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Nuclear Gamma-Ray Astrophysics

*uncovering how supernovae and other stellar explosions work to create the elements**

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Mark Leising[1], Steven Boggs[2], Cornelia Wunderer[2], John Beacom[3], Roland Diehl[4], Neil Gehrels[5], Dieter Hartmann[1], Margarida Hernanz[6], Mark McConnell[7], Peter Milne[8], Uwe Oberlack[9], Gerry Skinner[5], Sumner Starrfield[10], Allen Zych[11]

[1] Physics & Astronomy, Clemson University
[2] Space Sciences Laboratory, UC Berkeley
[3] Physics, Astronomy, Ohio State University
[4] Max Planck Institut für extraterrestrische Physik, Garching
[5] Astrophysics Science Division, NASA Goddard Space Flight Center
[6] Institut de Ciències de l'Espa, Barcelona
[7] Space Science Center, University of New Hampshire
[8] Steward Observatory, University of Arizona
[9] Physics & Astronomy, Rice University
[10] Physics, Arizona State University
[11] Physics, UC Riverside

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Nuclear γ-ray Astrophysics

"to uncover how supernovae and other stellar explosions work to create the elements"

Since the collapse of matter into galaxies and stars much of the visible matter in the Universe has been through the slow but spectacular lifecycle of matter: stellar formation and evolution ending in explosion and ejection of new elements to seed new generations of stars. We and our solar system are products of this cycle. In explaining the solar system abundances of the elements, nuclear astrophysics is a fifty-year-long tale of scientific success. This tale continues as we seek to explain the ongoing nuclear evolution of the Galaxy and the Universe in detail.

The potential of γ-ray lines as a tool to study nucleosynthesis has long been clear. Direct counting of newly synthesized radioactive nuclei as they reach γ-ray thin regions can elucidate more clearly nuclear burning processes than any other observations, except for direct neutrino measurements. The photons are penetrating, so even entire galaxies are insignificant obstacles. However, thick detectors are necessary to stop them, and with no γ-ray optics yet employed, large collection areas required large detector areas, and thus massive detection systems. Operating these above the Earth's atmosphere resulted in large photon and particle backgrounds, limiting sensitivity and making data analyses challenging. Many predictions long preceded even the possibility of experimental verification[1,2]. A series of later predictions have guided the experimental directions of the field[3,4,5,6,7,8]. Many of these detections have now been accomplished, but their full potential is far from being realized with high-precision measurements. Since pioneering space experiments thirty years ago, sensitivities have improved by only a factor of ten. Comparing this to visible wavelengths, with eight orders of magnitude improvement in sensitivity from first telescopes to contemporary ones, or ten orders of magnitude for radio telescopes from Jansky to the VLA, it is clear that a vast space for discovery in γ-ray lines remains to be explored. Technology improvements, including smarter, more efficient detectors, and high-energy lenses and mirrors now allow us to realize the potential of this field.[9,10,11,12]

Nuclear astrophysics is attacking some the most pressing astrophysical questions of our time, including understanding the physics of thermonuclear and core-collapse supernovae and their nucleosynthesis contributions to cosmic chemical evolution. Sensitive γ-ray line studies will provide the most direct insights into these objects.

Supernovae and Nucleosynthesis

Supernovae synthesize most of the elements heavier than carbon and supply much of the energy input to the interstellar medium. Most of the newly created atoms are indistinguishable from preexisting atoms; however, radioactive species among the ejecta serve as definitive tracers of the nuclear processing. The γ-ray lines from the decay of these nuclei reveal the location of the radioactivity within the ejecta through the time-dependence of the photon escape, and the ejection velocities of various layers from the line Doppler profiles. Therefore spectroscopy and light curve measurements of these γ-ray lines allow direct measurement of the underlying explosion physics and dynamics. The lines from interstellar nuclei show a unique picture of ongoing nuclear and high-energy processes throughout the Galaxy.

Standard Candles & Alchemists

SNe Ia, the thermonuclear explosions of degenerate white dwarfs, are profoundly radioactive events. As much as one-half of the white dwarf mass is fused to ^{56}Ni ($\tau_{1/2}$ =6.1d). After a short time, the decays of this nucleus and daughter ^{56}Co ($\tau_{1/2}$ =77d) power the entire visible display of the supernova. Most of this power, however, originates in the form of γ-ray lines, some of which begin to escape after several days (Fig. 1). These γ-rays are the most direct diagnostic of the dominant processes in the nuclear burning and explosion.

