The Observational Signatures of Primordial Pair-Instability Supernovae

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Abstract.
Massive Population III stars from 140 - 260 M⊙ ended their lives as pair-instability supernovae (PISNe), the most energetic thermonuclear explosions in the universe. Detection of these explosions could directly constrain the primordial IMF for the first time, which is key to the formation of the first galaxies, early cosmological reionization, and the chemical enrichment of the primeval IGM. We present radiation hydrodynamical calculations of Pop III PISN light curves and spectra performed with the RAGE code. We find that the initial radiation pulse due to shock breakout from the surface of the star, although attenuated by the Lyman-alpha forest, will still be visible by JWST at z ∼ 10 - 15, and possibly out to z ∼ 20 with strong gravitational lensing. We have also studied metal mixing at early stages of the explosion prior to breakout from the surface of the star with the CASTRO AMR code and find vigorous mixing in primordial core-collapse explosions but very little in PISNe. This implies that the key to determining progenitor masses of the first cosmic explosions is early spectroscopy just after shock breakout, and that multidimensional mixing is crucial to accurate low-mass Pop III SNe light curves and spectra.

INTRODUCTION

The masses of the first stars, or the primordial IMF, is key to the character of the first galaxies, the chemical enrichment and reionization of the early IGM, and the origin of the supermassive black holes found at the centers of most massive galaxies today. No direct observation of Pop III stars can yet constrain the Pop III IMF. However, detection of the first cosmic explosions could determine the masses of their progenitors, and thereby the Pop III IMF. Stellar evolution models predict that 15 - 50 M⊙ stars die in core collapse supernovae (SNe) and that 140 - 260 M⊙ stars die in much more energetic PISNe [2]. We have performed radiation hydrodynamical simulations of the light curves and spectra of primordial PISNe in anticipation of their discovery by JWST and the next generation of transient detection satellites.

SIMULATIONS

We performed a suite of ten numerical simulations with the RAGE code, an Eulerian adaptive mesh refinement radiation hydrodynamics code developed at Los Alamos National Laboratory (LANL) [1]. We considered five zero-metallicity and five Z = 10^{-4}Z⊙ progenitors with masses of 150, 175, 200, 225 and 250 M⊙. The progenitor stars were first evolved in the 1D implicit hydrodynamics code KEPLER and then exploded. The
PISN LIGHT CURVES AND SPECTRA

In the left panel of Figure 1 we show bolometric light curves of shock breakout for 150 and 200 M\(_\odot\) PISNe predicted by both semianalytical models and our 2T RAGE calculations. The semianalytical curve is constructed by first computing the position of the photosphere in successive snapshots of the RAGE hydrodynamical profiles assuming an electron-dominated opacity ahead of the shock, similar to what has been done in past studies [3]. The bolometric luminosity was then calculated taking the spherical shock to be a blackbody source at this temperature and position. In our simulated luminosity, we compute the true emission with radiation transport and frequency-dependent TOPS opacities. Note that the peak in calculated emission is over an order of magnitude less than that of the simple estimate, indicating that accurate reproduction of shock breakout mandates full radiation hydrodynamics. In the left panel of Figure 1 we show spectra (luminosity vs. wavelength) for a 150 M\(_\odot\) PISN at 5 times during shock breakout. A broad set of emission and absorption lines is present during this process. The initial burst of photons is at shorter wavelengths, 0.1 - 1 keV. As expected, as the shock expands and
FIGURE 2. Light curves (luminosity versus time) for several spectral bands for a 250 M⊙ PISN out to 1 year. The differences between the plots on the left and on the right are due to the inclusion of the Lyman break, which cuts off any emission shortward of 1216 Å. Most high-redshift SN searches for these PISNe will detect the shock breakout.

cools the emission at low wavelengths increases.

We show light curves for several spectral bands for a 250 M⊙ PISN out to 1 yr in Figure 2. In the left panel we include two bands consistent with the JWST bandpass, assuming that the source is at $z \sim 10$. Here, we account both the wavelength shift of the source emission and time dilation. Note that the shock breakout emission lasts for a week in the JWST frame. Several of the bands exhibit the classical initial peak and steady decline over 300 days in the rest frame but the NIR and mid-IR flux dips and then rises at late times.

What most distinguishes Pop III PISN detection from current Type Ia searches is the Lyman alpha forest. Most of the flux shortward of 1216 Å will be scattered out of the line of sight of the explosion by neutral hydrogen that has not yet been ionized by high-$z$ star-forming galaxies and quasars. We estimate the component of the source signal that would actually reach us by excluding all photons shortward of the Lyman limit, which we show in the right panel of Figure 2. Although the breakout flux is attenuated by a factor of ten by Lyman-$\alpha$ scattering, the residue still peaks at above $10^{41}$ erg s$^{-1}$, which our initial estimates indicate will be visible to JWST out to $z \sim 10 - 15$. Strong lensing may extend this detection limit to $z \sim 20$ (Holz, Whalen & Fryer in prep).

Because PISN are visible for 30 - 60 years in the rest frame, they will most likely be detected by their initial breakout pulse. It is not yet clear if future cosmic transient finders such as the successor to Swift will have the sensitivity to detect such explosions. However, they will be detected by JWST during deep-field surveys of $z > 10$ protogalaxies, with spectroscopic followup from large 30-meter class telescopes on the ground. Because CC SNe and PISNe have similar breakout LCs, early spectroscopy is the best bet for discriminating between them because heavy elements may appear sooner in CC SNe
FIGURE 3. Mixing in primordial supernovae prior to shock breakout from the surface of the star. **Left:** core-collapse explosion of a 25 $M_\odot$ zero-metallicity progenitor. **Right:** a 200 $M_\odot$ PISN. Vigorous mixing of metals to high altitudes occurs in the CC SN but elements remain clearly segregated in the PISN.

spectra. In Figure 3 we show 2D CASTRO AMR simulations of the distribution of elements in both CC SNe (left) and PISNe (right) in the star before the shock has reached the surface [4]. There is vigorous mixing of heavy elements from deep in the interior of the star to its outer layers in the CC case but not in the PISN. If these heavy elements appear in the emission spectra of the light curve just after shock breakout they would be a clear signature of a low-mass Pop III progenitor rather than a very massive one. Finally, we note that PISN remnants enclose large volumes of the IGM at later times, eventually depositing up to 50% of the original energy of the explosion into CMB photons that may be detectable as excess power at small scales in the CMB [5].

**ACKNOWLEDGMENTS**

This work was carried out in part under the auspices of the National Nuclear Security Administration of the U.S. Department of Energy at Los Alamos National Laboratory supported by Contract No. DE-AC52-06NA25396. DW acknowledges support by the McWilliams Fellowship at the Bruce and Astrid McWilliams Center for Cosmology at Carnegie Mellon University.

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