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The Dawn of Multimessenger Astronomy

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Abstract. The realization of multimessenger astrophysics is opening up a new field of exploration of the most energetic phenomena in the universe. Astrophysical messengers associated with each of the four fundamental forces reach detectors buried deep underground or underwater, spread across wide swaths of land, and orbiting high above us in space. Recent detection of coincident real-time signals amongst these experiments heralds the birth of high-energy multimessenger astronomy and enables us to begin exploring and understanding their astrophysical sources. The Astrophysical Multimessenger Observatory Network (AMON) is currently linking multiple current and future high-energy neutrino, cosmic ray, gamma ray and gravitational wave observatories into a single virtual system, facilitating real-time coincidence searches for multimessenger astrophysical transients. AMON will generate alerts that will enable rapid follow-up of potential electromagnetic counterparts. We present the science case, design elements, partner observatories, and status of AMON.

1. Introduction

Multimessenger astronomy is the observation of a single astrophysical source that has emitted two or more distinct messengers: photons, gravitational waves, neutrinos and/or cosmic-rays, representing the four fundamental forces. Detection and subsequent detailed follow-up observations of such sources help us unveil the underlying mechanism(s) that power them, perhaps helping to resolve the enduring mystery of how ultrahigh energy cosmic rays are produced. Multimessenger observations also provide a unique opportunity to study the instrinsic properties of the messengers themselves, coming to us as they do over extremely long baselines, all while traveling alongside other types of messenger particles, each type with its own set of distinct properties.

After decades of searching, we have but a handful of detections of multimessenger sources. At lower energies, we have detected photons and neutrinos from the sun and supernova SN1987A [1, 2, 3]. At higher energies, we have recently detected gravitational waves from a binary neutron star merger (GW170817) [4] in coincidence with numerous electromagnetic follow-up observations. Even more recently, we have also seen the first indication of a high-energy neutrino (IceCube-170922A) [5] in coincidence with an x-ray signal from Swift [6, 7], and clear flaring activity observed by the Fermi [8] satellite and the MAGIC [9] ground-based telescope from the active galactic nucleus (AGN) TXS 0506+056 [10], a known "blazar" (an AGN with its jet pointed towards earth).

These detections are very exciting, and our knowledge grows in leaps and bounds with each one. However, for multimessenger astronomy to grow as a field, the rate of coincident detections

will need to increase considerably. One way to accomplish this is to improve the sensitivity of the individual detectors. Detector upgrades are either underway or in the proposal stage for all four messengers (see, for example, [11, 12, 13, 14, 15, 16, 17, 18]), and while these upgrades are virtually guaranteed to improve the detection rate, the time it takes for them to be implemented is $\mathcal{O}$(years). In this proceeding we focus on a second approach that implements a virtual observatory to enable the various detectors to search jointly for coincidences, employing data that could not otherwise be used standalone for astrophysical source searches. Furthermore, this approach performs its searches and provides alerts to follow-up observatories in real-time, enhancing the sensitivity to transient astrophysical phenomena.

2. The Multimessenger High Energy Universe *Status Quo*

Particle astrophysics experiments typically began their searches for astrophysical sources with the goal of making standalone discoveries. These searches required very strong signals which, not surprisingly, are rare, coming about once per month. The strong but rare signals detected thus far include:

- gravitational waves from binary blackhole and binary neutron star mergers by the LIGO and VIRGO Collaborations [19, 20, 21, 4],
- astrophysical neutrinos from unidentified sources by the IceCube Collaboration [22], and
- ultrahigh energy cosmic-rays by the Telescope Array [23] and Pierre Auger [24] observatories.

(By contrast, large numbers of high-energy photons have been detected from a wide range of sources by ground-based observatories such as HAWC [25], H.E.S.S. [26], MAGIC [27], and VERITAS [28], and by satellite observatories such as Swift [29] and Fermi-LAT [30].)

