Death of Massive Stars (DoMaS) Probe

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I. INTRODUCTION

The death of massive stars is a fundamental process in the shaping of the Universe. The first massive stars are considered a significant contributor to reionization and the dispersal of the first metals. These first stars also form the seeds for the formation of supermassive black holes (e.g. 1-2). Later generations continue the production and dissemination of heavy elements, which shape planets, solar systems, future generation of stars, and galaxies. They form the neutron stars and black holes in the universe, dictating the characteristics and formation rates of X-ray binaries, X-ray bursts and gravitational wave sources (e.g. 3-5). Despite their importance, the nature of the first stars, when and how they reionized the Universe, and how massive stars end their lives, is not well understood. An astrophysics probe-class mission with greatly expanded capabilities, such as DoMaS, will readily address these problems.

II. SCIENCE DRIVERS

Massive stars end their lives as gamma-ray bursts (GRBs) and supernovae (SNe). Because of their extreme luminosities, GRBs are excellent probes for addressing the nature of the first stars and when and how they contributed to reionization, while the shock breakout (SBO) of SNe is one the best tools for ascertaining the nature and death of massive star progenitors.

2.1. Nature of the First Stars and Their Contribution to Reionization

The first stars are arguably massive (e.g. 6) and some will end their lives as GRBs (e.g. 7). Sufficiently high signal-to-noise (S/N) spectra of the corresponding afterglows will deliver measurements of the HI fraction in the IGM at the redshift of the bursts (i.e. 8). These afterglows will be exceptionally valuable targets for such studies, as they have featureless, synchrotron power-law spectra, permitting straightforward identification of the absorption signatures, thus uncovering the metallicity and ionization states in their host galaxy. These spectra will reveal the history of reionization, including variations along multiple sight lines; the escape fraction of ionizing radiation from high-z star forming regions, an important variable in reionization models; and the processes of metal enrichment in the early Universe.

2.2. Nature and Death of Massive Star Progenitors

The first electromagnetic signature in the death of massive stars is the SN SBO, which is strongly manifested in the soft X-ray and EUV regimes (e.g. 9-10; Fig. 1). High S/N spectra within seconds to minutes after the SBO event will uncover the true nature of the physics behind these events, an area that is still poorly understood. The properties of the SBO – such as temperature, energy, and photon diffusion time (11) – provide a powerful way of exploring the photosphere of the star and constraining the SN progenitor. These spectra are superb probes of: stellar radii, which are key in eliminating major uncertainties in binary population synthesis models (e.g. distinguishing between compact mergers being black holes and double neutron star systems - important for LIGO); stellar mass-loss that reveal the quantity of mass lost for different stars, ultimately determining the remnant mass distribution; and stellar mixing, crucial for removing major uncertainty in stellar evolution and SNe, including nucleosynthesis and galactic chemical evolution. Detection of SBOs also provides an alert to observers of a new SN immediately after core collapse.

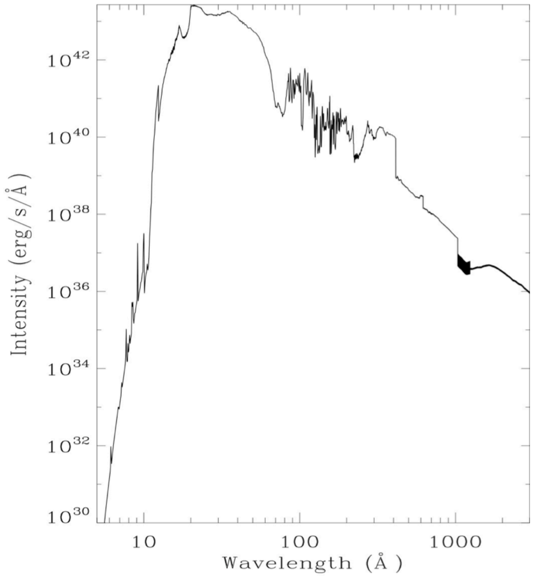

Fig 1. SBO model for a core-collapse SN. Peak flux is found in the soft X-ray and EUV regions.

