

The Hydra Constellation

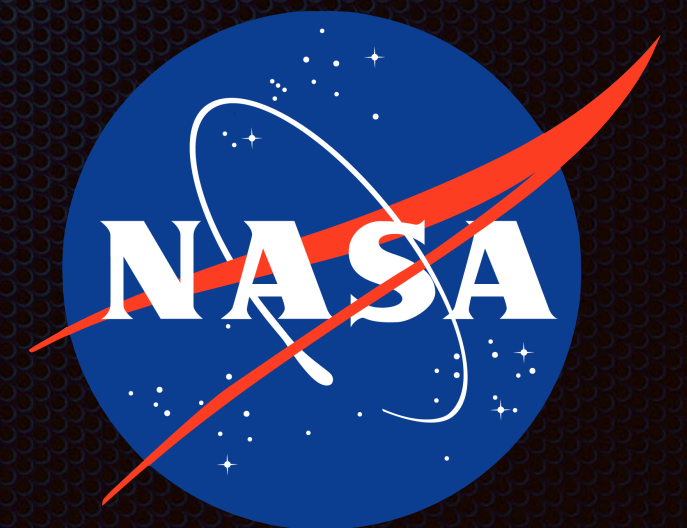
A Proliferated Space Architecture for Time-Domain Astrophysics



Hydra White Paper



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Entering the Follow-Up Limited Era

- ✦ Upcoming wide-field optical/NIR surveys are poised to generate a deluge of optical data
 - ✦ Vera C. Rubin Observatory, Nancy Grace Roman Space Telescope, and Argus Array
 - ✦ These surveys will quickly become the primary drivers of transient discovery
- ✦ LVK O4 run concluded in Nov 2025; the A+ upgrade (O5) will see rate increases
- ✦ IceCube upgrades complete and Gen2 promises major rate increases
- ✦ New and upcoming high-energy missions will contribute to increased transient detection rates
 - ✦ Einstein Probe, StarBurst, additional IPN nodes, etc
- ✦ TDAMM is quickly moving from a discovery-limited to follow-up limited era

A Critical Capability Gap

- ✦ The new discovery era is arriving while the workhorses of the TDAMM fleet are aging
- ✦ Swift demonstrated the power of tightly coupling discovery with rapid X-ray/UV/O follow-up
- ✦ The loss of Swift and the extended age of Fermi create gaps in:
 - ✦ All-sky high-energy discovery
 - ✦ Rapid X-ray localizations
 - ✦ Early space-based UVOIR characterization
- ✦ These capability gap coincides with the rapidly increasing discovery rate of high-impact transient sources that require immediate multiwavelength response

A Proliferated Space Architecture for TDAMM

- ✦ Instead of replacing Swift with another exquisite, monolithic observatory, build a strategic distributed observatory for TDAMM in the 2030s
- ✦ The constellation would disaggregate the functions of Swift across a coordinated fleet
 - ✦ Provide a persistent, low-latency, multiwavelength response system optimized for transients
- ✦ The constellation would serve as both a discovery and follow-up engine
 - ✦ Generating its own high-energy triggers and rapidly tasking its X-ray and UVOIR elements
 - ✦ Accepting high-priority external alerts and ToO requests for coordinated follow-up

Four Fundamental Science Questions

Science Objections ¹	Science Questions	Observables
1. Cosmic Accelerators	How do relativistic explosions, jets, and accretion flows work?	X-ray and gamma-ray transient detections; prompt light curves, spectra and localization; early X-ray and UVOIR afterglow light curves; host-galaxy properties
2. Cosmic Element Production	Where and when are heavy elements produced	High-redshift GRB afterglows; kilonova UVOIR light curves and spectra; host redshifts & metallicities;
3. Matter at Extreme Densities	What is the neutron star equation of state and does matter transition to phases	Gamma-ray counterparts; X-ray afterglows; kilonova properties tied to remnant lifetime and ejecta mass; mass-radius constraints from pulse profiles
4. Dark Energy	GW standard sirens plus electromagnetic counterparts to map cosmic expansion	Gravitational-wave distances from NS mergers; gamma-ray counterparts; afterglows and kilonova light curves; host redshifts; standard siren statistics

¹ *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, National Academy's Committee on the Physics of the Universe, 2002

Three Complementary Spacecraft Layers

- The mission would consist of coordinated spacecraft layers in real-time communication
- The baseline architecture would include three complementary layers
 - Gamma-ray discovery
 - Continuous wide-field monitoring and prompt alerts
 - X-ray discovery and follow-up
 - Rapid localization, afterglow characterization, arc second positions
 - UVOIR
 - Counterpart identification, colors, photometry, spectroscopy, polarimetry

Instrument Architecture

- The Hydra concept does not require every layer to use novel technology
- The architecture can be built from mature designs using heritage instruments
 - The emphasis isn't necessarily greater sensitivity, but rather rapid response and more flexible scheduling to observe transients early and often
- Hydra is fundamentally an operational architecture rather than a hardware architecture
- The concept white paper deliberately leaves individual layer implementation open for the ASTRA trade study

Why a Proliferated Architecture?

