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Weak Mass Loss from the Red Supergiant Progenitor of SN 2021yja

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Abstract. Recent observations of Type II supernovae have revealed that their red-supergiant progenitors lose a significant amount of mass during the last years of their evolution. However, because it is difficult to discover supernovae within days of explosion, the diversity of mass loss in red supergiants has not yet been fully mapped. This talk presented the case of SN 2021yja, which was serendipitously imaged within hours of explosion and observed with a sub-day cadence during its rise to peak. From the exceptionally long plateau period and the high nickel mass, we infer a relatively massive red-supergiant progenitor star. However, archival imaging from the Hubble Space Telescope places a stringent upper limit of $\lesssim 9\ M_\odot$ on its progenitor mass. We discuss these conflicting constraints in the context of the larger sample of exploding red supergiants. Our analysis helps illuminate the poorly understood mechanism(s) behind red-supergiant mass loss.

Keywords. stars: mass loss, supergiants, supernovae: general, supernovae: individual (SN 2021yja)

Type II (hydrogen-rich) supernovae are the core-collapse explosions of red supergiants (see Smartt 2009 for a review). As such, they can serve as probes of red-supergiant mass loss, reaching greater sample sizes than are available in the Milky Way and Magellanic clouds, and recording the latest mass-loss stages, i.e., years to months before explosion. The difficulty lies in connecting the supernova observables to the properties of the circumstellar material. Gal-Yam et al. (2014) and Yaron et al. (2017) showed that short-lived narrow emission lines in the very early spectra of core-collapse supernovae indicate interaction with a confined shell of dense material ejected before explosion. Morozova et al. (2017; 2018) also showed that circumstellar material produces a faster rise and sharper peak in light curves of Type II supernovae. By modeling these emission lines and light curves, one can constrain the density profile of the circumstellar material. However, in both cases, very early observations are required. After only a few days, the ejecta overrun the circumstellar material and these observables disappear.

SN 2021yja was discovered on the outskirts of the nearby ($d_L = 23.4^{+5.4}_{-4.4}$ Mpc) galaxy NGC 1325 by the Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2018), with prediscovery detections by the Distance Less Than 40 Mpc (DLT40) survey (Tartaglia et al. 2018) and an education and public outreach program on Las Cumbres Observatory (Kilpatrick 2021). These earliest images suggest that the progenitor exploded only about 5.4 ± 1.4 hours earlier. Starting immediately after discovery, we

