Last Year Before Death: Observations of SN 2020fqv by TESS and Friends

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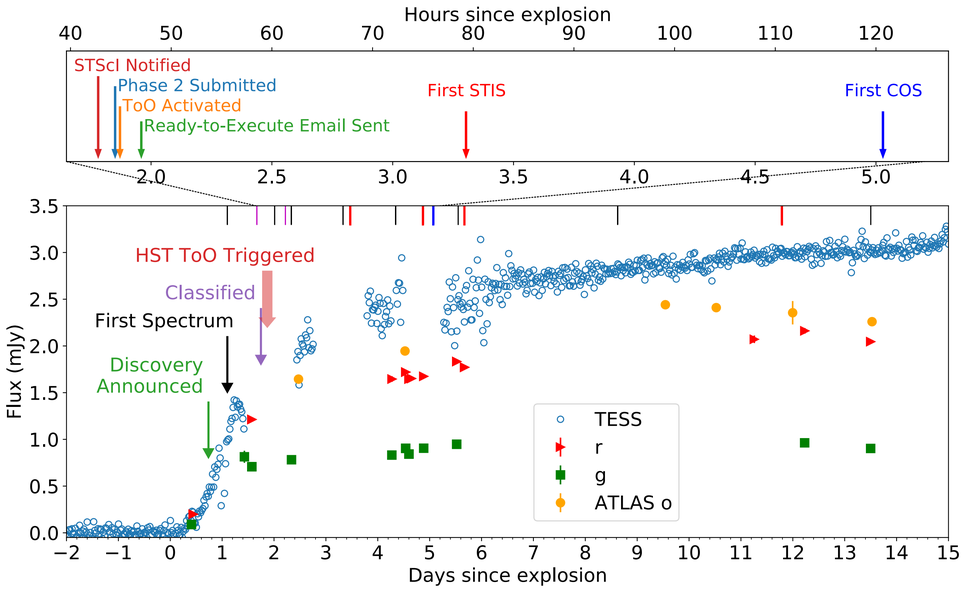
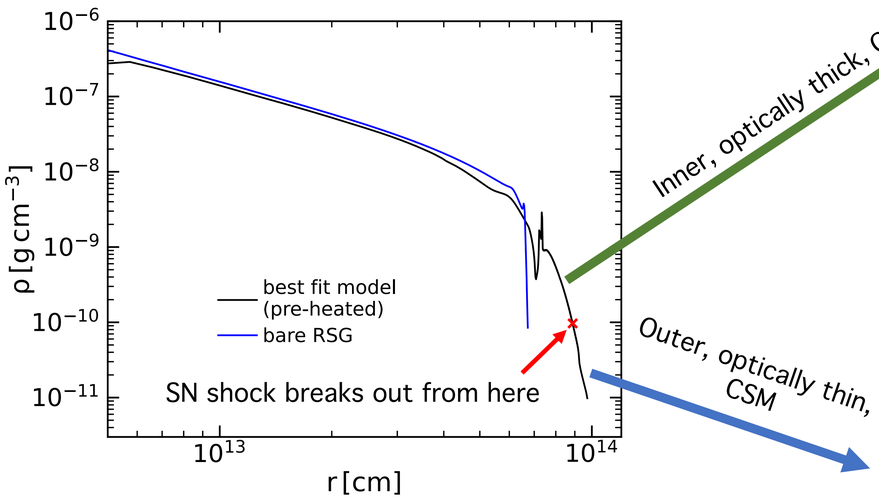
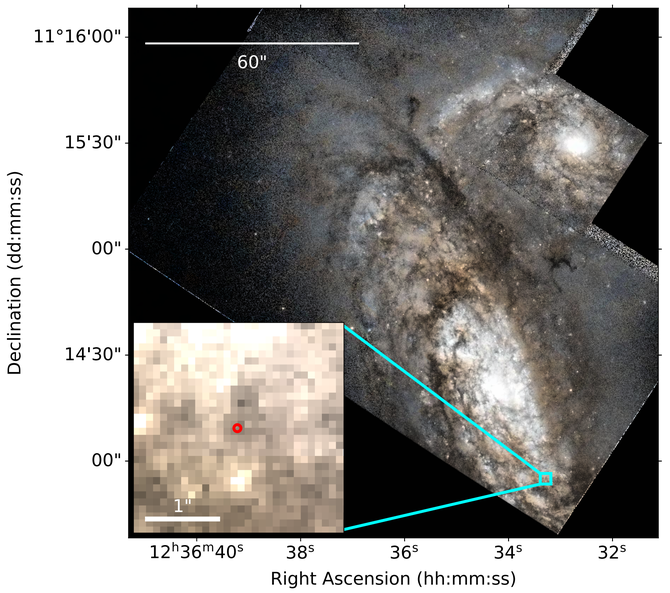
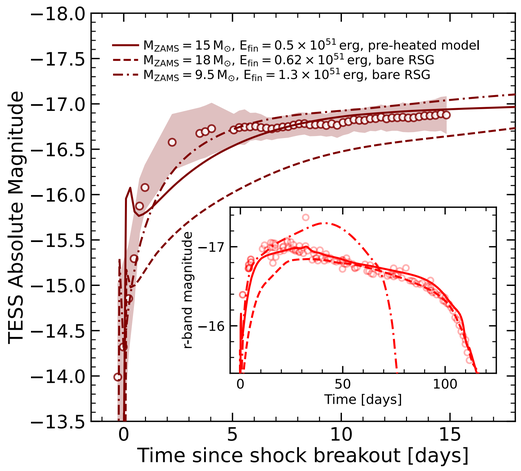
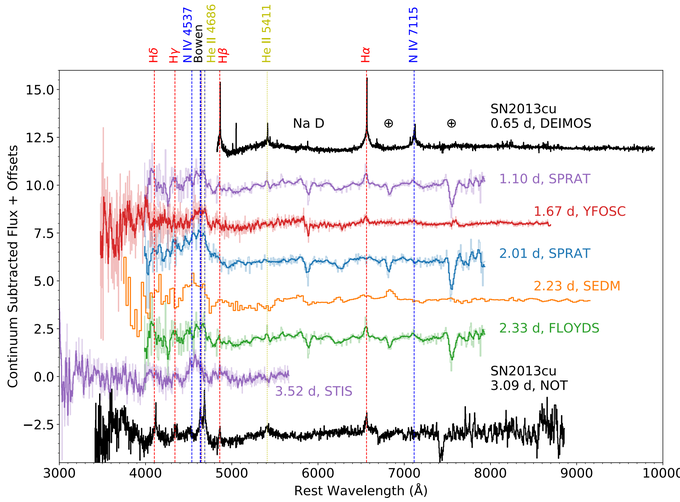