The next step taken by a number of these observatories was to send out their strong signals to partner observatories for follow-up. These bilateral, unidirectional agreements were established mostly with electromagnetic follow-up observatories, *i.e.*,, mainly with traditional telescopes. With $\mathcal{O}$(100) such follow-ups performed, the high energy astrophysics community has met with success twice, first with gravitational wave GW170817 [4] and then with the high-energy neutrino IceCube-170922A [5]. A great deal was learned through the follow-up of GW170817, including its redshift [31]; the follow-up to IceCube-170922A is not yet as well-studied, but its detection provides evidence in favor of the hadronic acceleration model for blazars (see, for example, [32]).

3. Multimessenger Virtual Observatories

In principle, particle astrophysics experiments can garner more signal by lowering their thresholds, but they are generally prevented from doing so by backgrounds that overwhelm the astrophysical signal. Gravitational wave detectors experience background from intrinsic detector and environmental noise, and strong signals that arrive during *single*-interferometer operations have inadequate pointing for follow-up; neutrino detectors cannot distinguish between atmospheric and astrophysical neutrinos at lower neutrino energies; and gamma-ray detectors have difficulty separating showers induced by gamma-rays from those induced by cosmic-rays. Below about 10^{19} eV, cosmic-ray detectors can no longer count on detected events pointing back to their source due to the effect of (inter)galactic magnetic fields. With pointing resolutions reaching up to thousands of square degrees, a remaining background is astrophysical, since in regions of space within particle astrophysics detectors' error circles there are always at least a few sources.

Virtual observatories provide a means to use these "sub-threshold" data as well as a mechanism for reducing the astrophysical background. They accomplish these two objectives by imposing a temporal and directional coincidence requirement on data from two or more detectors, and by issuing low-latency alerts to maximize the probability that follow-up observatories

Figure 1. Schematic of the AMON system, indicating the different types of observatories with their approximate locations around the globe. The central point designates the location of the AMON servers at the Pennsylvania State University in University Park, PA, USA.

will see transient or unusual flaring activity in the specified direction. The SuperNova Early Warning System (SNEWS) [33] network, running for well over a decade, is an early example of a virtual observatory. SNEWS uses sub-threshold neutrino signals from multiple detectors to increase our aggregate sensitivity to supernova neutrino bursts. Started in 2009, the Astrophysical Multimessenger Observatory Network (AMON) [34, 35] has created a virtual observatory with multiple particle astrophysics detectors sharing their sub-threshold data in real-time, and multiple follow-up observatories agreeing to view regions of the sky in response to coincidence alerts. More recently, The Astronomy ESFRI and Research Infrastructure Cluster (ASTERICS) [36] is being constructed with similar goals in mind. We focus the rest of this proceeding on the design, current status and near-term future plans of AMON.

4. The Astrophysical Multimessenger Observatory Network (AMON)

4.1. Design

AMON provides a robust, high-uptime software framework for multiple particle astrophysics experiments to share data and increase their aggregate sensitivity to multimessenger transient events. Operating in real-time with low latency, it gathers sub- and above-threshold data, executes searches designed by the participating observatories for temporal and directional coincidences, and issues alerts for rapid follow-up to designated partner observatories. AMON also supports archival searches. A schematic of the network is shown in Fig. 1.

AMON simplifies coincidence searches by establishing a standardized event transmission scheme based on the VOEvent [37] protocol, by creating a cleaner interconnect topology between triggering and follow-up observatories, and by providing a straightforward connection to the Gamma-ray Coordinates Network (GCN) [38], a trusted conveyer of astrophysical alert information. The standardized events are distillations of the originating observatory's data and are sufficiently small in size to keep the aggregate accumulated data flowing into the AMON database to about one TB/yr. The database will enable archival analyses for estimation of false alarm rates and for in-depth study of the past multimessenger behavior of coincidence signals detected in real-time. Furthermore, observatories need only sign a single AMON Memorandum of Understanding (MoU) [39] to begin working with any of the other participating observatories. Figure 2 shows the general layout of the AMON system.

