Evidence for a pulsar wind nebula in the Type Ib-peculiar supernova SN 2012au

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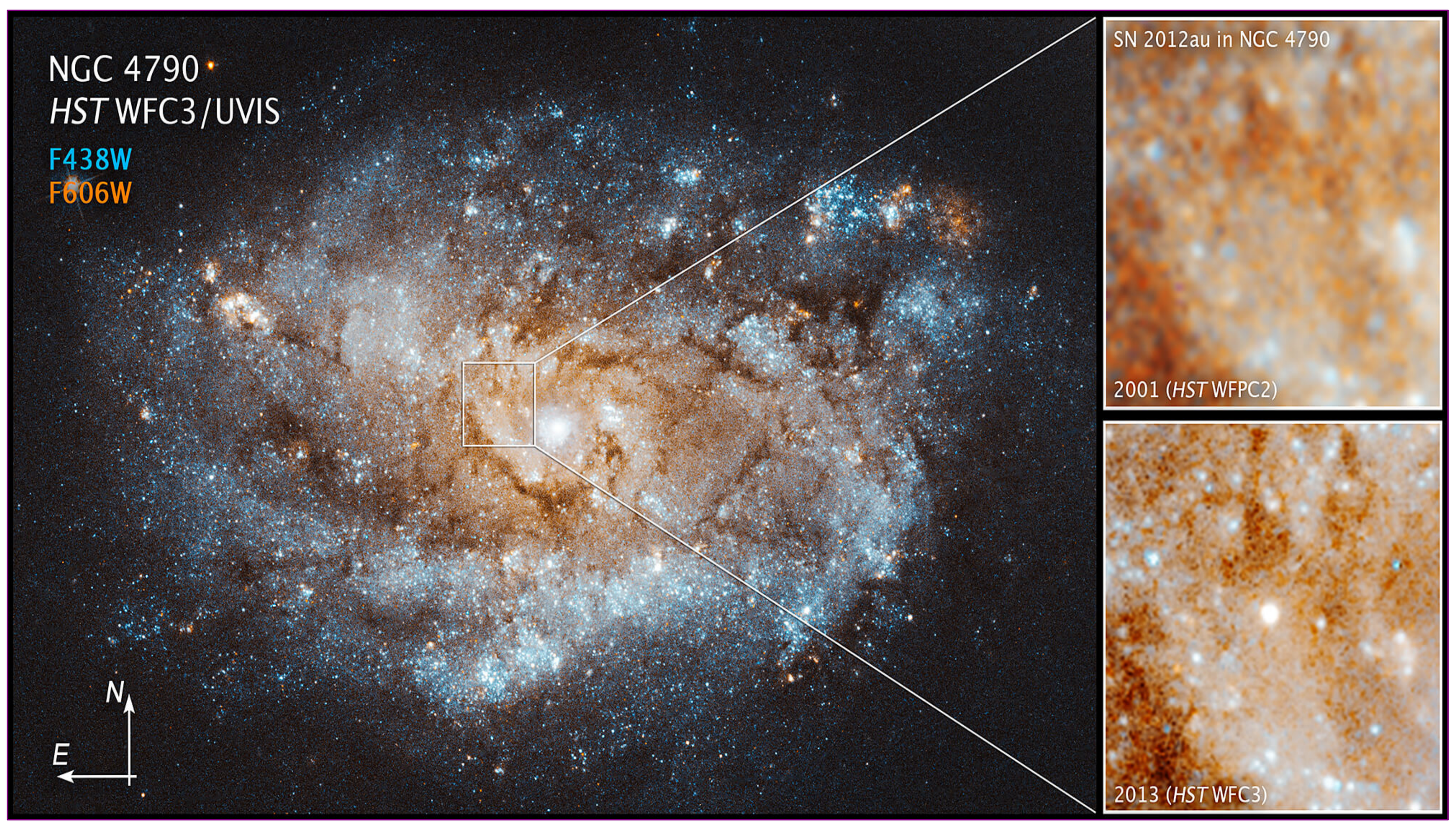