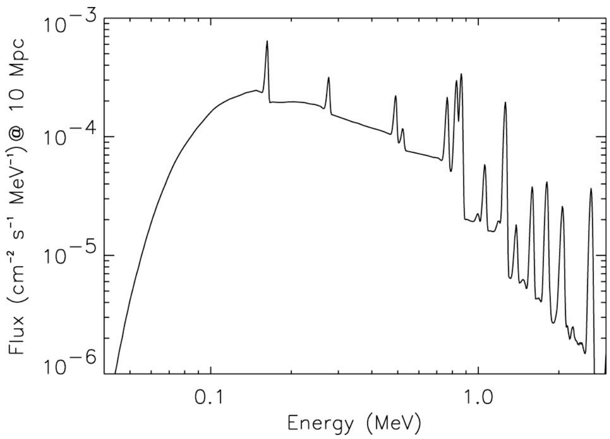

Fig. 1. *The γ-ray spectrum of delayed detonation model DD202c*[25] *at 25 days post-explosion. At this time lines of both* ^{56}*Ni (158, 749, 812 keV) and* ^{56}*Co (847, 1238, 2599, 511 keV) are prominent, as well as the Compton-scattered continuum. At this time, the Ni lines are declining while the Co lines are rising.*

Fundamental questions about these explosions remain unanswered. We do not understand:

- The physics behind the empirical calibration of their absolute magnitudes that allows them to be used as standard candles for measuring acceleration of the Universe.
- The nature of the progenitor systems[13]– whether the white dwarf companions are normal stars or other white dwarfs.
- How the nuclear flame propagates, how it proceeds as fast as it does, if, or where, it turns into a shock[14].
- To what extent instabilities break spherical symmetry, or whether their effects are wiped out by subsequent burning.

Thermonuclear supernovae are grand experiments in reactive hydrodynamic flows. Fundamental uncertainties in the combustion physics lead directly to differences in ^{56}Ni yields and locations[15], which in turn are directly observable with a sensitive γ-ray telescope. Previous attempts to detect ^{56}Co emission, a primary goal of earlier missions, were unsuccessful due to the instrument sensitivities and supernova distances[16,17,18].

Nuclear γ-ray lines from SNe Ia hold the key to solving these puzzles. There are two primary goals of these studies:

1. Standard Candles. Characterize the ^{56}Ni production distribution for SNe Ia, and correlate with the optical lightcurves to determine the relationship between empirical absolute magnitude corrections and ^{56}Ni production.

2. Explosion Physics. Clarify the nuclear flame propagation by measuring total and ^{56}Ni masses and their kinematics for a key handful of SNe Ia, to uniquely distinguish among current models of SNe Ia explosions.

Understanding Standard Candles

Although our understanding of SNe Ia is incomplete, they are used as calibrated standard candles to measure cosmologically significant distances - with dramatic implications[19,20]. Though their absolute magnitudes scatter, the Phillips relation is used to calibrate them based on their decline rates. This empirical relation assumes there is a one to one mapping between duration and luminosity[21]. Whether there is one characteristic of the explosion that determines both is not known[22]. Whether the same relationship should hold exactly to redshifts of unity and beyond, when, for example, the metallicity of the systems was lower, is also not clear[23]. Complete confidence in the accuracy of using SNe Ia to measure such distances awaits better understanding of the explosions themselves.

Direct correlation between the optical properties and the ^{56}Ni production – which is principal factor in the optical lightcurve variations – is key to these studies. Other possible causes of the light curve variation can be studied in γ-rays, such as ^{56}Ni distribution in velocity (through spectroscopy), and total ejecta mass (through light curve monitoring.) Such measurements will directly probe the underlying physical mechanisms driving the variations in visible light. Understanding the explosion mechanism and dynamics from near events will allow much greater effectiveness of the use of SNe Ia at high z, such as with the SNAP mission.