2.3. Ancillary Targets

Although not drivers of observatory requirements, due to the survey nature of the previous two science cases, important astrophysical targets of various kinds will also be observed. These include lower redshift sub-luminous, short, and long GRBs; thermonuclear bursts; flare stars; SNe Ia breakouts; superfast X-ray transients; classical novae; tidal disruption events; blazars; AGNs; soft γ-ray repeater flares; and hot OB stars with winds, to name a few.

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III. TECHNICAL CAPABILITIES

To address the first science problem, DoMaS requires GRB detection and afterglow instruments that are particularly sensitive to high-z GRBs. For GRB detections at high-z, the optimal instrument is a wide-field soft X-ray telescope (WFSXT) rather than one tuned for the harder X-ray or gamma-rays (cf. 12). Using the new and exciting Lobster-eye technology, such an instrument can achieve sensitivities that are 100 times better than current coded apertures (13). Afterglow follow-up requires a large aperture (~1m) narrow-field near-IR telescope (NIRT) capable of medium resolution slit spectroscopy in order to capture the afterglow at its brightest and maximize the spectral S/N. Based on a fluence of ~10^{-9} erg cm^{-2} and field-of-view (FoV) for the WFSXT, convolved with models of high-z GRBs based on *Swift*, *Fermi*, and CGRO data (14), DoMaS would detect ~350 $z>8$ GRBs and ~30 $z>12$ in a 5-year mission.

Tackling the second science question necessitates detection and follow-up spectroscopy of SNe SBO events. As with GRBs, because of their paucity, detecting breakout events requires a wide FoV instrument such as WFSXT. For follow-up spectroscopy, a medium aperture (~50cm) narrow-field far-UV telescope (FUVT) capable of medium resolution slit spectroscopy is required for capturing strong key diagnostic lines. Based on the FoV of the WFSXT and the core-collapse SNe rate (e.g. 15), DoMaS would detect ~400 SBO events out to 100 Mpc in a 5-year mission.

A near-geostationary orbit with telescopes pointed anti-sun is ideally suited for this observatory. The WFSXT will continuously monitor the sky for GRB and SBO events, while the narrow-field instruments observe formerly triggered events or ancillary science targets. When the WFSXT triggers an event, the spacecraft rapidly (~0.5°/s) slews to the target allowing the co-aligned narrow-field instruments to begin immediate observations. Public rapid notifications of the target location, brightness, and redshift are sent through TDRSS to ground-based observers. Key instrument parameters are provided in Table 1. The total cost for the observatory, based on cost models (MICM, NICM, PCEC), is $762M in FY16 dollars.

Table 1. Key Instrument Parameters

Telescope	Energy/ Wavelength	Angular Resolution	FoV	Resolving Power (R)	Sensitivity
WFSXT	0.2-5.0 keV	1 arcmin	2.4 sr	40	1.6×10^{-11} erg cm^{-2} s^{-1}
NIRT	0.7-2.5 μm	1 arcsec	30 arcmin	1000	3.9×10^{-20} erg cm^{-2} s^{-1} Å^{-1} @ 1.6 μm in 1 s
FUVT	130-300 nm	1 arcsec	30 arcmin	1000	2.4×10^{-17} erg cm^{-2} s^{-1} Å^{-1} @ 1700 Å in 1 s

IV. NEW TECHNOLOGIES

With the exception of a GaN microchannel plate (MCP), all technologies are TRL 6 or higher. The GaN MCP is at TRL 4 and is estimated to be at TRL 6 or higher within a 5-year period.

V. PROBE-CLASS MISSION NEED

Because of the rarity of high-z GRBs, a steradian-level FoV is required for the WFSXT. A MIDEX-class mission is not capable of accommodating the required number of WFSXT modules to achieve such a FoV. Rapid high S/N spectroscopic follow-up requires an ~1m NIRT which also cannot be accommodated on a MIDEX. The high-z GRB science objectives are readily met within a probe-class mission.

Simulations show that SBO physics is much more complex than the simple semi-analytic models predict, while full transport calculations reveal that the details of the explosion can also alter the SBO. A high event rate (which can't be done with a MIDEX for the same reason as GRBs), but reasonable narrow-field follow-up is needed to constrain the explosion parameters and extract information about the stars from the observations.

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