- The Hydra constellation takes inspiration from the Proliferated Warfighter Space Architecture (PWSA) currently being pursued by the Space Force's Space Development Agency (SDA)
 - Traditional reliance on a small number of exquisite, high-cost satellites replaced by a resilient, low-Earth-orbit architecture composed of many smaller, more rapidly developed spacecraft
 - Use of common bus technology on each node to reduce spacecraft development costs
- Creates scientific capabilities that a single spacecraft would struggle to provide
 - Increased sky coverage and observing responsiveness, enabling multiple high-priority transients to be followed simultaneously
- Allow for graceful degradation if individual nodes fail and replenish or upgrade over time, as well as commercial, international, or philanthropic-contributed nodes to join over time
- Treats TDAMM as a persistent science capability rather than a single fixed-duration mission

What an ASTRA Study Should Determine

- An ASTRA study should be conducted to investigate a strategic disaggregated TDAMM observatory
- Science trades:
 - What combination of gamma-ray, X-ray, UV, Optical, and IR capabilities maximizes the TDAMM return in the 2030s
- Architecture trades:
 - How many nodes? Which orbits? Hosted payloads vs dedicated spacecraft? What real-time comms solution meets the alert/command latency requirements?
- Implementation trades:
 - What layer should be first? What can we adapt from existing heritage? What technology maturation is required? How should interoperability and replenishment be structured?

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 - Provide a persistent, low-latency, multiwavelength response system optimized for transients
- Hydra would serve as both a discovery and follow-up engine
 - Generating its own high-energy triggers and rapidly tasking its X-ray and UVOIR elements
 - Accepting high-priority external alerts and ToO requests for coordinated follow-up
 - Hydra would discover and localize short and long gamma-ray bursts, fast high-energy transients, magnetar giant flares, tidal disruption, relativistic supernova shock breakouts, and other explosive events
 - Hydra would also respond to external triggers from GW detectors, neutrino observatories, as well as discoveries by Rubin, Roman, Argus, and radio facilities

4.6 Observing Plan Structure

- ✦ Scientific Motivation
- ✦ High-Priority Subclasses
- ✦ Triggering Criteria & Expected Event Rates
- ✦ Discovery & Alert Channels
- ✦ Observatory Roles and Capabilities
- ✦ Observing Strategy and Timeline
- ✦ Lessons Learned from Past Events

4.8 CBM Plan Information

Sub-classes	Science Motivation	Trigger Rate
Binary Neutron Star (BNS) Merger	Probe merger remnant, NS EOS, and jet structure	~few during O5
Neutron Star-Black Hole (NSBH) Merger	Probe merger remnant, NS EOS, and jet structure	~few during O5

Timeline	Phase	Observations
$T_0 + 0\text{--}1$ hour	Detection	GW, g-ray detection
$T_0 + 1\text{--}24$ hours	Search Phase	Wide-field optical/NIR imaging, spectroscopy
$T_0 + 1\text{--}24$ hours	Post-Identification	UV/O/NIR imaging and spectroscopy
$T_0 + 1\text{--}14$ days	Peak Characterization	High-cadence UV/O/NIR, Radio, and X-ray
$T_0 + \text{weeks--months}$	Afterglow Monitoring	Radio, X-ray, and optical bands

Observatory	Wavelength	Unique Capability	Ideal Use Case
HST	UV/Optical	High-resolution imaging	Imaging
JWST	NIR/MIR	NIR/MIR spectroscopy	Spectroscopy, deep imaging
Swift	UV/X-ray	Rapid follow-up	Early-time UV/X-ray monitoring
Rubin	Optical (Wide-field)	Counterpart searches over large localization area	KN ID
Keck, Gemini, ect	Optical	KN spectroscopy, deep optical imaging	Events with a clear counterpart
VLA, MeerKAT, etc	Radio	Jet and ejecta studies	Late-time afterglow
ASKAP	Radio	Wide-field radio imaging	Radio counterpart ID, afterglow
Chandra	X-rays	High spatial resolution X-ray imaging, host galaxies assoc	Late-time afterglow