Working Group Report on “HST in the era of Time Domain Multi-messenger Astrophysics”

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The committee reached out to 36 key time-domain scientists, who were strongly involved with the follow up of GW170817, both based in Europe and in US. We received feedback on our document from 12 of them.

This document is structured as follows:
Document 1: HST Observing Strategy of electromagnetic counterparts of gravitational wave triggers.
Document 2: Policies
Document 3: Coordination among observatories in the multi-messenger era
Document 4: Maximizing the HST impact on Time Domain Science at large

1. HST observing strategy of electromagnetic counterparts of gravitational wave triggers

Editors: S. B. Cenko, R. Margutti

SUMMARY OF MAIN GOALS and OBJECTIVES: The main objective of this chapter is to help designing an HST observing strategy for GW follow-up that maximize the scientific returns from HST observations. In particular, we solicited community feedback on the following topics: (i) Lessons learned from HST Observations of GW170817, what was great, how can we improve; (ii) Unique contributions of HST to GW science; (iii) What HST can do, but can also be done from the ground.

1.1 Lessons learned from HST Observations of GW170817

The joint discovery of gravitational waves and electromagnetic emission was a watershed moment for astrophysics. Heralding the dawn of a new era of multi-messenger astrophysics, results from this single objects touch upon such diverse scientific topics as nuclear physics, radiative transport, general relativity, and relativistic astrophysics.

HST observations played a critical role in this multi-messenger discovery:

- The deep sensitivity, particularly at redder wavelengths, uniquely enabled the detection of off-axis "afterglow" optical emission at late times (dt > 100 d).
- The high angular resolution afforded by HST enabled detailed characterization of the environment of the merger (host galaxy properties, location within the host).
- HST provided the latest detection of the fast fading kilonova UV emission (much more sensitive than, e.g., Swift UVOT).
- Photometry and spectroscopy of the kilonova at near-infrared wavelengths provided complementary observations to ongoing monitoring on the ground.
- HST data also enabled the most precise distance measurement for the host via the surface brightness fluctuation method.

Despite these notable successes, we identify several "lessons learned" from this first attempt at following up an electromagnetic counterpart of a gravitational wave discovery:

- A lack of ultra-rapid (dt < 2 days) follow-up precluded characterization of the early (and fast-fading) blue kilonova component. Deep UV observations **at early times**, both spectroscopy and photometry, are a) scientifically critical (to characterize the composition of this emission) and b) can be uniquely obtained by HST.
- The UV spectrum that was obtained for GW170817, at dt ~ 6 days after merger, did not detect any significant emission from the source. Given the UV light curve observed from Swift, this was apparent before the observations were executed, but operational constraints rendered it impossible to re-schedule the HST observations.
- Template host observations were repeated for each individual group. Sharing of these templates could reduce redundancy at late times (when coordination is much easier).
- In one instance the WFC3-IR grism observations were split over multiple days (i.e., G141 on August 24, G102 on August 26). Given the relatively rapid evolution, such observations should be executed as close together in time as possible.
- For this specific event, based on the results from NIR spectroscopy from the ground, it was pretty clear that HST IR grism spectroscopy would have been complementary to the NIR from the ground, but not really competitive.

1.2 Unique contributions of HST to GW science

We provide below a list of key potential HST contributions to GW science divided into PRIORITY 1 and PRIORITY 2.

- PRIORITY 1: Early-time UV spectroscopy and/or photometry of the blue kilonova component. Ultra-rapid HST response over <=2 days is a key need.
- PRIORITY 2: For nearby events that can be imaged from the ground: late-time photometry to either sample the decay of the KN component or the emergence of the afterglow. Or photometry of faint, distant events.
- PRIORITY 2: Imaging of the environment to get precise localization and constrain the merger environment properties (not time sensitive), as well as the distance of their host galaxies.
- PRIORITY 2: Multi-epoch IR spectra to map spectral features of the KN and their evolution, if observations from the ground will not be able to reach the necessary depth.

1.3 What HST can do, but can also be done from the ground

- Optical and IR photometry of the source while bright.
- IR spectroscopy. For the specific case of GW170817 (nearby and bright) HST IR spectroscopy offered only complementary insight into the event, compared to the ground. However, this might not be the case for fainter, more distant targets (or even for nearby targets if the weather does not cooperate...)