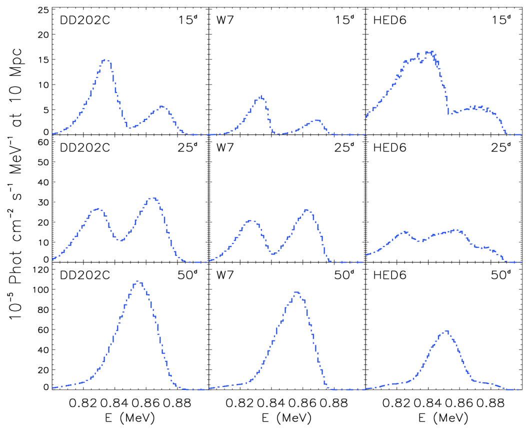

Fig. 2. *The spectrum near 800 keV of three models described in the text at three epochs (15, 25, 50 days, top to bottom, since explosion.) These models can be distinguished by sensitive single observations of modest energy resolution (~100) or by longer-term monitoring of the γ-ray light curves.*

Uncovering the Explosion Physics

Three dominant SNeIa scenarios have emerged: (1) Single CO white dwarfs grow to the Chandrasekhar mass by accretion; (2) Double white dwarf mergers; and (3) Helium shell detonations triggering thermonuclear runaways in sub-Chandrasekhar mass white dwarfs. Within the generally favored first scenario, the nuclear flame can proceed entirely sub-sonically as a deflagration, or it might accelerate into a detonation in the outer layers of the exploding white dwarf (a delayed detonation). Fig. 2 shows three models for comparison: a Chandrasekhar mass deflagration (W7[24]), a delayed detonation (DD202C[25]) and a sub-Chandrasekhar mass explosion (HED8[25]). The γ-ray spectra from merger scenarios are likely intermediate between sub-Chandrasekhar mass models and Chandrasekhar mass models.

To succeed we must clearly discriminate among these models for ≥ one SNe Ia per year, and therefore to distance 20 Mpc. With peak line fluxes of $\sim 10^{-5}$ cm^{-2} s^{-1} for even near SNe Ia (~15 Mpc), it is clear that a significant improvement in sensitivity over previous and current missions, by a factor 30-50, is required. With such sensitivity, several tens of SNe Ia will be detected per year.

While the combined information from optical and γ-ray studies will be crucial, γ-ray data alone will constrain the models. The differences between the models manifest themselves in both the light curves and the Doppler-broadened profiles of the nuclear emission lines (Fig. 2). These lines are broadened to 3–5%, so that broad line sensitivity is the most important instrumental requirement; good energy resolution would provide valuable additional information.

SNe Ia Gamma-Ray Background

It should be possible[26] to measure the cosmic star formation history from the diffuse cosmic background of γ-rays from the integrated SNe Ia in the universe. The accumulated redshifted γ-ray line spectra form a continuum, with its normalization and spectral features probing the rate and redshift evolution of the contributing SN Ia. While both COMPTEL and SMM measured a γ-ray continuum in the MeV region[27,28], it was unclear if it could be associated with the expected SN Ia signal[29,30]. The normalization of the SN Ia prediction was quite uncertain, and the data were not precise enough to conclusively test for the expected spectral features.

The SN Ia contribution to the cosmic γ-ray background depends on three ingredients: (1) the cosmic star formation rate history, (2) the progenitor models of SNe Ia, which determine the efficiency and time delay with which newly formed stars produce SN Ia, and (3) the γ-ray emission per SN Ia. Recent improvements in the measurements of the star formation rate and cosmological parameters have helped constrain (1). Assuming ~0.6 M_{sol} of ^{56}Fe per SN Ia, and the limited SN Ia rate data available, the SN Ia contribution to the cosmic γ-ray background falls short of the measured data[31].

