Astro2020 Science White Paper

Core Collapse Supernovae and Multi-Messenger Astronomy

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☑ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☑ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics

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Abstract: Multi-messenger diagnostics for core-collapse supernovae (CCSN) have been used for over half a century when astronomers began using dust grains to probe the yields from supernovae. But the concurrent neutrino and electromagnetic observations of SN 1987A, a core-collapse supernova in the Large Magellanic Cloud, cemented the importance of multi-messenger diagnostics for these transients. Although rare in the Milky Way where supernovae can be probed by multiple messengers, the science enabled in each event is enormous. Most of the gravitational energy released during collapse is emitted in MeV neutrinos that should be detectable within a few Mpc with next generation (NG) neutrino experiments. They may also be detected by future gravitational wave (GW) interferometers. Including dust grains (and other nucleosynthetic yield probes), cosmic rays and high-energy neutrinos that probe shocks, and a broad range of thermal and non-thermal photon emission, these messengers probe nearly all aspects of the supernova physics and its progenitor evolution. The multitude of diagnostics from a nearby supernova will allow us to tightly constrain our theories to maximize what we can learn about the universe from more distant, but less-well diagnosed, supernovae.

1 Introduction: CCSN affect many aspects of astronomy, ejecting many of the elements heavier than beryllium into their host galaxy, driving the matter flow in these galaxies, producing neutron stars and black holes, and powering some of the brightest transient outbursts in the universe. As such, it is not surprising that a wide range of diagnostics has been used to better understand supernovae. Electromagnetic emission probes a range of supernova engine and progenitor properties. Gamma-rays from radioactive decay and dust grains probe the production of elements (and through this production, the explosion energy). High-energy gamma-rays, cosmic-rays and high-energy neutrinos have the potential to probe the shock properties. Thermal neutrinos and GWs each probe different properties of the central engine powering the supernova.

CCSN are driven by the potential energy released when a massive star's core collapses down to a proto-neutron star. The collapse of the core is halted by neutron degeneracy and nuclear forces. This produces a bounce shock that moves through the star until it stalls (because it loses energy through neutrino emission and dissociation of the shocked material). Although the details are not completely known despite nearly 25 years of multi-dimensional simulations (Herant et al., 1994; Fryer & Young, 2007; Takiwaki et al., 2014; Lentz et al., 2015; Melson et al., 2015; Burrows et al., 2018; Radice et al., 2018), it is believed that hydrodynamic instabilities above the proto-neutron star and below the stalled shock are able to increase the efficiency at which the potential energy is converted into kinetic energy to drive an explosion (only a few % is needed to produce a successful explosion). Understanding this engine and its implications is important to both understanding how CCSNe shape their host galaxies and using these CCSNe to probe the early universe.

The breadth of some of the messengers makes it difficult to make a one-to-one correspondences between the messenger and the specific part of CCSNe it probes. For example, thermal photons, MeV radioactive decay photons, and shock accelerated/cosmic ray produced gamma-rays all come from very different physical sources and different features of the explosion. Multi-messenger observations add to the broad set of probes, studying the CCSN engine, the stellar structure, and the circumstellar medium as well as aspects of the physics ranging from dense nuclear matter and neutrino physics to particle acceleration in shocks. Although many diagnostics are limited to nearby events, using these messengers to calibrate our understanding will allow us to better understand CCSNe observed with limited diagnostics at large distances. In the next 6 sections, we review these multi-messenger signals individually, concluding with a brief description of how these messengers tie together to place strong constraints on the explosions produced in stellar collapse.

2 Electromagnetic Emission: The electromagnetic emission from core-collapse CCSNe probe a range of properties of both the progenitor and the explosive engine, depending both upon the wavelength observed and the phase of the CCSN explosion. Shock breakout, peak light-curves, and late-time nebular phases all probe different aspects of the CCSN.

Shock breakout is the term used to describe the burst of UV/X-ray photons arising from the CCSN shock as it breaks out of the star and the radiation is no longer trapped in the flow. Simple analytic models suggest that this emission can be used to probe the stellar radius, but this radiation is also sensitive to both the transition region between the star and its wind as well as the broader characteristics (e.g. turbulence in the winds, explosive mass loss phases) of the stellar wind (Bayless et al., 2015; Lovegrove et al., 2017). Swift has dramatically increased the number of observed shock breakout events (Modjaz et al., 2009; Roming et al., 2010; Huang et al., 2018), and NG transient telescopes have been designed to dramatically increase the observed database of