With the current AMON membership, 94% of 4π sr-yr is within the view of three or more observatories, and at least two observatories view any given part of the sky at the same time. A key requirement for any real-time follow-up operation, especially one with such high coverage,

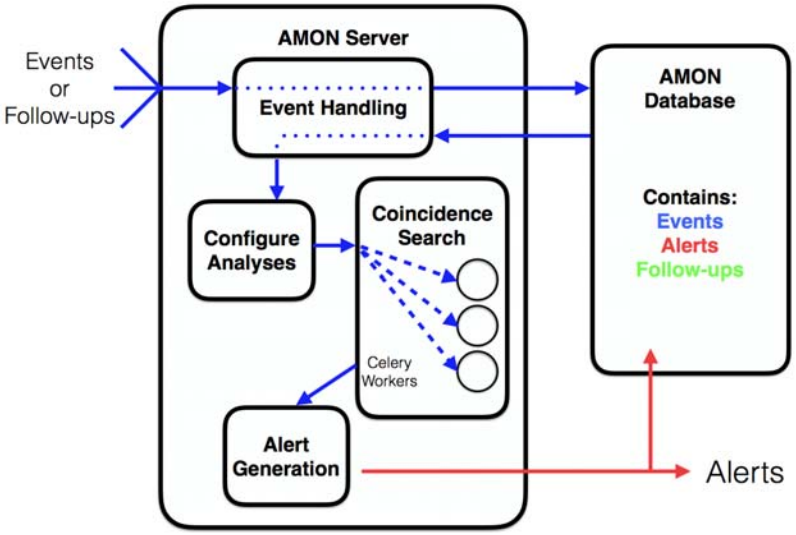

Figure 2. Diagram showing the processes running in the AMON servers. Events arrive at the server asynchronously (using the Python-based Celery [40] package), are written into the local database and simultaneously searched for coincidences based on pre-programmed algorithms provided by participating collaborations. Alerts are saved in the database and are also sent to GCN for broader (private or public) distribution.

is to maximize system uptime. AMON has met this goal by deploying two redundant, high-uptime servers in distinct physical locations. With full backup power and a clustered database, the system has experienced less than one hour of downtime per year during its first three years of operation.

4.2. Current Status

The first phase of AMON operations was to enter public data into the AMON database and perform archival searches for sub-threshold multi-messenger coincidences. This phase has been completed, with several published studies involving combinations of Fermi-LAT, VERITAS, and IceCube public data [41, 42]. The second phase of operations moved AMON into the real-time realm, with the system acting as a "pass-through" for IceCube real-time HESE and EHE neutrino alerts [43], and with prototype real-time sub-threshold analyses using scrambled data. The third and final phase will move AMON into true real-time operations, using sub-threshold data from participating triggering observatories and issuing alerts to follow-up observatories. Table 1 shows the observatories currently participating in AMON.

5. Conclusions

An impressive array of innovative and exciting particle astrophysics have come online in recent years, giving us access for the first time to astrophysical messengers from all four fundamental forces. Initially concentrating on making standalone discoveries of astrophysical sources, often focusing first on known sources of high-energy electromagnetic radiation, the collaborations subsequently teamed up with traditional EM telescopes to perform rapid follow-up with the aim of finding transient sources. AMON extends this program in a powerful way by enabling

Observ-atory	Stream name	Stream content	TLS certificates	Test (simulations)	Test (blinded data)	Real-time data
IceCube	singlet	✓	✓	✓	✓	in progress
IceCube	multiplet	✓	✓	✓	✓	✓
IceCube	HESE	✓	✓	✓	✓	✓
IceCube	EHE	✓	✓	✓	✓	✓
Pierre Auger	sub-threshold	✓	✓	✓	✓	in progress
FACT	sub-threshold	✓	✓	✓	✓	in progress
HAWC	daily-maps	✓	in progress	in progress	in progress	in progress
Swift BAT	sub-threshold	✓	n/a	n/a	n/a	✓
Fermi LAT	sub-threshold	✓	n/a	n/a	n/a	✓

Table 1. Status of the active AMON real-time streams. All the non-public data streams have been established and tested, and real-time operations have commenced for IceCube HESE and EHE pass-through data. Real-time operations with coincident searches using sub-threshold IceCube and HAWC data will begin soon.

triggering observatories to use sub-threshold data inaccessible to standalone analyses due to high backgrounds. Providing a real-time network, standardized data transfer and format protocols, AMON facilitates cooperation between disparate particle astrophysics observatories, leveraging the large investments in these cutting-edge detectors to enlarge their discovery space in a meaningful and potentially tranformative way.

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