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Catching Element Formation In The Act

The Case for a New MeV Gamma-Ray Mission:
Radionuclide Astronomy in the 2020s

A White Paper for the 2020 Decadal Survey

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Stan Woosley, University of California Santa Cruz
Jin Wu, Argonne National Laboratory
Chris Wrede, Michigan State University
Shoichi Yamada, Waseda University
Patrick Young, Arizona State University
Remco Zegers, Michigan State University
Michael Zingale, Stony Brook University
Simon Portegies Zwart, Leiden University

Thematic Areas:
PRIMARY: Stars and Stellar Evolution
SECONDARY: Galaxy Evolution

Projects/Programs Emphasized:
1. All-sky Medium Energy Gamma-ray Observatory (AMEGO)
`https://asd.gsfc.nasa.gov/amego/`
2. e-ASTROGAM
`http://eastrogam.iaps.inaf.it`
3. Compton Spectrometer and Imager (COSI)
`http://cosi.ssl.berkeley.edu`
4. Electron-Tracking Compton Camera (ETCC)
5. Lunar Occultation Explorer (LOX)

1 Executive Summary

Gamma-ray astronomy explores the most energetic photons in nature to address some of the most pressing puzzles in contemporary astrophysics. It encompasses a wide range of objects and phenomena: stars, supernovae, novae, neutron stars, stellar-mass black holes, nucleosynthesis, the interstellar medium, cosmic rays and relativistic-particle acceleration, and the evolution of galaxies. MeV γ-rays provide a unique probe of nuclear processes in astronomy, directly measuring radioactive decay, nuclear de-excitation, and positron annihilation. The substantial information carried by γ-ray photons allows us to see deeper into these objects, the bulk of the power is often emitted at γ-ray energies, and radioactivity provides a natural physical clock that adds unique information.

New science will be driven by time-domain population studies at γ-ray energies. This science is enabled by next-generation γ-ray instruments with one to two orders of magnitude better sensitivity, larger sky coverage, and faster cadence than all previous γ-ray instruments. This transformative capability permits: (a) the accurate identification of the γ-ray emitting objects and correlations with observations taken at other wavelengths and with other messengers; (b) construction of new γ-ray maps of the Milky Way and other nearby galaxies where extended regions are distinguished from point sources; and (c) considerable serendipitous science of scarce events – nearby neutron star mergers, for example. Advances in technology push the performance of new γ-ray instruments to address:

- ⋆ How do white dwarfs explode as Type Ia Supernovae (SNIa)?
- ⋆ What is the distribution of ^{56}Ni production within a large population of SNIa?
- ⋆ How do SNIa γ-ray light curves and spectra correlate with their UV/optical/IR counterparts?
- ⋆ How do massive stars explode as core-collapse supernovae?
- ⋆ How are newly synthesized elements spread out within the Milky Way Galaxy?
- ⋆ How do the masses, spins, and radii of compact stellar remnants result from stellar evolution?
- ⋆ How do novae enrich the Galaxy in heavy elements?
- ⋆ What is the source that drives the morphology of our Galaxy's positron annihilation γ-rays?
- ⋆ How do neutron star mergers make most of the stable r-process isotopes?

Over the next decade, multi-messenger astronomy will probe the rich astrophysics of transient phenomena in the sky, including light curves and spectra from supernovae and interacting binaries, gravitational and electromagnetic signals from the mergers of compact objects, and neutrinos from the Sun, massive stars, and the cosmos. During this new era, the terrestrial Facility for Rare Isotope Beams (FRIB) and Argonne Tandem Linac Accelerator System (ATLAS) will enable unprecedented precision measurements of reaction rates with novel direct and indirect techniques to open perspectives on transient objects such as novae, x-ray bursts, kilonovae, and the rapid neutron capture process. This ongoing explosion of activity in multi-messenger astronomy powers theoretical and computational developments, in particular the evolution of community-driven, open-knowledge software instruments. *The unique information provided by MeV γ-ray astronomy to help address these frontiers makes now a compelling time for the astronomy community to strongly advocate for a new γ-ray mission to be operational in the 2020s and beyond.*