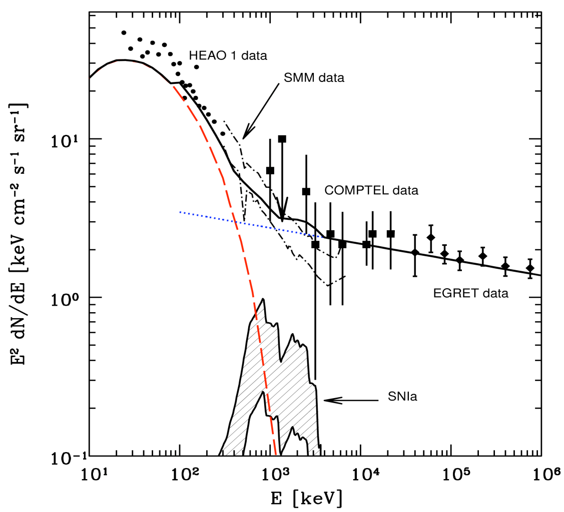

Fig. 3. *The γ-ray background, as measured by the HEAO-1, SMM, COMPTEL and EGRET instruments[32]. The expected contributions from active galaxies, Seyferts (red-dashed) and blazars (blue-dotted), are shown to reasonably reproduce the HEAO-1 and EGRET data. The shaded band is the contribution from SN Ia for one choice of the star formation history.*

If this star formation rate and SNe Ia delay are correct, there is presently no accepted explanation for the MeV cosmic γ-ray background. Extrapolations of the backgrounds from active galaxies may account for some of the data (Fig. 3). The MeV region is of special importance for constraining models of exotic physics, e.g., dark matter decay or annihilation[31]. In order to make further progress on resolving this puzzle, better characterization of the rates and emission from both SNe Ia and active galaxies are needed, as well as a detailed measurement of the MeV spectrum.

The Radioactive Milky Way

Diffuse line emissions from interstellar radionuclides, electron-positron annihilations, and nuclear excitations by accelerated particles afford us the opportunity to study stellar evolution, the ongoing production of the elements, and the most energetic processes throughout the entire Milky Way. The decay of ^{26}Al shows directly (Fig. 4) a million years of massive star and supernova activity[33]. A deep, wide-field survey would enable detailed study of the production of ^{44}Ti, ^{26}Al, and ^{60}Fe in various types of supernovae. With greatly improved sensitivity and angular resolution, we expect these apparently diffuse emissions to be resolved, at least in part, into hundreds of distinct regions, associations, and individual objects.

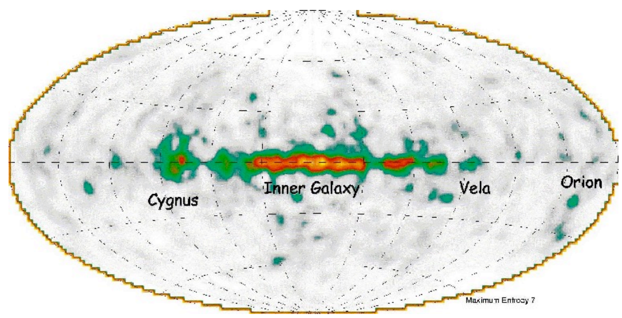

Fig. 4. *CGRO/COMPTEL image of the full sky in the intensity of the 1.809 MeV line of ^{26}Al decay[33].*

^{26}Al Decay

The proton-rich isotope ^{26}Al decays to the first excited state of ^{26}Mg at 1.809 MeV with mean lifetime of 1.04×10^6 yr. This is the most apparent radioactivity in the sky. In the *CGRO* COMPTEL map we see a line flux of ~3×10^{-4} cm^{-2} s^{-1} from the central Galaxy (longitudes ±30°), and smaller fluxes from a handful of other star-forming regions[33]. A source related to population I stars, most likely massive star winds and explosions, best explains this distribution. With a wide-field instrument surpassing COMPTEL and INTEGRAL/SPI sensitivity by an order of magnitude or more, we could expect to see ^{26}Al 1.809 MeV emission from nearby clusters, OB associations, and individual supernova remnants, as well as from stellar ejecta already merged into the interstellar medium. Any minor contributions from longer-lived progenitors, AGB stars and classical novae might be identifiable from their smooth spatial distributions or sites far from any recent star formation. Through this nuclear decay we can study global galactic nucleosynthesis[34], the massive star content and evolution of associations, and – given improved sensitivity – the nucleosynthesis yields of individual objects, including the dynamics of a handful of supernova remnants. For example, precise measurements of the ^{26}Al yield from nearby Wolf-Rayet star γ^2 Vel, and from the Vela and Cygnus Loop supernova remnants, will constrain models of those events and allow us to use the global galaxy observations to understand the rates and distributions of these sources. With an instrument capable of resolving e.g., the Vela SNR, we could also study the dynamics of the mass ejection, such as, for example, whether the fast fragments seen in X-rays also contain ^{26}Al. The nearest AGB stars and classical novae could be studied to finally assess directly their contributions to the global ^{26}Al production. For nearby star forming regions, such as the Orion molecular clouds, where the present stellar inventory is well documented (and where there is some evidence of ^{26}Al line emission), we would have the chance to study the massive-star inventory of the recent past.

