Late-time observations of interacting supernovae (Type IIn/Ibn) provide critical information about the nature and mass-loss history of massive stars immediately before core collapse. The Type IIn/II-L SN 1998S is a relatively nearby SN thought to have had a red supergiant (RSG) progenitor that underwent a phase of very heavy mass loss prior to explosion. Spectroscopic analysis over the first few years of evolution revealed evidence for non-spherical geometry in the envelope of circumstellar material (CSM). We report late-time spectroscopic observations of the Type IIn SN 1998S 14 years post-explosion using the Large Binocular Telescope (LBT) and Multi-Object Double Spectrograph (MODS). The data provide clues about the extent of the CSM, the geometry of the outflow, and the recent formation of obscuring dust.

Figure 1: Ground-based (left) and Hubble Space Telescope (center) images of SN 1998S in 1998 and 2000, respectively, and our LBT/MODS image from 2012 Feb 27 (right).

Figure 2: LBT/MODS spectrum of SN 1998S (black), compared to earlier spectra from Fassia et al. (2001, red). The latest spectrum implies that strong CSM interaction continues. The last decade of spectral evolution has exhibited a strengthening of the oxygen transitions relative to Hα, evidence that the late-time emission is powered by increasingly metal-rich SN ejecta crossing the reverse shock near the SN-CSM interface. The disappearance of the multi-peaked narrow Hα components perhaps indicates that the non-spherical or ring-like component of the CSM, suggested earlier, has since been overtaken by the shock. The latest spectrum of SN 1998S closely resembles that of SN 1980K at a similar late-time epoch (Fesen et al. 1999, yellow).

Figure 3: Hα luminosity curves for SN 1998S, and the similar SN 1980K. The luminosity at epochs <1000 days is consistent with the 111.5-day mean lifetime of radioactive $^{56}$Co decay (dashed line), but later epochs from day 1093 onward fall above this trend by as much as 10 dex, requiring interaction with dense CSM. The late-time Hα luminosity of SN 1998S (currently ~8000 $L_\odot$) and the overall trend appears most consistent with model predictions for an RSG density profile of the envelope (Chevalier & Fransson 1994; solid line), more so than a power-law density profile (dotted line).

Figure 4: Close-up of the multi-peaked [O I] $\lambda$6300 Å profile of SN 1998S on days 1093 and 5079. The dashed line marks the rest wavelength of the of the transition. The dotted lines mark the center wavelengths/velocities of the triple peaks, assuming they all represent $\lambda$6300. The multiple peaks could represent individual metal-rich structures from an non-spherically symmetric explosion. The redshifted portion of the line has become more sharply suppressed over the last decade, and the reddest individual peak has disappeared. We interpret this a the result of dust which has formed in the post-shock medium over the last decade and is obscuring emission from ejecta components on the receding hemisphere of the explosion.

Figure 5: Nebula surrounding the red supergiant VY Canis Majoris, a potential Galactic analog for the progenitor of SN 1998S. The diameter of this nebula, which includes multiple asymmetric arcs, is ~4500 AU, comparable to the estimated CSM dimensions of SN 1998S. The superwind of VY Canis Majoris has been blowing for ~1000 years at a mass-loss rate of $4\times10^{-4}$ $M_\odot$ yr$^{-1}$; we have derived similar parameters for the SN 1998S progenitor. VY Canis Majoris could likely produce a Type IIn explosion very similar in appearance to SN 1998S.

References: