure 1: *Multi-frequency radio/mm observations of the jetted TDE Sw J1644+57 fit with a synchrotron emission model [20]. If AT2022cmc follows a similar evolution, our proposed GBT observations (∼300-500 days post-discovery) in combination with our approved VLA monitoring will constrain the location of its SED peak and the optically thin spectral index, which are needed to determine physical parameters like the jet energy.*

The best example to date of a TDE that launched a relativistic jet is Swift J1644+57 [7]. This TDE was originally discovered as a gamma-ray transient, and was quickly localized to the nucleus of a distant galaxy ($z = 0.354$) based on its luminous X-ray and radio emission [1, 8–10]. The radio and millimeter emission were well-modeled as synchrotron radiation produced in the forward shock between a powerful, initially relativistic jet and the dense circumnuclear medium (Figure 1). Millimeter observations were particularly crucial at early times, when the synchrotron spectrum was self-absorbed at lower frequencies, but are also important for constraining the slope of the optically thin portion of the SED at later times. Broad spectral coverage spanning several decades in frequency is essential to capture the peak of the SED and its evolution with time; if the peak is well-measured, then it can be used to derive important physical properties of the system, including the jet energy and the density of the

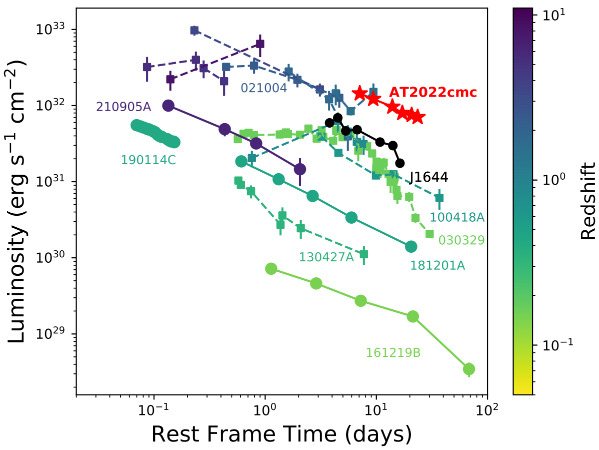

Figure 2: *Millimeter light curves of long GRBs (colored circles and squares) and the jetted TDE Swift J1644+57 (black circles). AT2022cmc (red stars) is more luminous than any known relativistic transient on comparable timescales, providing a rare opportunity to study the lifecycle of a powerful relativistic jet. Due to its high luminosity, AT2022cmc is expected to remain detectable in the mm to a later epoch than any previous extragalactic relativistic transient.*

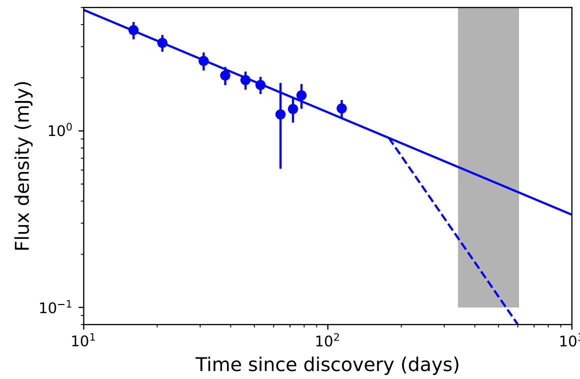

Figure 3: *Our GBT observations of AT2022cmc at 90 GHz show a steady power-law decline over 5 months ([19]; program GBT 22A-459). The timing and (1σ) depth of our proposed observations is shown by the shaded gray region. If the current evolution continues, AT2022cmc will remain easily detectable with MUSTANG2 throughout semester 2023A (solid line). If instead a jet break is observed, the light curve will begin to decline more steeply (dashed line); in this case, we will cease observations when the flux density falls below our detection threshold. We request ~monthly monitoring of AT2022cmc with MUSTANG2, which we will coordinate with our approved VLA monitoring of this target when possible.*

ambient medium [11]. The synchrotron radiation from Swift J1644+57 remained detectable in the millimeter-band for months, and an extensive radio and millimeter monitoring campaign revealed complexities such as late-time energy injection (probing the jet structure) and a roughly $\rho \propto r^{-3/2}$ density profile, consistent with expectations for spherical Bondi accretion [12].