FINAL RECOMMENDATION: Scientifically, we identified as “Priority 1” obtaining very early time UV spectroscopy/photometry of the kilonova emission, which would require the execution of ultra-rapid ToOs (i.e. repointing within ~36-48 hrs since the alert is received by HST). We discuss recommendations for implementing such observations (and how to deal with TAC approved programs) in the subsequent document on “HST Policies”.

Additional observations of gravitational wave counterparts, including UV photometry (unique to HST due to its sensitivity), NIR imaging and spectroscopy (ditto due to sensitivity and higher angular resolution), are also strongly recommended when beyond the reach of ground-based facilities.

Several other minor recommendations to improve the scientific yield from gravitational wave follow-up, including improved communication and more carefully coordinated spectroscopic follow-up, also result from this analysis (addressed in “Coordination among observatories in the multi-messenger era” document).

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2. Policies

Editors: Iain Reid, Ben Farr

SUMMARY OF MAIN GOALS and OBJECTIVES:

Gravitational wave astronomy is barely beginning, and widespread, rapid dissemination of associated datasets throughout the community is a highly effective mechanism for maximizing the science returns. At the same time, procedures need to pay due regard to the intellectual investment from individual scientists.

2.1 Community program

The working group believes the best approach to enabling *several ultra-rapid observations of GW* counterparts and maximizing scientific gain is a community program. Rapid observations would be enabled by a community-developed, *predetermined* decision tree to guide the observing strategy for a given trigger. The data from such observations would be made public immediately. There would likely be no funding associated with these observations, but alternative schemes (e.g., pay for page charges and a conference trip for results derived from HST data products) should be considered by STScI. Subsequent observations of events would be left to GO programs (i.e., the usual path, with PIs and proposals selected by the TAC, and associated funding). Proprietary periods for such programs should be minimized, if not eliminated, to maximize scientific gain. The community ultra-rapid ToO program has to be viewed as a backup in case nothing similar is approved by the TAC, or if approved proposals run out of ultra-rapid triggers before the relevant HST cycle is over.

For community ultra-rapid follow-up to succeed, we need:

1. A direct channel of communication between observers and STScI.
2. A clear decision tree in place to trigger the ultra-rapid observations.
3. A mechanism for announcing the observations are happening.

2.2 Proposals involving multiple teams

Going forward, it will be important to avoid having numerous conflicting ToO programs trigger on the same object. GO programs with multiple Principal Investigators leading separate teams offer a mechanism for competing teams to combine their efforts while receiving an appropriate share of the resources (observations and grant funding). For HST, multiple investigators can be specified as co-PIs; however, we still require a single point of contact as the PI to sign off on administrative details (e.g., changes to budgets, additions of new co-investigators).

Finally, to resolve any remaining conflicts between ToO programs, establishing a decision tree of which proposal triggers in different scenarios before the start of LIGO/Virgo's next observing run may be necessary to avoid redundant observations.

2.3 Director's Discretionary Time proposals

DDT proposals provide an avenue for the community to apply for HST time to enable rapid follow-up observations of transient phenomena. Proposals receive peer review from ~3 community members who have past experience in reviewing past HST proposals and have specialized knowledge in the relevant science area. The reviewers are selected by members of the STScI Science Policy Group, and are chosen to maximize expertise and minimize conflicts. By policy, DD proposals cannot preempt TAC-approved GO programs.

There was consensus that any steps that could be taken to streamline the review process would be beneficial. Those steps include:

- Establishing direct, proactive communications between LIGO/Virgo and STScI to verify high-priority alerts.
- Creating a decision tree to guide what types of proposal might be appropriate to particular events.
- Identifying a group of knowledgeable community members who would agree in advance to respond quickly to requests to review DDT proposals.

DDT proposals often require multiple iterations between the STScI Program Coordinator and the PI before they can be implemented. The more complete the proposal at submission, the faster this process can be completed. Direct communication between the PC and PI may be most effective.

The working group received feedback suggesting the creation of a central location for reporting GW-related observations, possibly updated in real time. This reference site should include summaries of programs already planned for execution on Hubble, and potentially other facilities, providing a guide to the community on where DDT programs might be most useful/required.