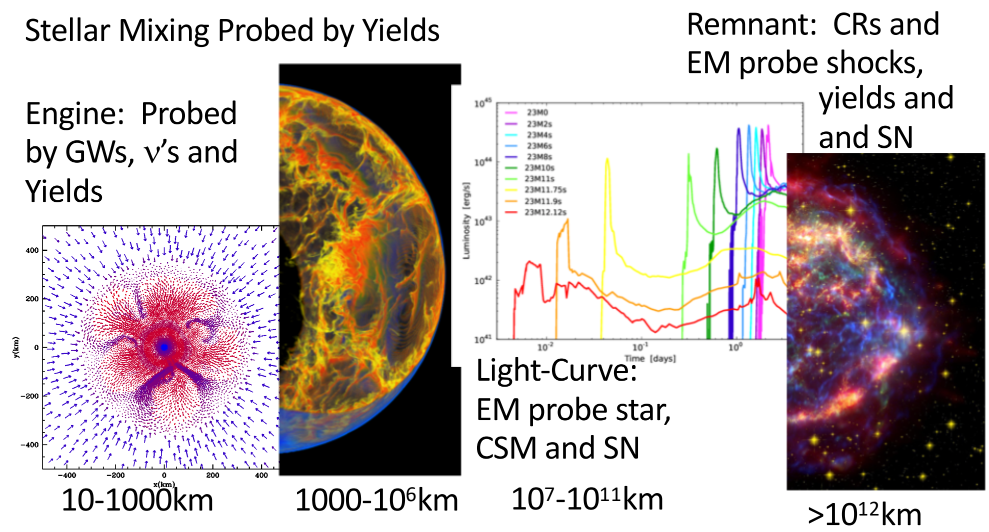

Figure 1: CCSN observations probe a broad range of physics and aspects (regions, timescales) of a CCSN. This figure shows different regions from the inner engine to shock interactions, labeling which diagnostics probe each region. GWs, neutrinos, and yield measurements probe the inner engine, yields can also probe stellar mixing. EM observations of the CCSN emission probe both aspects of the CCSN and the circumstellar medium. At later times, shocks accelerate particles and observations can probe this acceleration physics.

shock breakout observations (e.g. Roming et al. (2018)). In addition, increasingly sophisticated models of this phenomenon are being developed (e.g., Bayless et al. (2017)). Comparing these models to observations will allow astronomers to probe the stellar transition and wind characteristics of massive stars.

Astronomers have gathered a large amount of data of the CCSN light-curve at peak emission, both broad-band emission and spectra (Filippenko, 1997). Although these observations can be made to large distances, the theoretical models of this phenomenon depend upon a complex set of physics, and even determining the ejecta mass from this emission can be problematic. A complete first-principles calculation will include uncertainties that limit the modeling errors including the implementation of opacities in a relativistic outflow as well as shock-heating effects. Despite these uncertainties, studying CCSNe out to large distances provide probes of the early star formation rate, galactic chemical evolution, galactic dynamics, metallicity effects on stellar evolution and compact object formation, . . . To fully take advantage of this rapidly-growing data set of extragalactic CCSNe, we must leverage well-studied, nearby events. The broad diagnostics from multi-messenger observations of a CCSN will allow astronomers to better understand the physics behind CCSN light-curves, verifying our models so that light-curve observations can probe the ejecta mass, CCSN energetics and composition.

The complex physics simplifies, to some extent, at late-times when the CCSN becomes increasingly optically thin. Although the atomic physics must be modeled in detail to determine the out-of-equilibrium level states, and much more work (together with atomic physics) must be done to make precision models, simulations exist that can be used to probe the details of the ejecta composition (Maurer et al., 2011). Measuring the composition (as we shall discuss in section 3) places strong constraints on the progenitor evolution and the CCSN explosion. This phase occurs after the peak of the light-curves, and the data for such CCSNe are limited to those within 100 Mpc (encompassing the Virgo cluster).

SN 1987A had the distinction of being the first CCSN whose progenitor, Sanduleak -69 202°, was serendipitously observed prior to its collapse and the formation of the CCSN (Walborn et al., 1989). Because astronomers had spectra and images of the region where SN 1987A resided prior to explosion, they could pinpoint the progenitor star by determining which star disappeared after the emission from the CCSN died away. The spectral and luminosity characteristics of the progenitor could then be compared to stellar models for classification. Surveys with the Hubble Space Telescope have dramatically improved the number of CCSN progenitor observations (Smartt, 2009). Although there are uncertainties in current stellar models that make it difficult to infer the exact characteristics of the stellar progenitor from, usually serendipitous, observations, these observations place among the strongest constraints on CCSN progenitors and, hence, ejecta mass, in a CCSN explosion. A better understanding of stellar models coupled to new high-angular resolution survey telescopes will dramatically increase the strength of this probe.