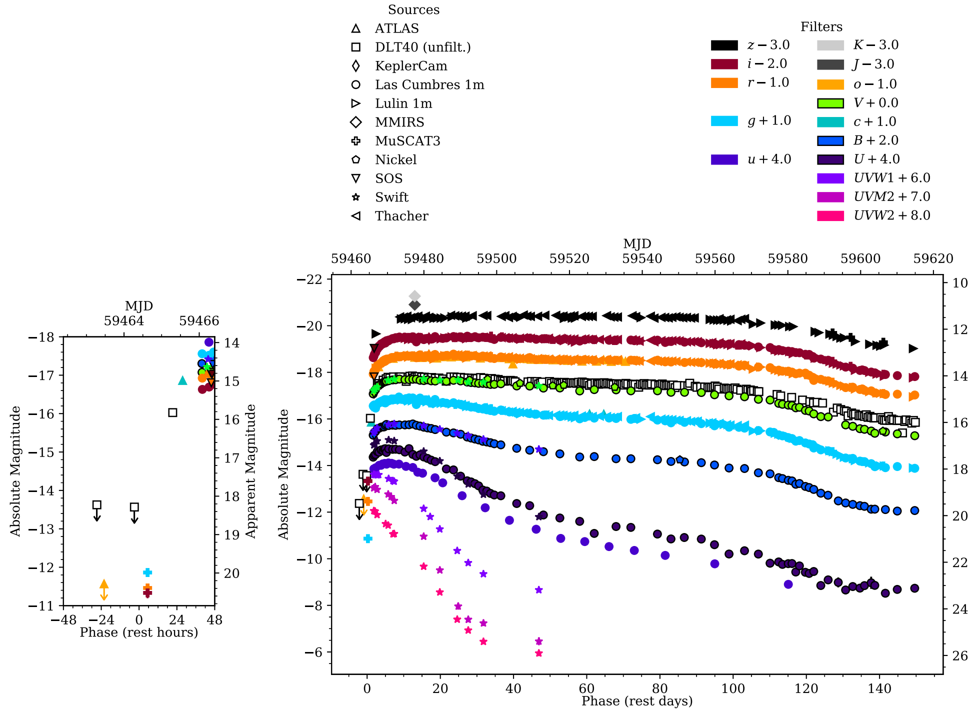

Figure 1. The light curve of SN 2021yja shows a fast rise, possibly indicating interaction with circumstellar material. The unusually long plateau, followed by a short fall onto the radioactive-decay-powered tail, indicate a large mass of ^{56}Ni, and possibly a massive progenitor star. The left panel shows the first two days of observations with no filter offsets. The supernova was serendipitously detected ≈5.4 hours after explosion by the MuSCAT3 imager at Las Cumbres Observatory. (From Hosseinzadeh et al. 2022; reproduced by permission of the AAS.)

obtained a densely sampled light curve (Figure 1) and spectral series. We also analyzed an archival image of NGC 1325 from the Hubble Space Telescope to place a limit on the luminosity, and therefore mass, of the progenitor star of SN 2021yja. I summarize the results of our analysis below; see Hosseinzadeh et al. (2022) for more detail.

In the absence of circumstellar material, the early light curves of core-collapse supernovae are powered by shock-cooling emission (see Waxman & Katz 2017 for a review). These models can be used to determine the radius of the progenitor star. We fit the shock-cooling model of Sapir & Waxman (2017) to the first 10 days of our light curve, and it appears to provide a good fit. However, it yields a best-fit radius of ≈2000 $R_\odot$, larger than expected for a red supergiant progenitor. This may an indication that the models are not a good description of the data, despite the reasonable match.

We also measured the mass of radioactive ^{56}Ni produced in the explosion by comparing the luminosity on the light-curve tail to the luminosity of SN 1987A at the same phases. This gives a nickel mass of $M_{\rm Ni} = 0.141^{+0.074}_{-0.049}\ M_\odot$, which is among the highest nickel masses for a Type II supernova (Anderson 2019). Eldridge et al. (2019) find a correlation between nickel mass and progenitor mass, suggesting a very massive ($\gtrsim$20 $M_\odot$) progenitor for SN 2021yja.

Despite the appearance of a good fit to the shock cooling models, SN 2021yja does show some evidence for circumstellar interaction. Its colors are very blue, and it is among

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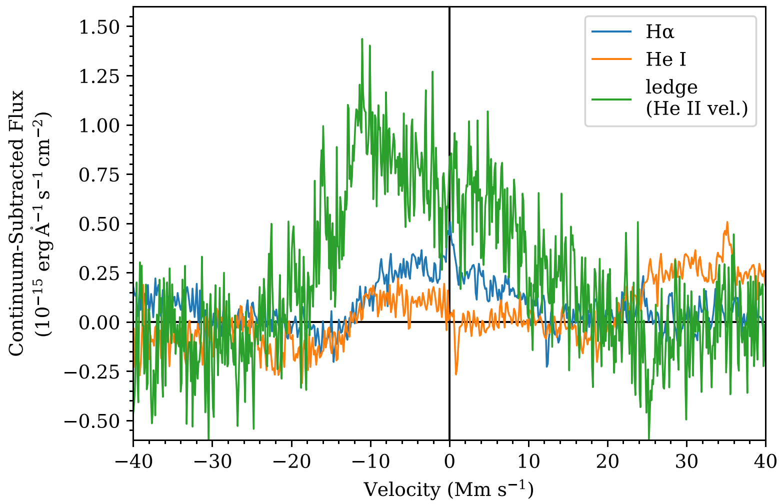

Figure 2. The ledge-shaped feature (green) in the earliest spectrum of SN 2021yja, compared to the P Cygni profiles of Hα (blue) and He I (orange) in the same spectrum. This feature, a blend of lines possibly including He II, has been interpreted as evidence for weak circumstellar interaction. It also resembles features in models of exploding red supergiants with extended atmospheres by Dessart et al. (2017). (From Hosseinzadeh et al. 2022; reproduced by permission of the AAS.)

most luminous Type II supernovae observed in the ultraviolet by the Neil Gehrels Swift Observatory (Brown et al. 2014). In addition, its earliest spectra (2–4 days after explosion) show an unusual broad "ledge-shaped" feature (Figure 2), which has previously been interpreted as evidence for weak circumstellar interaction (Bullivant et al. 2018, Andrews et al. 2019, Soumagnac et al. 2020, Bruch et al. 2021). This feature also appears in models of red supergiant explosions by Dessart et al. (2017) in which the photosphere lines within an extended atmosphere.