2.4 Limits on ToO allocations

Hubble currently limits the number of ultra-rapid and rapid ToO activations allowed within a cycle; this reflects both the resources required to execute those observations and the overall impact on the scheduling efficiency. Currently, Hubble also does not allow ultra-rapid ToO observations with COS, ACS/SBC and the STIS-MAMA detectors; all of these detectors require bright object screening in order to ensure that the safety of the detectors, so this restriction is also largely a matter of resources.

The working group recommends that STScI consider allocating additional resources in both areas, to respond the science priorities enabled by observations of multiple sources, as discussed elsewhere in this report, and to allow full exploitation of HST's unique UV capabilities at the earliest opportunity.

FINAL RECOMMENDATION: The working group recommends creating a community program that focuses on ultra-rapid ToOs of GW sources. Beyond the ultra-rapid ToO observations at t<2days, we encourage multi-PI GO proposals across GW follow-up teams to alleviate the problem of overlapping observations and conflicts. The WG further recommends that STScI consider allocating additional resources to safely execute ultra-rapid ToOs with all the relevant HST instruments.

3. Coordination among observatories in the Time Domain and Multi-messenger era

Editors: Erik Kuulkers, Emily Levesque

SUMMARY OF MAIN GOALS and OBJECTIVES: Efforts are underway on an international basis to explore the design of an effective system for coordinating transient follow-up among multiple observatories. That structure can complement and enhance HST observational initiatives. Topics of interest include: getting the alerts, improving coordination and communication, planning the observations, and the prioritization of follow-up efforts.

3.1 Intro

Over the last years the scientific demands for simultaneous observations across the electromagnetic spectrum are continuously increasing. This has been amplified by the detection of non-electromagnetic events of astrophysical origin, such as high energy neutrino events, and, in particular, gravitational wave (GW) events. It has culminated with the detection of prompt transient gamma-rays coincident with a GW event caused by the merger of two neutron stars (GRB170817A/GW170817). The latter event involved many facilities on the ground and in space and represented all currently accessible wavelengths (Abbott et al. 2017). Moreover, the transient nature of the event required fast reaction times, in order not to miss any possible `afterglow' emission. With other facilities coming online soon which will report on transient events across the EM spectrum (e.g., LSST, SKA -ZTF alerts are already public now-), efficient and fast coordination is a must in order to maximize the scientific output. STScI is not an appropriate organisations to lead those efforts, but HST science can be enhanced through participation in those coordination efforts.

3.2 Getting the alerts

First one has to be informed that a transient event is taking place or has just happened. Various alerts for all kinds of transients already exist (ATel, GCN, AMON, VO-alerts, etc). Receiving notification of an event may be as simple as signing up for these existing feeds/alerts (and in the future to those from, e.g., LSST, SKA), and establishing a means of making a first (automatic) decision on which events are most important for follow-up. The decision can be based on clearly-defined characteristics of the event; these criteria for follow-up observations will likely evolve through the mission. The final decision to trigger an observation should be done by a human in the loop.

3.3 Improved coordination/communication

When follow-up observations need to be planned, coordination is crucial. Good coordination requires good *communicatio*n tools. It is key is to establish good communication channels (network) with relevant people from other facilities, i.e., Principal Investigators or Project Scientists (those who make decisions about the observations) and observation planners (those that build the observing schedule) from other missions and observatories. E-mail is one means to communicate, but it is ad-hoc and cannot address a full group simultaneously (unless one uses a mailing list). One possibility is to use an open online messaging and collaboration tool such as Slack. Users can update the community, in real-time or even in advance, of planned and/or executed follow-up observations, and can in turn use the public information to better optimize their planned programs.

Another key issue is *rapid response*. Fast transients need fast response times (both in observations and communication). Again, with automation (e.g., the planning/visibility info; see below) communication becomes more efficient. Based on the available info, a decision tree (e.g., can observations be coordinated with another facility observing at a certain wavelength?) could be used to decide on a go or no-go for follow-up observations.