^{60}Fe Decay

The neutron-rich isotope, ^{60}Fe ($\tau_{1/2}$ =1.5 My) is ejected by core-collapse supernovae from some of the same regions as ^{26}Al. RHESSI and INTEGRAL have detected[35] line emission from ^{60}Co, the shorter-lived daughter of ^{60}Fe. Measuring the total galactic production as well as individual source yields of ^{60}Fe and ^{26}Al will provide unprecedented constraints on core collapse nucleosynthesis calculations. If the nuclear flame proceeds slowly in the initial burning in thermonuclear supernovae, a significant older stellar population could also be seen in ^{60}Fe emission. The spatial comparison of these two million-year radionuclides will teach us about the nucleosynthesis of both, clarify the contributions of different sources, and constrain hydrostatic and explosive nucleosynthesis models.

Core-Collapse Mass Cut and Jets

In core collapses, ^{44}Ti ($\tau_{1/2}$=59 y) is in the deepest material ejected, providing an excellent probe of the explosion mechanism, specifically how the large neutrino energy is transferred to the inner ejecta. NuSTAR, with its sensitivity to the 68 and 78 keV lines from ^{44}Ti, will make great strides in these studies on known sources such as Cas A and SN 1987A. If the solar abundance of ^{44}Ca, which is almost certainly produced as ^{44}Ti, is made in normal supernovae, then with the next-generation γ-ray survey we expect discovery of several more ^{44}Ti supernova remnants in the inner Galaxy. If axial jets occur in core-collapses, as suggested by current understanding of GRB's, some ^{44}Ti and other radioactivity might be ejected with relatively high velocity[36]. High spectral resolution observations will allow this matter to be distinguished from the slower core material. Moreover, spatial resolution of nearer remnants, possibly in several isotopes and via positron annihilation, will permit a complementary study of the dynamics of the explosion and expansion.

Cosmic Ray Interactions

The light elements Li, Be and B are thought to come from cosmic-ray/ISM nuclear interactions. The 10–100 MeV/nucleon cosmic rays responsible dominate heating of some phases of the ISM, yet are otherwise undetected. The de-excitation γ-rays from spallation reactions (namely from C and O) should be detectable just below current sensitivities from the 3-kpc molecular cloud ring and from nearby star forming regions if particle acceleration occurs in the vicinity of dense phases.

Classical Novae

The basic nova description, a surface thermonuclear runaway on a white dwarf has been in place for four decades, yet many commonly observed features remain unexplained. Studies of the ejected radioactivity, ^{7}Be, ^{22}Na, and ^{18}F, in γ-ray lines offer again a uniquely powerful diagnostic of the nova systems and physics therein.[37]

Positron Astrophysics

The bright positron annihilation line and triplet-state positronium continuum delineate the escape of positrons from extreme environments over a million years. Interstellar positrons entrained in galactic magnetic fields provide part of the complex 511 keV map, which should include individual supernova remnants and stellar and compact object wind nebulae, and possibly the galactic center. With energy resolution of ~0.5% at 511 keV, the conditions in the various annihilation media will be revealed through the line profile and the annihilation physics.

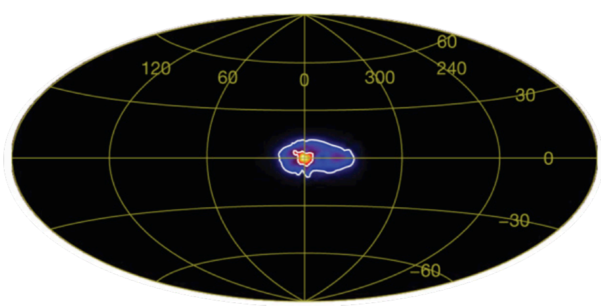

***Fig. 5**. The intensity of the 511 keV line as mapped by INTEGRAL/SPI. The apparent flux is dominated by the bulge component, whose positrons are of unknown origin. The weak disk shows an asymmetry, similar to that of hard LMXB's.*

Despite the fact that the 511 keV line produced by the annihilation of positrons with electrons is the brightest γ-ray line in the sky, the source of the Galaxy's bulge positrons remains a mystery. Efforts to solve this puzzle will include investigating the spatial distribution, the time-variability, the line profile, and the fraction of positron-electron annihilations that occur after the temporary formation of the hydrogen-like positronium bound state.

