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A cosmic multimessenger gold rush

***By* Joshua S. Bloom[1,2] *and* Steinn Sigurdsson[3]**

[1]Department of Astronomy, University of California, Berkeley, CA 94720, USA. [2]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA. [3]Department of Astronomy and Astrophysics, Penn State University, University Park, PA 16802, USA. Email: joshbloom@berkeley.edu

Merging neutron stars provide an electromagnetic counterpart to gravitational waves

Direct detection of gravitational waves (GWs) from black hole (BH) mergers began in earnest in 2015, but until this August, astronomers hunting for electromagnetic (EM) counterparts to GW events were left in the dark. Published in *Science*'s First Release this week, teams led by Kasliwal (*1*), Evans (*2*), Hallinan (*3*), and Coulter (*4*) detail the exciting search and discovery of a panchromatic transient, dubbed EM170817, which they argue is the first unassailable EM counterpart to a GW event. That event (GW170817) was promptly recognized by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo collaboration (*5*) as resulting from the merger of two neutron stars (NSs), compact stellar remnants about 40% more massive than the Sun but only a few kilometers in radius. The reported observations, connecting GWs to both gamma-ray bursts (GRBs) and a long-theorized—but hitherto undetected—short-lived EM transient represents a watershed moment in astrophysics.

Unlike BH coalescence, the merger of NSs is a messy astrophysical affair. Although most of the mass forms a nascent BH, several percent of a solar mass ($M_\odot$) of hot and heavy, neutron-rich material is flung outward at ~0.1 to 0.2 times the speed of light (c). It was postulated that this ejecta, as it expands and undergoes rapid nucleosynthesis, could give rise to a detectable EM transient (*6*). These kilonovae, named as such from a theoretical expectation that their peak brightness would be about 1000 times that of common novae (*7*), had never been conclusively observed. But 12 hours after GW170817, a team observing in Chile reported a new source (*4*) on the outskirts of a previously cataloged galaxy at a distance of 120 million light-years. Its position was consistent both with a GRB (*8*) and the GW event (preceding the GRB by 2 s) identified in offline analysis. Observers rushed to confirm this transient and determine its connection to GW170817. Consistent with expectations of a kilonova, its infrared light rose to peak brightness over the first few days.

Also as predicted, and unlike any other extragalactic transient, the temperature and bolometric luminosity of the transient dropped rapidly by the second day. The spectrum showed broad undulating infrared features consistent with large-velocity outflow (~$0.1c$). Although the individual spectral lines are blended, Kasliwal *et al.* suggest that the features are due to $>0.05M_\odot$ of heavy elements created during rapid explosive nucleosynthesis (called the r-process) (*9*). Estimating the cosmic rate of such events leads to the astonishing inference that merging NSs may be the dominant channel of r-process element creation in the universe. If true, we have some ancient NS merger in the solar neighborhood to thank for the world's store of gold and smartphones.

Merging NSs have long been considered candidates to produce short-duration extragalactic GRBs (*10*), whereby high-energy radiation comes from a narrow collimated relativistic (velocities very close to c) jet. However, using observations at radio, x-ray (*11*), and γ-ray wavebands, the studies reported here rule out such a classical GRB origin. Instead, they suggest that the merger remnant was shrouded in a cocoon, a hot ball of fast-expanding material. Here, the γ-rays (*8*) arise when the cocoon breaks through the slower-moving ejecta (see the figure).

NS mergers are a natural consequence of the discovery of NS binaries that are slowly spiraling toward each other as the binaries radiate GW energy (*12*). But, using known NS binaries in the Milky Way, extrapolations of the expected rate of such mergers in the detectable LIGO/Virgo volume have been uncertain. Ab initio simulations suggest that the rate depends on how many such systems are made over galaxy lifetimes, not how many are produced during recent star formation (*13*). If so, many GW/EM events will be detected in massive, old galaxies such as that which hosted GW/EM170817. Mergers in such galaxies should typically be offset from their birth location by thousands of light-years or more, having been kicked out of their stellar nurseries during formation.

EM170817 is now tucked away behind the Sun, and astronomers eagerly await its return to visibility. Indeed, late-time radio measurements may spatially resolve the expanded ejecta and help solidify (or refute) the theoretical models proposed. The discovery of more GW events in the coming years will help hone our understanding of the cosmic rate and, inevitably, portray a diversity of EM phenomenology. Will face-on mergers that also produce GWs accompany a more traditional short GRB and concomitant afterglow? Will highly inclined orbits lead to any detectable high-energy emission? We also look forward to other flavors of events, such as NS-BH mergers (which may be as abundant). Detecting high-energy neutrinos from NS mergers could lead to a deeper understanding of the physics of the relativistic outflows (*14*, *15*).

With three distinct GW sites operational at the same time, the GW localization was remarkably precise, not just on the sky, but in distance (which is encoded in the GW waveform). This allowed astronomers to focus on just a few known galaxies. Not all events will be so well localized, so close by, and so bright. Wide-field telescopes like the Zwicky Transient Facility (*16*) will be needed to quickly join the hunt for GW triggers. For those with visible-light instruments, it comes as some relief that EM170817 had appreciable optical emission, not entirely suppressed at early times by line blanketing. Now that we have at least one exemplar as a template, astronomers can also search for untriggered cocoon/kilonovae signatures in past and future imaging surveys.