Here we request MUSTANG2 observations of the recently discovered transient AT2022cmc, which shares many of the same properties as Swift J1644+57. Given the potential for this event to be an extremely rare (once in a decade) transient, a large scale multi-wavelength follow-up effort is underway in the community (e.g. NICER, *Swift*, HST, VLA). Based on our GBT observations to date (carried out under program GBT22A-459, PI: Alexander), AT2022cmc is expected to remain detectable throughout semester 2023A, providing a unique opportunity to track the full lifecycle of a transient relativistic jet (Figures 2, 3). We will combine the observations requested here with lower-frequency data from our approved VLA program (20B-377), to construct a multi-frequency SED at each observing epoch. We request one observation per month (10 observations total), to roughly coincide with our VLA monitoring cadence (exact coordination is not necessary). Our total time request is **17.5 hours**.

Prior to AT2022cmc, only three relativistic TDEs had been discovered [14, 15]. With the exception of Swift J1644+57, these events were not studied in detail. The discovery of AT2022cmc provides an unparalleled opportunity to characterize the long term evolution of a relativistic TDE for the first time since the discovery of Swift J1644+57, providing critical insight into the formation and evolution of relativistic jets.

2. AT2022cmc: A New Jetted TDE

AT2022cmc was discovered on 2022 February 11 by the ZTF survey as a fast-fading optical transient [17]; subsequent spectroscopic observations revealed a redshift of $z = 1.193$ [18]. The source exhibits extremely bright millimeter emission, with a luminosity exceeding that of virtually all known long GRB afterglows at comparable rest-frame times (Figure 2). It also exhibits extremely luminous and highly variable X-ray emission, similar to the early X-ray light curve of Swift J1644+57 (and dissimilar to GRBs). Radio observations taken with the VLA reveal a highly self-absorbed synchrotron spectrum, with evidence for a break between the cm and mm bands (Figure 4). Continued mm monitoring on longer timescales is critical to track the full evolution of key physical parameters such as the jet energy, the ambient density around the SMBH, and the magnetic field strength, which are inputs to models of the detailed process of accretion disk formation and jet launching [24, 25]. The observations proposed here will complete the SEDs for ongoing follow up at other wavelengths (most importantly our approved VLA program), providing the full spectral coverage necessary to characterize the dynamical evolution of this rare event. In particular, our proposed GBT observations will allow us to:

- **Measure the collimation of a relativistic jet launched by a TDE for the first time.** Based on its high luminosity and the high energy inferred from preliminary modeling of the radio+mm SED presented in Figure 4, AT2022cmc's mm emission likely originates in a relativistic jet viewed close to on-axis. We can constrain the structure of AT2022cmc's outflow by searching for a jet break in the mm light curve. As seen in long GRBs, if AT2022cmc's emission originates in a collimated relativistic jet, the light curve will begin to decline more sharply after the jet decelerates and spreads [16]. Post-break observations are critical to constrain the timing of this jet break, which determines the opening angle of the jet. The high cadence ($\sim$monthly) observations possible with GBT are particularly useful for this purpose (Figure 3). Knowing the jet opening angle is essential to convert from isotropic-equivalent energy to the actual kinetic energy of the jet, which is an important parameter for determining the jet-launching mechanism (e.g. [24]).