2 Supernovae And Other Cosmic Explosions

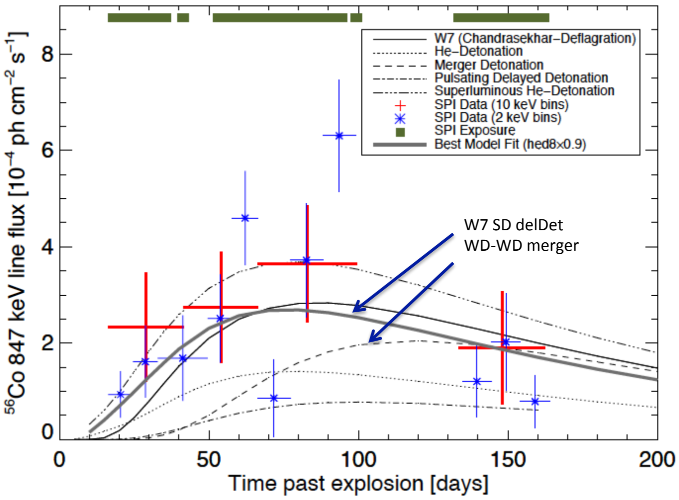

Figure 1: *SN2014J was the first SNIa within reach of current γ-ray telescopes*[14;27;28]*. As the signal from ^{56}Co γ-rays is split into temporal bins, statistical precision is compromised (blue: 11 time bins; red: 4 time bins; 1D models are shown as dashed/dotted/solid curves). Non-spherical effects may be more important than 1D models indicate, based on the measurements of radiation processed by the supernova envelope. A future γ-ray telescope will measure many SNIa with a significantly improved precision that complements UV/optical/IR measurements.*

Empirically, SNIa are the most useful, precise, and mature tools for determining astronomical distances[49]. Acting as standardizable candles[15;90;91] they revealed the acceleration of the Universe's expansion[96;88] and are being used to measure its properties[129;40;35;89]. In stark contrast, the nature of the progenitors and how they explode remains elusive[124;69]. The lack of a physical understanding of the explosion introduces uncertainty in the extrapolations of the characteristics of SNIa to the distant universe. In addition, SNIa are expected to be a major source of iron in the chemical evolution of galaxies[12;72;120;64;17], cosmic-ray accelerators[31;98], kinetic energy sources in galaxy evolution[106;71], and a terminus of interacting binary star evolution[51;127;118;32]. Essentially all SNIa light originates in the nuclear γ-rays emitted from the radioactive decay of ^{56}Ni synthesized in the explosion[16], making their detection the cleanest way to measure the poorly constrained ^{56}Ni mass. This bonanza of astrophysical puzzles highlights the need for a multi-spectral approach to study such explosions – extending to the deployment in space of a new and significantly better γ-ray telescope.

A line sensitivity 1–2 orders of magnitude better than previous generation instruments ($\simeq 1 \times 10^{-7}$ ph cm^{-2} s^{-1} for broad lines over the 0.05–3.0 MeV range) and a large field of view ($\gtrsim 2.5$ sr) will, for the first time, unlock systematic time-domain SNIa population studies. High-precision measurements of the ^{56}Ni γ-ray light curve (see Fig. 1) can check and improve the optical/IR derived luminosity-width relation. Measuring SNIa γ-ray light curves beginning within 1 day of the shock breaching the stellar surface and extending to 100 days, coupled with resolving key radionuclide line features (not just ^{56}Co)[99] in the spectra every 5 days, of 10-100 events/yr out to distance of ≤ 100 Mpc, will provide a significant improvement in our understanding of the SNIa progenitor system(s) and explosion mechanism(s). Time-domain characterization of the emergent SNIa γ-rays will facilitate the extraction of physical parameters such as explosion energy, total mass, spatial distribution of nickel masses[29], and ultimately lead to the astrophysical modeling and understanding of progenitors and explosion mechanisms. The relevant γ-ray light curves can be extracted from integrated MeV spectra (bolometric), resolved nuclear lines, or physics-motivated energy bands. Detection of several SNIa will distinguish between the models; population studies involving $\gtrsim 100$ SNIa will be transformational.

An MeV γ-ray mission will also act as an early time monitor/alert system of SNIa in dusty environments like the Milky Way plane and nearby starburst regions. Dust obscuration could delay optical/IR identification of a SNIa for $\gtrsim 2$ weeks, but a γ-ray line detection will be a unique means of identifying SNIa as early as $\lesssim 10$ days, especially if surface ^{56}Ni exists as suggested by SN2014J γ-ray observations[92;27;52] (see Fig. 1), increasing early detection rates and maximizing science returns.