A particular advantage of good communication is in designing ground-based (or space-based) observations that can complement or improve observations to be done with HST. With a maximum HST response time of ~48 hours, ground-based (or space-based) observations in the immediate aftermath of a trigger can provide key initial data that can be used in planning HST observations, and ensure rapid acquisition of specific observations (e.g., IR spectroscopy) where ground-based coverage is equivalent or even superior to HST's capabilities, thus freeing up HST time for observations that are impossible from the ground (e.g., UV observations, high-resolution imaging).

3.4 Planning the observations: visibility and planning information

Some degree of coordination for non-HST GW follow-up is already de facto be in place as a result of the HST joint programs with various observatories (Chandra, XMM-Newton, Gemini, and NRAO). In reality, GW follow-up will also be carried out at a large number of observatories independent of existing HST programs, and the ability to coordinate effectively between these facilities is necessary in order to maximize the science.

The process of long- and short-term planning in general and coordinating observations in particular are becoming more complex in the near future. Automatic elements can make coordination more efficient by cross-correlating visibility and planning information of all involved facilities to generate an optimized observing plan. However, currently, visibility and planning (past, current, and future) information is not available in a uniform way. At present there is a proposal, led by ESA XMM personnel, to define international standards for how observing facilities can make this information available: facilities provide two services in an agreed standard format allowing clients to make queries via URLs and receive results in JSON (JavaScript Object Notation) format following existing VO (Virtual Observatory) Protocols (this has been presented to the International Virtual Observatory Alliance - IVOA, or short VO - for endorsement with the goal of VO certification in November 2018). The implementation of these services could commence rapidly after VO certification, and each facility, including HST, could build a tool to access the information from the services of all other facilities.

One recommendation is to draw up an “ideal” set of observations or an observational decision tree. For GW events this set can be based initially on that done for GW170817/GRB170817A, and subsequently revised with each GW trigger. This can lead to an automatic trigger of follow-up across a predetermined suite of ground-based telescopes. The initial data resulting from these observations could become immediately publicly available and include much of the basic preliminary work (localization imagery, color data, etc.) that can be used to optimize later follow-up observations and HST joint program planning.

3.5 Prioritization of follow-up efforts

Prioritization of transient follow-up observations is going to become key in the next decade - with facilities such as LSST and SKA coming online, as well as the increase in sensitivity of GW and high-energy neutrino facilities, the number of transient detections with an “urgent” need for follow-up will skyrocket. Managing the priority and immediacy of these triggers will become a significant challenge. In addition to prioritizing types of ground-based observations so that they can complement HST data (and vice versa), a broader prioritization of “types” of follow-up should also be established: one has to determine how urgent follow-up of a given event is and whether other work - including other transient follow-up observations - should be interrupted (for example, should a search for the optical counterpart of a GW trigger be interrupted for follow-up imaging of a nearby core-collapse supernova?).

Conclusions

The era of time-domain and multi-messenger astronomy (when hundreds of astrophysical alerts happen every night) leads to the need for improved communication and efficient managing of future transient events. New ways of communication need to be set up and (automatic) decision trees need to be put in place, allowing us to maximize the scientific output of follow-up observations to transient events. High-profile facilities like HST can enhance their science impact through participation in these processes. The working group furthermore received feedback from the community to explore the possibility of increasing the amount of time allocated for joint observations of HST with other facilities.

FINAL RECOMMENDATION: We recommend implementing a public and easy-to-use communication system that the community can use to share information about guaranteed, planned, and recently-executed observations. The planning information for these observations should follow existing VO protocols. Follow-up complementing HST observations should also be prioritized over other ToO triggers. We recommend exploring the possibility for larger HST joint observing proposals.

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4. Maximizing the HST impact on Time Domain Science at large

Editors: Ori Fox and Dan Milisavljevic

SUMMARY OF MAIN GOALS and OBJECTIVES: As new surveys (e.g., ZTF, LSST) come online, HST will need to keep pace with the increasing number of discovered transients, which will increase from a rate of thousands per year to thousands per night. Overall, most of the transient targets can be categorized as supernovae, GRBs, GWs, or tidal disruption events (TDEs). Current HST proposal guidelines limit the number of rapid (<21 days) and ultra-rapid (<5 days) to eight and one trigger per cycle, respectively. In actuality, STScI is executing rapid observations (i.e. within 21 days whether or not intended as disruptive) 7.65 times per year from DD and 28.6 (conservatively) times per year from ToO activations. This implies an average frequency of one response every 10 days. The traditional number of ToOs may not be sufficient, so it is important to understand types of science, required observations, and expected frequency of triggers in this new era.