As Scott Hughes of MIT noted at a high-energy astrophysics meeting just 5 days after GW170817, the "end of the beginning" for direct GW detections has arrived. However, these conclusive observations of EM signatures following a GW event is a crucial milestone, allowing in-depth study not just of the dynamical physics of space and time in the strong-gravity regime, but also the astrophysics of the progenitors and the connection to the well-studied transient universe.

These results are enriching and enlightening indeed—double meanings intended!

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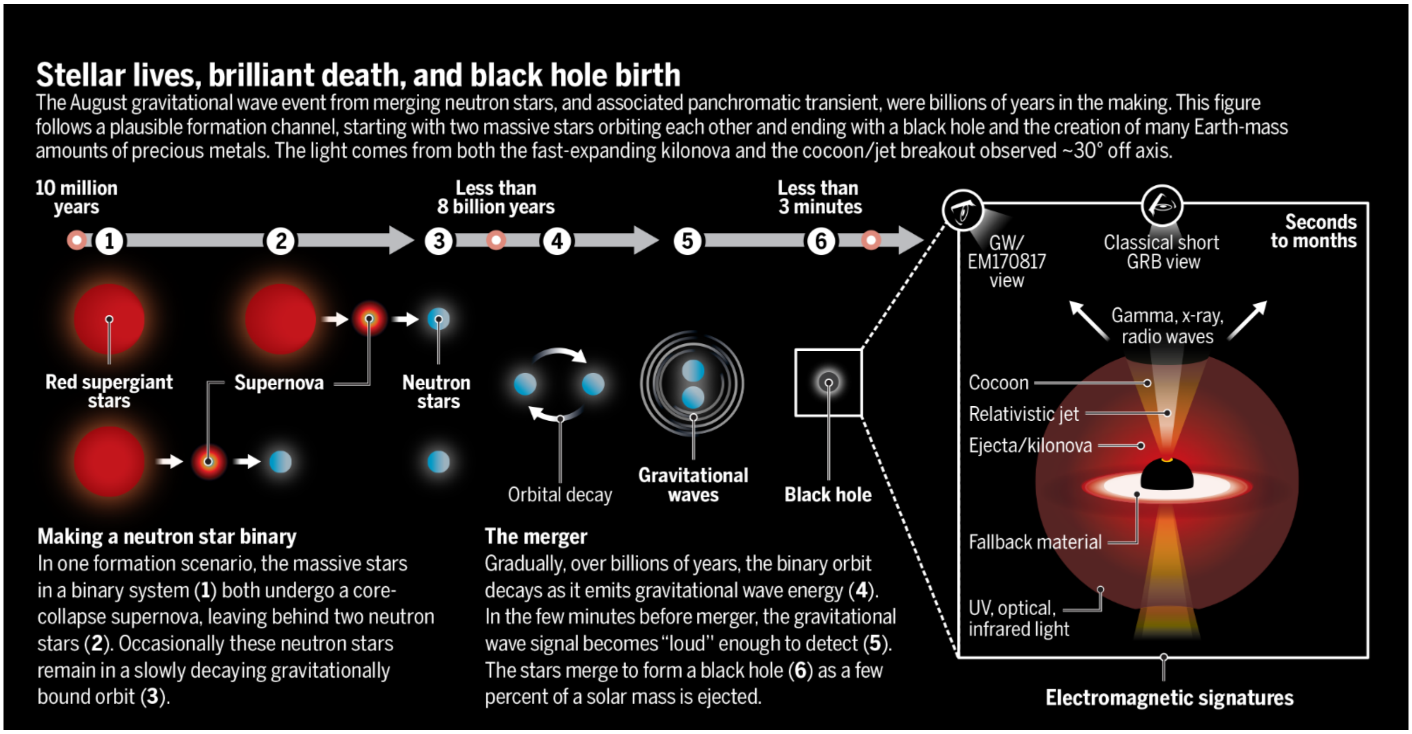

Stellar lives, brilliant death, and black hole birth
The August gravitational wave event from merging neutron stars, and associated panchromatic transient, were billions of years in the making. This figure follows a plausible formation channel, starting with two massive stars orbiting each other and ending with a black hole and the creation of many Earth-mass amounts of precious metals. The light comes from both the fast-expanding kilonova and the cocoon/jet breakout observed ~30° off axis.
10 million years
Less than 8 billion years
Less than 3 minutes
1
2
3
4
5
6
Red supergiant stars
Supernova
Neutron stars
Orbital decay
Gravitational waves
Black hole
GW/ EM170817 view
Classical short GRB view
Seconds to months
Gamma, x-ray, radio waves
Cocoon
Relativistic jet
Ejecta/kilonova
Fallback material
UV, optical, infrared light
Electromagnetic signatures
Making a neutron star binary
In one formation scenario, the massive stars in a binary system (1) both undergo a core-collapse supernova, leaving behind two neutron stars (2). Occasionally these neutron stars remain in a slowly decaying gravitationally bound orbit (3).
The merger
Gradually, over billions of years, the binary orbit decays as it emits gravitational wave energy (4). In the few minutes before merger, the gravitational wave signal becomes "loud" enough to detect (5). The stars merge to form a black hole (6) as a few percent of a solar mass is ejected.

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