A new γ-ray radionuclide mission is timely: the current *INTEGRAL* and *NuSTAR* missions are in their late phases. A new γ-ray radionuclide mission improved by technological advances made in the past decade will provide unique data of significant interest across a range of topics to the broad astronomical community, complementary to the multi-messenger data also provided by *JWST*, *LSST*, *ALMA*, *TESS*, *fermi*, *TMT*, *GMT*, *SKA*, *Gaia*, *IceCube*, *CTA*, *JUNO*, *FRIB*, *ATLAS* and *LIGO*.

Cataclysmic variables are semi-detached binary systems consisting of a white dwarf accreting from a low mass stellar companion[58;38;103;54;84]. They are progenitors for nova events, with classical novae being the most optically luminous subclass[53;109;78]. Some classes of novae may be the progenitors of a population of SNIa[45;102;108;109;101]. Two types of MeV γ-ray emission are expected from novae: prompt emission from e^-e^+ annihilation with the e^+ originating from ^{13}N and ^{18}F, and a longer-lasting emission from ^{7}Be and ^{22}Na decays[62;39]. The prompt emission has a $\lesssim 1$ day duration and appears $\simeq$ 1–2 weeks before optical maximum, and the longer-lasting emission persists for $\simeq 0.1$–3 yr. Recent UV detections of a few novae suggest the ^{7}Be ejecta mass is larger than current 1D models produce[110;111;76]. A next-generation γ-ray mission as described above will allow, for the first time, systematic time-domain studies of novae populations. Such explorations will address key uncertainties about mixing between the accreted matter and the white dwarf, the conversion of radioactivity into optical emission, and the contribution of novae to galactic enrichment. In addition, measurements at facilities such as *ARIEL*, *ATLAS*, and *FRIB* and stable beam facilities will approach a complete set of reaction rates for classical novae[7] on a similar timeline for a next-generation gamma-ray mission.

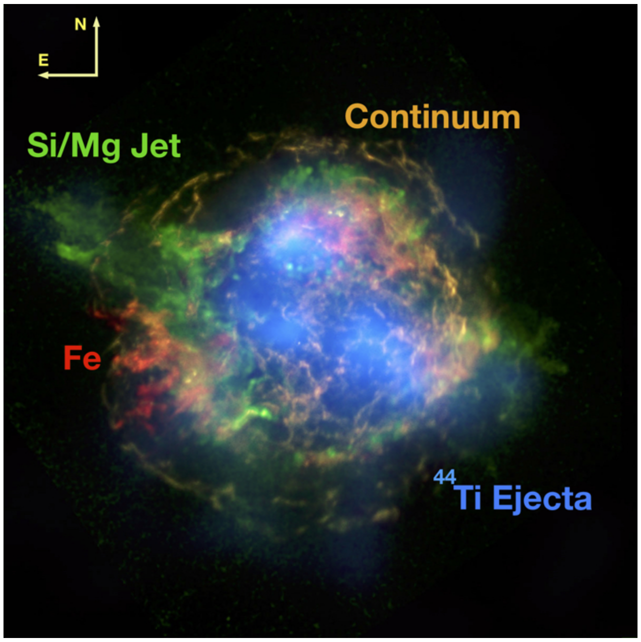

Figure 2: *3D distribution of Cas A ejecta. NuSTAR ^{44}Ti in blue, Chandra continuum in gold, Si/Mg band in green, X-ray emitting iron in red*[43].

Other cosmic explosions such as core-collapse supernovae (CCSN), pair instability supernovae, neutron star mergers, fast radio bursts, and gamma-ray bursts are also expected to exhibit key signatures about their interior workings that can be observed with a modern γ-ray telescope. For example, the spatial distribution of elements in young supernova remnants directly probes the dynamics and asymmetries traced by, or produced by, explosive nucleosynthesis[80;128].