- **Determine the energetics and structure of the ejected material.** The evolution of the radio/mm data track the dynamical evolution and total energy of the outflow [11]. In the case of Swift J1644+57, radio observations revealed a significant injection of energy starting about a month after the initial detection [12]. The additional energy was likely carried by initially slower-moving material that caught up to the shock front as the jet decelerated; thus, the energy evolution contains clues to the structure of the ejected material [12, 13]. In contrast, AT2022cmc has so far shown a steady decline in its light curve, with no sign of energy injection yet (Figure 3). Our proposed GBT observations will allow us to determine whether such energy injections are common in jetted TDEs by searching for evidence of later-onset energy injection in AT2022cmc.

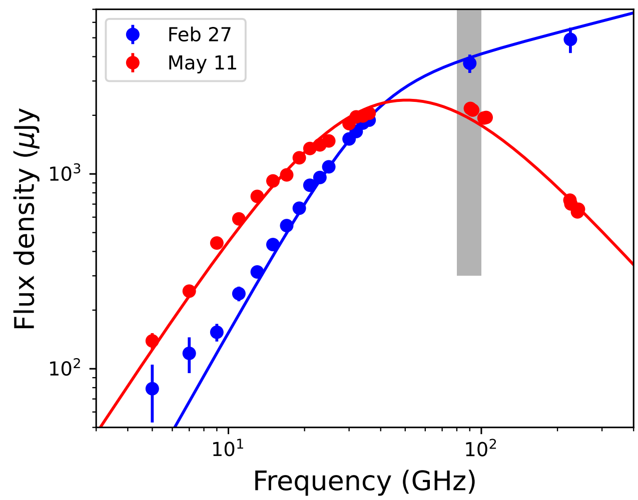

Figure 4: *Preliminary radio-to-millimeter SED of AT2022cmc (our VLA & GBT programs and [22]). GBT observations are important for tracking the evolution of the optically thin portion of the SED, as well as constraining the peak flux, the location of the self-absorption break ν_a, the characteristic synchrotron frequency ν_m and (in the future) the synchrotron cooling frequency ν_c (currently above the sub-millimeter). The gray band indicates the 3σ sensitivity of our proposed observations, which will capture the flux density even after the significant fading expected by the start of semester 2023A.*

- **Probe the circumnuclear environment around formerly-quiescent SMBHs at otherwise unresolvable scales.** The radio emission from the expanding outflow probes the ambient density and its radial profile (and hence accretion history) on parsec scales, which are not accessible for extragalactic SMBHs with other techniques. The circumnuclear density in Swift J1644+57's host roughly follows a $\rho \propto r^{-3/2}$ profile (typical of Bondi accretion), while a steeper density profile closer to the SMBH (as observed in the bulk of the non-relativistic TDE population; Figure 5) may point to a more active past [23, 24]. The observations obtained with this proposal will allow us to determine whether jetted TDEs occur in similar environments.

3. Description of Observations

We request 10 new MUSTANG2 observations of AT2022cmc in semester 2023A, to be carried out ∼monthly for as long as the TDE remains detectable at 90 GHz. Our cadence does not need to be perfectly uniform, so when possible, we will schedule our observations together with MUSTANG2 observations for other programs to decrease overheads. We will roughly align the timing of our approved VLA observations with the GBT observations requested here, so that we can construct quasi-simultaneous SEDs for our synchrotron monitoring. However, an exact alignment is not necessary (observations within $1-2$ weeks are acceptable for our science, given the likely slow evolution of the TDE on these timescales).

Our sensitivity request is driven by our science goal of searching for a jet break in AT2022cmc's mm light curve. As the precise timing of the jet break depends on the jet opening angle (which is unknown a priori), we choose a conservative model in which the light curve break is observed shortly after the present epoch ($\sim$ 6 months post-discovery; dashed line in Figure 3). In this case, a sensitivity of 0.1 mJy will allow us to obtain a $\geq 3\sigma$ detection of AT2022cmc in our first observation, to be scheduled within the first ∼month of semester 2023A. We request the ability to modify our nominal observing cadence of 1 epoch per month depending on the evolution of the source and the availability of the MUSTANG2 instrument; if AT2022cmc fades rapidly, we may request to trigger subsequent epochs sooner in order to maximize our chances of detection in later observations. We require 1.75 hours per epoch (including overheads) to achieve our target sensitivity of 0.1 mJy. Our total time request, including overheads, is **17.5 hours**.