Fig 1. Progenitor System: Analysis of Geneva stellar evolution models in combination with pre-explosion archival Hubble Space Telescope images of the region encompassing SN 2012au in NGC 4790 (D = 23.5 ± 0.5 Mpc) loosely constrain the progenitor star zero age main sequence mass to be < 80 $M_{\odot}$. The explosion site is 0.6 kpc in projected distance from the galaxy nucleus. *Image courtesy of J. DePasquale (STScI).*

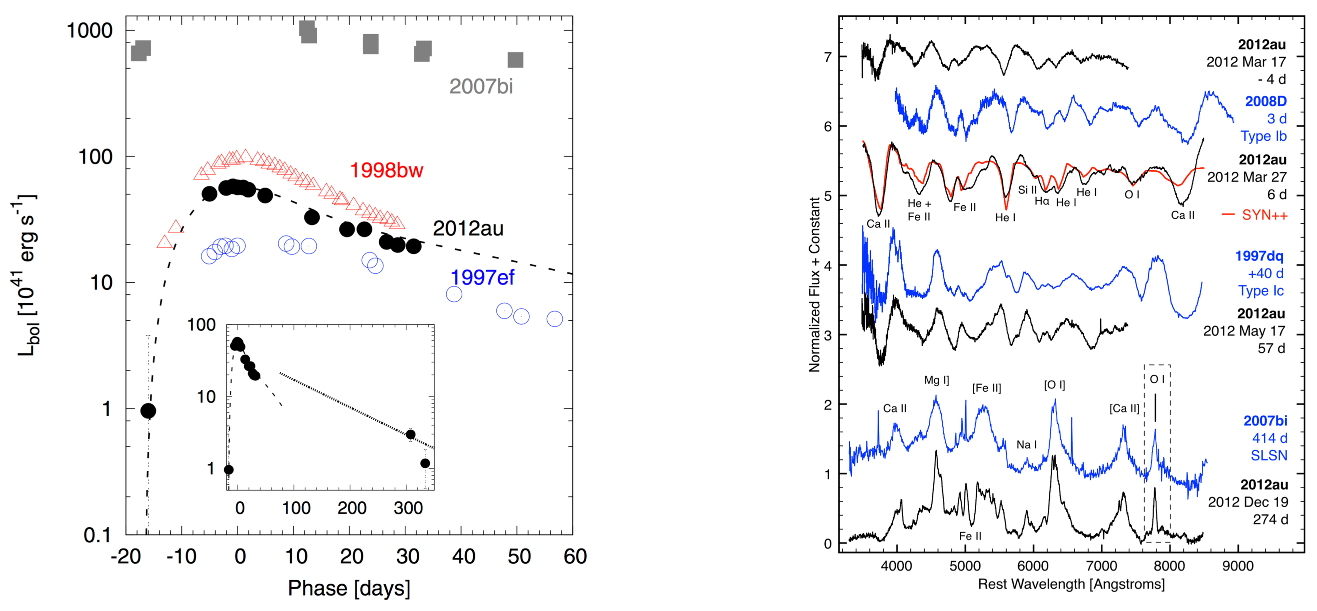


Fig 2. Bolometric and spectroscopic properties in the first year: SN 2012au was an energetic ($E_K \sim 10^{52}$ erg) explosion with slow-evolving light curve. Optical spectra were originally consistent with a Type Ib classification. However, at nebular phases (t > 200 days post explosion), its late-time emissions strongly resembled subsets of energetic and H-poor SNe and SLSNe (including SN 2007bi [11]), suggesting shared progenitor and explosion characteristics. Adapted from [6].