CGRO/OSSE and INTEGRAL/SPI observations (Fig. 5,6) suggest a constant emission that features a very large bulge contribution compared to what is expected from the bulge emission at other wavelengths[38,39,40]. The bulge emission is apparently diffuse, rather than from a point source near the galactic center. New theories are being explored to explain the bulge and/or halo positrons. Mapping the spatial distribution of this emission, as well as constraining the time-variability, is limited by the low S/N of the current measurements.

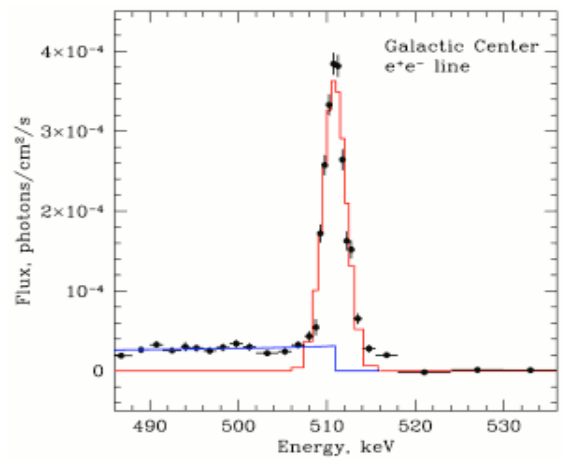

***Fig. 6**. INTEGRAL/SPI spectrum of the e^+e^- annihilation radiation from the galactic bulge. Red shows the annihilation line model; blue shows the three photon continuum of the ortho-positronium decay[43].*

The line-to-continuum ratio suggests that ≥93% of positron-electron annihilations occur after first forming positronium[39]. The profile of the 511 keV line appears to be composed of two components, a narrow line (~1.5 keV wide), and a broader line (~6 keV)[41]. Collectively, the positronium fraction, line widths and narrow-to-broad line ratio are consistent with the expected signature of positron-electron annihilation occurring in a warm medium[42,41,43]. The intense bulge emission dominates this conclusion so far, but a more sensitive instrument with spatially resolved spectroscopy will enable investigation of the positron annihilation locally in the galactic disk and the halo as well. The mystery of the positron sources underscores the infancy of positron astrophysics. Potential sources include hypernovae from an episode of starburst activity in the bulge[44], SNe Ia[45,46], pulsar winds[47], and annihilation or decay of proposed light dark matter particles[48,49,50].

These potential sources reflect the myriad ways in which positrons are produced in nature. Only with much more detailed study of the annihilation photons will the positron yields and transport from the sources be understood. The apparent asymmetry of the disk emission might offer clues to the source(s)[51].

Advances will be achieved by producing superior global maps of annihilation radiation and by its detection from individual compact objects and SNRs. As an example, collective study of nearby SNe Ia remnants (e.g. Tycho's SNR, SN 1006, Lupus Loop) will quantify the contribution of type Ia SNe to galactic positrons. Positron escape from a nearby SN Ia could be observed directly via the 511 keV line to 847 keV line ratio[52]. For each of the potential sources, observations of individual objects will offer new insight into the physics of that source, and into its contribution to the global galactic positron budget.

Synergies

Sensitive γ-ray line studies will measure nucleosynthesis yields with 1-10% precision, challenging astrophysics theory for explanations for decades (c.f., ^{44}Ti in Cas A); provide confidence – perhaps corrections – to the use of supernovae as probes of dark energy; offer unique constraints on candidate dark matter particles; complement X-ray studies of abundances in supernova remnants and galaxy clusters; and show multiple new global views of the multiwavelength Milky Way and its ongoing chemical evolution. Now is the time to realize this long-discussed potential.

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