3 Nucleosynthetic Yields: The nucleosynthetic yields of CCSNe probe both the progenitor evolution and the explosion properties. One of the primary uncertainties in stellar modeling is the nature of shell burning. Approximations in the mixing and overshoot of material make it difficult to determine even the extent of this burning. Alpha elements are an ideal probe of the size of these shell layers. In addition, rare, neutron-rich isotopes probe detailed aspects of this shell burning. The distribution of isotopes produced near the proto-neutron star surface also provides strong probes of the explosive engine. The mixing of ^{56}Ni in SN 1987A was what led scientists to pursue the current standard engine behind CCSNe (Arnett et al., 1989; Colgate et al., 1993) and these observations have been used to probe the asymmetries in CCSNe (Hungerford et al., 2005). More recently, the ^{44}Ti distribution in the Cassiopeia A remnant (Grefenstette et al., 2017) provided a direct probe of the asymmetries in the engine, supporting the standard convective engine and refuting jet models.

Observations of nucleosynthetic yields are broad multi-messengers in themselves. They are observed in IR/optical/UV spectra, especially in the nebular phase (Black, 2018), in gamma-ray decay lines both during the explosion and in the diffuse interstellar medium (Walborn et al., 1989; Grefenstette et al., 2017), in CCSN remnants (Guest et al., 2019), in stellar spectra after they are re-incorporated into new stars (Nomoto et al., 2013), in interstellar dust grains (Draine, 2003), and in stardust grains recovered from meteorites (Nittler & Ciesla, 2016). These observations span a wide range of diagnostics and scientific fields. In some cases (e.g. ^{56}Ni and ^{44}Ti production and detection in hard X-ray and gamma-rays), the theory is well developed and these observations can be used to study various aspects of CCSN. NG hard X-ray and gamma-ray detectors will expand what we can study with these remnants. In others, calculating the yields from the observation requires detailed theoretical analysis and errors associated with the analysis are major uncertainties. The data from a Galactic CCSN with full bandwidth electromagnetic observations will produce a detailed map of a wide range of yields. In addition, the analysis of individual CCSNe stardust grains for their isotopic composition contain information on the nucleosynthesis yields and on mixing processes that led to the formation of these dust grains. New instruments to measure the isotopic composition of these stardust grains (e.g., Stephan et al., 2016) recently started allowing us to determine isotopic abundances of multiple elements in individual, μm-sized grains (Stephan et al., 2018).

4 Compact Remnants: Compact object binaries, low and high-mass X-ray binaries, binary pulsars, and now, GW detected binaries, measure both the mass and spin of the compact remnants. The remnant masses of both neutron stars and black holes have been shown to depend on the growth of convection in the engine and the mass distributions have been used to help probe the CCSN engine (Fryer et al., 2012).

Remnant spins probe the stellar boundary layers and coupling between these boundary layers. Highly coupled stars produce low-spinning cores (as is observed in low-mass stars). However, the birth spin rate of pulsars and black holes in X-ray binaries suggests that some stellar cores are spinning relatively rapidly at collapse (Miller & Miller, 2015). In contrast, constraints on the spin rates of binary black hole systems from GW detections suggest slower spinning cores (Belczynski et al., 2017). Each observation probes its own subset of systems and understanding these differences and how they fit together is key in utilizing this probe. Current and NG detectors will continue to grow the database of remnant masses and spins and we expect this wealth of data to help produce a coherent picture that will then constrain CCSN progenitors and engines.

5 Cosmic Rays: Particle acceleration in shocks (e.g. Fermi acceleration) can produce high energy electrons and ions that, in turn can produce high energy neutrinos and gamma-rays. Observations of these particles could potentially constrain aspects of the shock. But, given the our understanding of particle acceleration mechanisms, observations of these messengers are a more important constraint on the acceleration model itself. By understanding this acceleration mechanism, we understand better the sources of cosmic rays in the universe.

6 Neutrinos: 99% of the energy released in a CCSN is emitted in neutrinos and 10^5 neutrinos would be detected with current and next generation detectors (Super-Kamiokande, DUNE, JUNO, IceCube). Along with GWs, neutrinos provide a probe of the central collapsing core (properties of the collapse, bounce and the hydrodynamic instabilities in the CCSN engine). In addition, neutrinos have the potential to probe nuclear and neutrino physics from neutrino oscillations to multi-body interactions developing in matter at extreme densities (e.g.Fuller (2002)). This science will be limited to nearby supernovae (e.g. in the Milky Way) for current and near-term neutrino detectors (Seadrow et al., 2018).