Despite the evidence above for a very massive red supergiant progenitor, the image of NGC 1325 taken 25 years before the explosion shows no point source at the position of SN 2021yja, down to very deep limits. By comparing to single stellar evolutionary tracks from Choi et al. (2016), this image allows us to place a limit of $\lesssim 9\ M_{\odot}$ on the initial mass of the progenitor of SN 2021yja (Figure 3). The conflict between this limit and our conclusions from the supernova itself can be lessened by assuming that the progenitor was variable; extreme dimming events in red supergiants are rare (Conroy et al. 2018) but not unheard of (Levesque & Massey 2020, Jencson et al. 2022). Variability may also be enhanced in the years to decades before explosion (e.g., Jacobson-Galán et al. 2022).

In summary, while our results regarding the mass of the progenitor of SN 2021yja are in conflict with each other, we do infer weak circumstellar interaction for the first several days of its evolution, despite the absence of the narrow emission lines described by Gal-Yam et al. (2014) and Yaron et al. (2017). This adds to the growing sample of red supergiant progenitors with preexisting circumstellar material, suggesting that some level of mass loss may be ubiquitous. Future analyses must consider that the supernova observables that indicate interaction are highly dependent on the details of the density profiles of both the progenitor atmosphere and its circumstellar material, in order not to miss cases of weak mass loss like we see here.

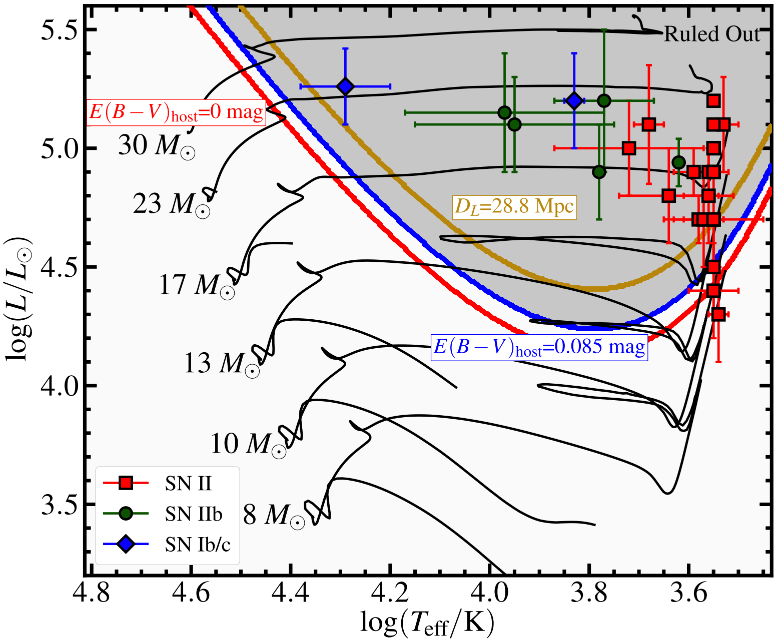

Figure 3. Hertzsprung-Russell diagram showing the single stellar evolutionary tracks of Choi et al. (2016), compared to core-collapse supernova progenitors observed by Cao et al. (2013), Smartt (2015), and Kilpatrick et al. (2021). The archival Hubble Space Telescope image constrains the initial mass of the progenitor of SN 2021yja to be $\gtrsim 9\ M_\odot$ (gray region, blue line), assuming a single-star origin. A larger distance estimate can weaken our limit (gold line), or a smaller estimate of the host galaxy extinction could strengthen it (red line). (From Hosseinzadeh et al. 2022; reproduced by permission of the AAS.)

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