One crucial diagnostic in young remnants is the relative production of ^{44}Ti, ^{56}Ni, and ^{28}Si. These have indirectly been observed in X-rays from atomic transitions, and γ-rays from radioactive decay have shown how this can be misleading about where the newly-formed elements actually reside (see Fig. 2). The physical processes that produce these isotopes in CCSN depend on the local conditions of the shock during explosive nucleosynthesis[115;116;131;119;68;13]. The isotope ^{44}Ti ($\tau_{1/2} \simeq 60$ yr[44;3]) offers a key diagnostic of the explosion mechanism[94;50;41;9;42;43] because its synthesis is the most sensitive to the local conditions. For example, Cas A was an excellent target for current γ-ray instruments because it is young ($\simeq$ 340 yr) and nearby ($\simeq$ 3.4 kpc). Its ejecta has been monitored for decades at X-ray/optical/IR wavelengths, which are now understood to only provide complementary insight into the dynamics and asymmetries of a young supernova remnant[34;22;95;74;4;65], while radioactive decay unambiguously traces the flow and dynamics of new ejecta.

To date, only Cas A and SN 1987A have been used to place constraints on CCSN progenitors and explosion mechanisms[114;104;60;100;121]. A new MeV γ-ray mission with the characteristics described above will detect $\simeq$ 8 young supernova remnants in the Milky Way[30] and provide a precise abundance measurement of ^{44}Ti in the remnant of SN 1987A[41;9;121]. New measurements of a few CCSN in their ^{44}Ti light will add to our knowledge; population studies with a four-times larger sample size to determine the variation in ^{44}Ti yields from CCSN will be groundbreaking.

3 Tracing Chemical Evolution

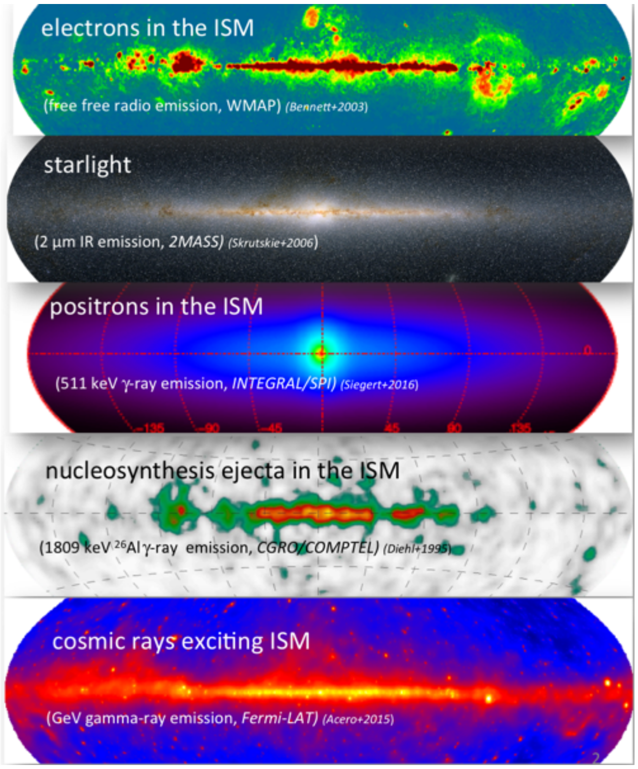

Figure 3: *Deciphering the Milky Way. A modern MeV γ-ray instrument will help solve how newly created elements are produced, transported, mixed, and distributed.*

The star-gas-star cycle operating in the evolution of galaxies includes at least four phases where MeV γ-ray astronomy provides unique and direct diagnostics of cosmic explosions and chemical evolution. (1) The ejected yields of radionuclides by stars and explosive nucleosynthesis events tell us about the otherwise hidden conditions of nuclear fusion reactions in these sites. (2) The flow of stellar ejecta into the ambient gas (i.e., mixing in chemical evolution) is directly traced by radionuclides over their radioactive lifetimes, which is possible because the γ-ray emitting nuclear decays are independent of the thermodynamics or composition of the ambient gas. (3) Positrons emitted by radioactive decays, visible through their annihilation γ-rays, tell us about the nucleosynthesis in individual events and the structure and dynamics of the Galaxy. (4) Nuclear de-excitation γ-rays caused by cosmic ray collisions with the ambient gas provide the most direct measurements of the cosmic ray flux at MeV energies and illuminate otherwise invisible fully-ionized gas (e.g., the hot ISM and IGM). These four items are the science drivers for a new γ-ray mission in the 2020s.