Early observations are key to understanding what happened in the last year prior to the star's death. SN 2020fqv was discovered within a day and we obtained the first spectrum 26 hr post-explosion. SN 2020fqv shows signs of interaction and is within an active *TESS* sector prompting us to trigger the first ultra-rapid *HST* program ever to obtain early-time UV-optical spectra with STIS and COS. **The earliest STIS spectrum was obtained only 79 hr post-explosion.** *TESS* captures the rise of this SN, allowing us to model it to constrain the explosion time and other properties of the explosion.



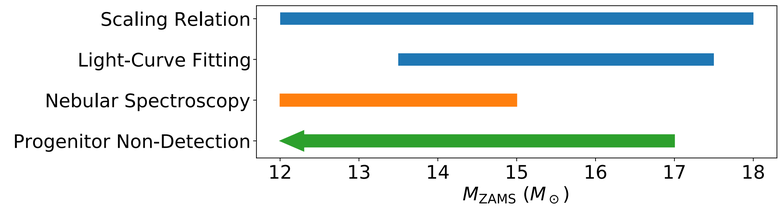






Select References: Morozova+ 2015, 2018, 2020; Vallely+ 2021; Jerkstrand+ 2014, 2018; Gal-Yam+ 2014, Wu&Fuller 2021, Fuller 2017, Quataert&Shiode 2012, Bowen 1935.

SN 2020fqv comes from a red supergiant with a dense circumstellar environment. From the light curve fitting, pre-explosion image from *HST* (non-detection, F606W, shown on left), and late-time nebular spectroscopy (see different ranges of mass below), we are able to constrain that SN 2020fqv is an explosion of a **red supergiant (RSG) with a zero-age main sequence mass (ZAMS) of 13.5-15 $M_\odot$.** Further, the fast rise time and the early-time excess flux of SN 2020fqv, along with narrow emission lines in the spectra, point to a dense circumstellar medium (CSM) immediately outside of the progenitor star of SN 2020fqv.



Circumstellar Medium of SN 2020fqv

We find 0.23 $M_\odot$ of CSM within 1450 $R_\odot$ from the star. Modelling our observations shows that the density profile of the RSG progenitor of SN 2020fqv does not just drop off like normal at about 1000 $R_\odot$, but has a CSM component extending out to ~1450 $R_\odot$, containing ~0.23 $M_\odot$ of material. The density and optical depth is so large that the SN shock only breaks out at the edge of this CSM, marked with a red cross in the bottom left figure. These CSM properties are not unusual among the population of SNe II (Morozova+ 2018). **Our models show that the CSM is a result of an energy injection of 5x10^{46} erg into the envelope about 300 days before the explosion, which may be related to instability in late-stage nuclear burning** (e.g., Quataert & Shiode 2012, Fuller 2017, Wu & Fuller 2021).

The inner part of the CSM leaves an imprint on the SN's early light curve. Middle right figure compares the light curve models with and without the CSM. The data points are binned *TESS* light curve with uncertainty. The solid line model shows the light curve expected with the CSM component; it matches the data best. Bare RSG models (dashed and dotted-dash lines) cannot explain the entire light curve. This light curve is affected most by the bulk of the CSM inward of the shock breakout point.

The outer part of the CSM forms narrow emission lines. Lower right figure shows the early-time spectra of SN 2020fqv both from the ground and from *HST*/STIS. They show the emission features around 4600 Å from high-ionization metal species like N III and C III. They originate from the outer CSM getting radiatively ionized by the shock breakout. These features have been observed in a growing number of CCSNe with early-time spectra, e.g. SN 2013cu shown here (Gal-Yam+ 2014).