Although NG detectors will not be able to detect individual supernovae out to the Virgo cluster, the detection of the diffuse flux of neutrinos coming from all CCSNe in our universe is finally within reach (Beacom, 2010). Its detection will mark the beginning of a new era in neutrino astronomy. The observation of the diffuse supernova neutrino background with NG neutrino detectors has the potential to place limits on the CCSN populations (Møller et al., 2018).

7 GWs: GWs are produced in the collapse, bounce and engine phase of CCSNe. The strongest GW signal is produced in rapidly rotating stars and GWs are an ideal probe of stellar rotation. GWs also probe asymmetric collapse and the convective engine. A concurrent detection of GW and neutrinos will enable a test of our current understanding of the CCSN mechanism.

Fast rotating stars are susceptible to a wide range of instabilities including fragmentation and secular or dynamical instabilities. These instabilities produce extreme emission of GWs. If these instabilities occur, the signal from CCSN can be detectable by aLIGO out to 10 Mpc (Abbott et al., 2016; Fryer et al., 2002; Fryer & New, 2011). The LIGO A+ upgrade (with a planned start time in 2024) is expected to be $\sim$70% more sensitive, potentially allowing astronomers to observe fast-rotating CCSNe out to the VIRGO cluster. This will greatly increase the rate of detections. Certainly, the proposed LIGO Voyager upgrade (late 2020s) will be able to detect these out to the VIRGO cluster. The planned future generation detectors planned in late 2030s, like Cosmic

Explore or Einstein Telescope, will be able to detect these instabilities ten times further than aLIGO (Abernathy et al., 2011). The uncertainty lies in the number of systems with such high angular momenta. Observations and theory already constrain the role of rotation to some extent. The birth period of pulsars is roughly 100-150 ms with a Gaussian spread of an equal magnitude (Faucher-Giguère & Kaspi, 2006; Popov & Turolla, 2012). The rotation rates needed to produce strong GW signals would produce sub ms pulsars and such pulsars appear to be rare.

For these most-likely systems, the expected GW signal is roughly $\Delta L/L \sim 10^{-21}$ at 10 kpc and, for systems within a few kpc, an aLIGO signal will be able to study the details of the instabilities above the proto-neutron star (Powell et al., 2017). Because of differences in the GW signal between convection, rotation and asymmetric collapse, Milky Way CCSNe will be able to determine asymmetries and rotation in stellar collapse. High rotation (and/or a more sensitive detector) is needed to detect a CCSN beyond the Milky Way.

8 Summary: In CCSN, what we can study depends upon the distance. While much of the thermal emission (shock breakout, primary light curves, nebular phase) can be observed out to the Virgo cluster and beyond, many other signals are currently limited to events in the Milky way itself. For example, a CCSN at a few kpc, aLIGO will get a strong enough signal to probe the details of the convective engine and current neutrino-detectors will probe detailed equation of state physics and NG γ-ray detectors will probe detailed nuclear yields produced at all layers in the star. If the CCSN is within the Milky way, aLIGO will probe the nature of rotation and asymmetric collapse and NG GW detectors will be able to probe the hydrodynamical instabilities. Neutrino detectors will probe non-standard physics scenarios. NG $\gamma - ray$ detectors will probe key isotopes produced in the star and the explosion. Cosmic ray detectors will be able to test models accelerating particles in shocks. As we move out to the local group, many of our diagnostics will continue to place constraints (both through detections and non-detections) but, in many cases, the signal will not be strong enough to study detailed physics. NG detectors will allow stronger constraints for GWs and neutrinos through the local group. NG $\gamma - ray$ detectors will probe ^{56}Ni decay in the local group.

As detectors improve, a broad range of diagnostics will be able to reach the Virgo cluster. Improved transient detectors will increase the number of shock breakout events. Better detectors will increase the number of CCSNe studied in the nebular phase. As survey telescopes improve, the number of progenitors observed prior to the CCSN explosion will also increase, increasing the database of CCSN progenitors to truly constrain the stars that produce CCSN. In addition, stellar surveys and enhanced studies of dust grains will improve our understanding of galactic chemical evolution and isotopic abundances.

Only a few diagnostics can be used at large distances and many of these (emission at peak luminosity) are based on complex theory and their potential is limited by the lack of understanding in this theory. However, if we can validate (and, more likely, calibrate) these models with well-studied nearby events, we can use these distant diagnostics to study CCSN into the early universe.

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