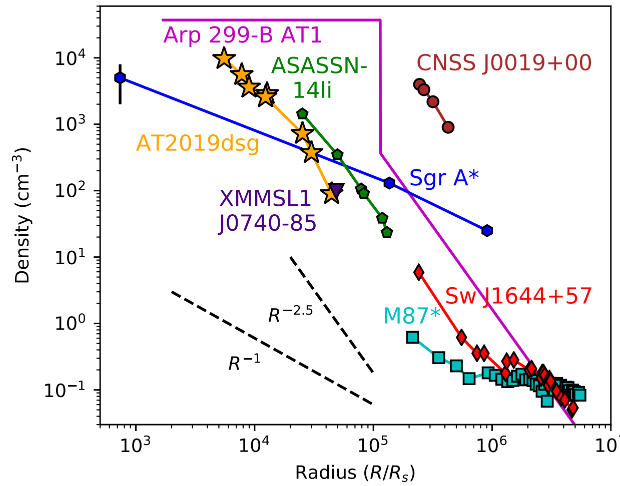

Figure 5: *The circumnuclear density profiles around radio-detected TDEs [21] at a physical distance of $\lesssim$ 1 pc from their SMBHs, as derived from the synchrotron model [20]. Such distances cannot be probed by other observational techniques at the high redshifts typical of jetted TDEs like Swift J1644+57 and AT2022cmc. The density profile for Swift J1644+57 is consistent with $\rho \propto r^{-3/2}$, the expectation for spherical Bondi accretion, while non-relativistic TDEs exhibit steeper profiles. Our GBT observations will determine whether the density profile of AT2022cmc is similar to that of Swift J1644+57, and hence whether the presence of jets in TDEs is correlated with their environmental properties.*

4. References

[1] Zauderer, B. A., et al. 2011, Nature, 476, 425
[2] Rees, M. J. 1988, Nature, 333, 523
[3] Strubbe & Quataert 2009, MNRAS 400, 207
[4] Sari et al. 1998, ApJ, 497, 17
[5] Komossa, S. 2002, Rev. Mod. Astr., 15, 27
[6] Alexander et al. 2020, Space Sci Rev 216, 81
[7] Crumley et al. 2016, MNRAS, 460, 396
[8] Bloom, J. S., et al. 2011, Science, 333, 203
[9] Burrows, M. C., et al. 2011, Nature, 476, 421
[10] Levan, A. J., et al. 2011, Science, 333, 199
[11] Barniol Duran, R., et al. 2013, ApJ, 772, 78
[12] Berger, E., et al. 2012, ApJ, 748, 36
[13] Zauderer, B. A., et al. 2013, ApJ, 767, 152
[14] Cenko, S. B., et al. 2012, ApJ, 753, 77
[15] Brown, G. C., et al. 2017, MNRAS, 472, 4469
[16] Sari, R., et al. 1999, ApJ, 519, L17
[17] Andreoni et al. 2022, GCN 31590
[18] Tanvir et al. 2022, GCN 31602
[19] Alexander, K. D. et al. 2022, ATel 15269
[20] Eftekhari, T., et al. 2018, ApJ, 854, 86
[21] Cendes, Y., et al. 2021, ApJ, 919, 2, 127
[22] Perley, D. et al., 2022, GCN 31627
[23] Alexander, K. D., et al., 2016, ApJ, 819, L25
[24] Coughlin, E., et al. 2014, ApJ, 781, 82
[25] Tchekhovskoy et al. 2014, MNRAS, 437, 2744