Because their lifetimes are long (ten times longer than observables at any other wavelength) compared to the interval between massive star supernovae, yet abundant enough to yield detectable emission when they decay, the radionuclides ^{26}Al ($\tau_{1/2} \simeq 7.3\times10^5$ yr[82;117]) and ^{60}Fe ($\tau_{1/2} \simeq 2.6\times10^6$ yr[97;85]) are valuable tools of γ-ray astronomy for advancing our global understanding of massive stars and their supernova explosions. This includes the complex late phases of stellar evolution[130;11;20;19;10;79;83], actions of neutrinos[36;86;87] and supernova shockwaves[8;33], and how ejecta of new elements from these sources are spread in galaxies[57;123]. The clock inherent to emission from radioactivity again helps here, as in the case of Cas A above, to illuminate otherwise invisible, tenuous gas flows. The short-lived radionuclides ^{26}Al, ^{60}Fe, ^{53}Mn, and ^{182}Hf present in the early Solar System play a pivotal role in constraining its formation and chronology. Furthermore, ^{26}Al is the major heating source for thermal and volatile evolution of small planetesimals in the early Solar System[122;61;77;112;66].

Current γ-ray instruments measure the diffuse emission from ^{26}Al and ^{60}Fe decays in the inner portions of the Milky Way Galaxy[93;107;25;125] (see Fig. 3), and the bulk dynamics of ^{26}Al through Doppler shifts and broadening of the γ-ray line for 3–4 massive-star groups / OB associations[70;26;59]. This provides a key test for models of stellar feedback in galaxies, including massive-star winds, supernova explosion energy, and abundance mixing physics. A new γ-ray instrument with a line sensitivity 1–2 orders of magnitude better than previous instruments ($\simeq 1 \times 10^{-7}$ ph cm^{-2} s^{-1} for broad lines over 0.05–3.0 MeV), angular resolution of 1–2°, and energy resolution of 0.1% (to differentiate the emission lines from specific OB associations against the diffuse radioactive afterglow of stellar activity), will increase the number of γ-ray observed OB associations by an order of magnitude to 25–35 based on observed distances to OB associations[70;26;73].

Another signal addressed by the same new γ-ray telescope is positron annihilation and its characteristic γ-ray spectrum, including a line at 511 keV. Current telescopes have established a morphology of our Galaxy's annihilation γ-rays peaking in the inner Galaxy[56;126;105], while most candidate sources reside in the Galaxy's disk. Solving this puzzle includes re-examining cosmic rays, supernovae[21], pulsars, microquasars, the Fermi bubbles, neutron star mergers[37], and possibly dark matter emission.

4 When Opportunity Knocks

A new MeV γ-ray observatory offers considerable serendipitous science for uncommon or surprising events such as a nearby CCSN, neutron star merger, or fast radio burst[23]. Their detection in γ-rays could entirely restructure our understanding of both the transient itself and its implications for astrophysics as a whole. For example, a detector with a line sensitivity 50 times greater than current instruments will detect 7 radioactive isotopes (^{48}Cr, ^{48}V, ^{52}Mn, $^{56-57}$Co, $^{56-57}$Ni) from a CCSN occurring within 1 Mpc and 7 more (^{43}K, ^{44}Ti, ^{44}Sc, ^{47}Sc, ^{47}Ca, ^{51}Cr, ^{59}Fe) if within 50 kpc. These radionuclides provide a unique and powerful probe of the explosion of massive stars[81;24]. Similarly, γ-rays from the radionuclides produced during the r-process[18] in a neutron star merger such as GW170817[1;2] would be detectable at 3-10 Mpc[48]. Exact yields from GW170817 are difficult to determine from optical/IR measurements alone, and it is not settled that GW170817 produced the heavy r-process elements[63;18;46;47]. A sufficiently strong γ-ray signal, coupled with a set of multi-messenger signals, could distinguish between light and heavy r-process production to possibly cement neutron star mergers as the dominant r-process site.

5 Imagining the Future

The time is ripe for the astronomy community to strongly advocate for a new MeV γ-ray mission to be operational in the 2020s. Such a mission will be based on advanced space-proven detector technology with unprecedented line sensitivity, angular and energy resolution, sky coverage, polarimetric capability, and trigger/alert capability for, and in conjunction with, other multi-messenger instruments. Potential missions include *AMEGO*[5], *COSI*[55], *e-AstroGAM*[6], *ETCC*[113], *HEX-P*[67], and *LOX*[75]. A new MeV γ-ray mission will open unique windows on the Universe by making pioneering observations of cosmic explosions and the flow of their newly created elements into Galactic ecosystems.

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