4.1 Transformative Science Opportunities

ToO's triggers mostly consist of transient phenomena. HST's unique contributions (compared to ground-based observatories) consist of early time UV observations. The UV probes high-energy events that have a variety of origins, including shock breakout from the star, a very hot photosphere early on in the transient evolution, "Flash Spectroscopy", and shock interaction with a surrounding circumstellar medium. The other advantage that HST offers is high spatial resolution. Some triggers also make use of these observations, such as progenitor astrometry.

As new surveys come online, the number of transient discoveries will certainly increase, but very young transients will comprise one of the largest currently unexplored areas of discovery space. Prompt UV observations are quite powerful for questions of *progenitors,* including ``flash spectroscopy'', Type Ia companion interaction, and fast transients. We also acknowledged the possibility of exploring other transients at early times for which we do not have the expertise (e.g., asteroids, novae, etc).

4.2 Total ToOs (disruptive/non-disruptive) and turnaround time

Ultra-Rapid (2-5 days): There is an overwhelming consensus in the community that there is an urgent need for ultra-rapid ToOs on the 2-5 day timescale with HST. These provide the most significant opportunities for transformative science. Given the limitations of ultra-rapid ToO detector safety concerns, the STIS MAMA's may not always be available, and the WFC3/UVIS grism offers a safe and potentially faster alternative. This should be considered in many cases since most sources should be relatively bright at early times and, given the high velocities, high-resolution spectra are not necessarily required. A more in depth study should be conducted that weighs the trade-offs between the grism and slit.

Rapid (5-21 days): The current limit of eight rapid ToO's is great for *current* science needs. This should be noted. Future surveys will result in more transients, but an increase in rapid ToOs is not obvious since most optical follow-up can be obtained from the ground and UV spectroscopy resulting in transformative science is not as demanding at >5 days. That said, the committee notes that future discoveries may very well alter this perspective.

Non-Disruptive (>21 days): Increasing the number of non-disruptive ToOs (t>3 weeks) would also benefit the time domain community. At present this does not seem to be an urgent need, but may become so as these surveys continue operations and scientific objectives expand. The present allocation is valuable and efficiently utilized.

4.3 Host Environment Mapping and Progenitor Systems

HST has made incremental but invaluable progress in our understanding of the progenitor systems of supernova explosions through direct imaging of explosion sites. HST must continue this program to continue the momentum of progress. We urge HST to consider placing greater importance on developing a more complete archive of nearby galaxies in multiple bands spanning UV and optical. This legacy data set would provide information about the host galaxy environment and have ample synergy with many other research areas. If a more limited approach is desired, the committee has identified the LSST deep drilling field(s) as a potential region of interest for HST pre-explosion imaging.

4.4 Community Programs

ZTF, LSST, and WFIRST guarantee an increase in discovery space. Given the astronomical communities push to prioritize transient astronomy, the committee sees HST as a possible community tool that could be used in a similar manner as recommended for LIGO follow-up. Our goal is to make HST most relevant in the era of large area surveys like LSST. This could include early-time UV spectroscopic database of transients, or something else of common interest to the transient community.

The implementation of such a community program is not clear, given any science would have to go through the TAC process. However, the current number of rapid ToO's would potentially limit the number of proposal submissions, especially risky ones, to the current TAC process. A community *ultra-rapid community trigger* may be considered in the future as science demands evolve. In the more immediate future, however, the committee recommends the institute harness the advantage that most non-disruptive ToOs are executed in less than 21 days. This fact opens the possibility that a general set of non-disruptive ToO trigger criteria be allowed with the expectation that a significant fraction of will be executed much sooner.

FINAL RECOMMENDATION: There is consensus from the working group about obtaining ToOs on the 2-5 day timescale for non-GW science (e.g. shock breakout, interaction, very fast evolving transients). We anticipate that other research areas would benefit from increasing the number of ultra-rapid triggers (e.g., including asteroids, novae). We also urge HST to prioritize developing a more complete archive of nearby galaxies in multiple bands spanning UV and optical. This legacy data set would be invaluable for time domain science and have synergy with many other research areas.