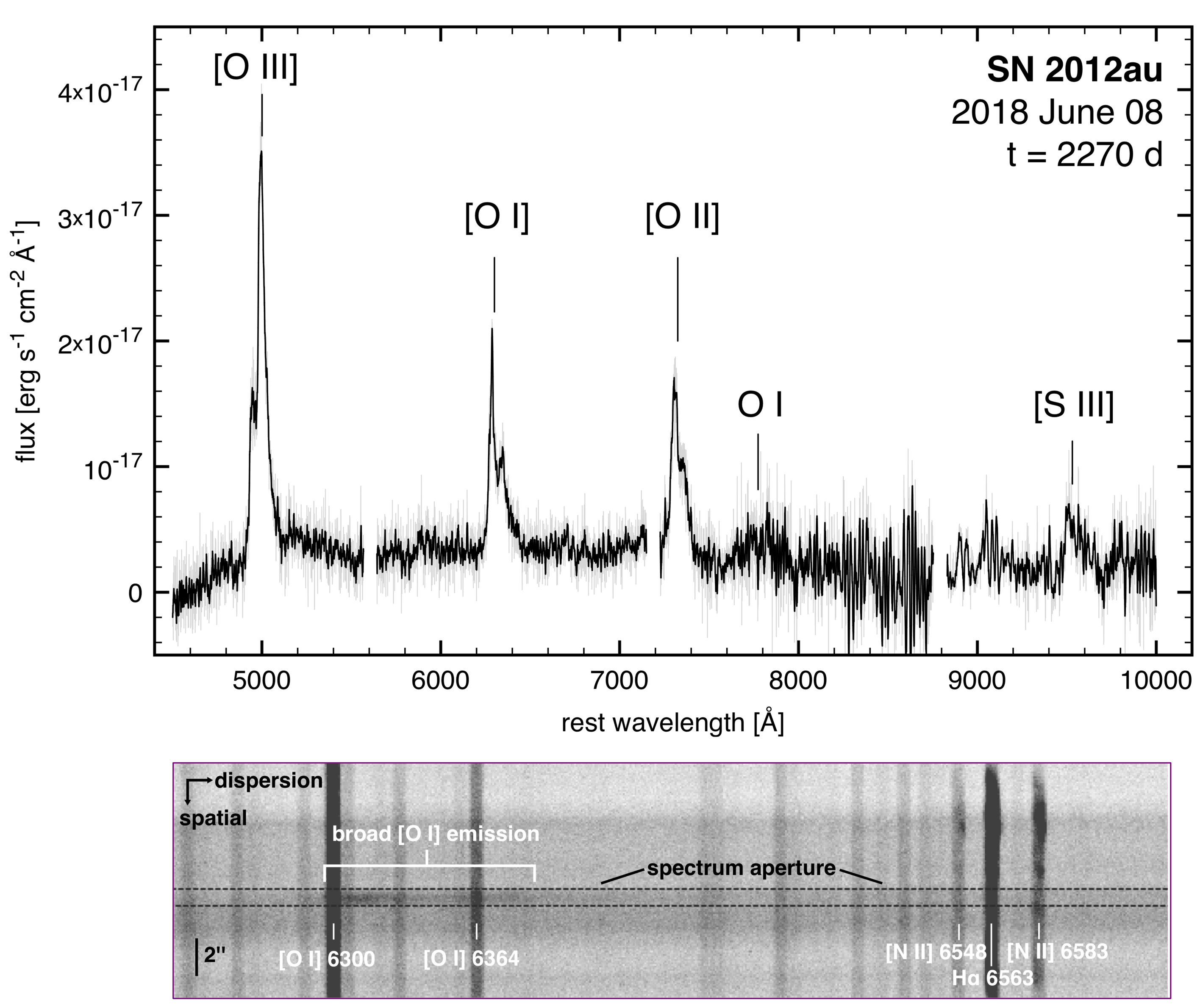


Fig 3. New energy source powering emission at extremely late times: Our optical spectra obtained six years post explosion show that the SN has strong emission lines largely unlike those observed at t ~ 1 yr. The forbidden oxygen and sulfur emissions cannot be powered by radioactive ^{56}Co and thus a new energy source must be present. Conspicuous narrow emission lines local to the SN and/or X-ray emission are not detected, largely ruling out SN interaction with a circumstellar material. **Pulsar interaction with expanding SN gas is the favored scenario.** A PWN is generated by the spin-down power of a central pulsar, and the resulting photoionization of the inner regions of the expanding ejecta shell can be the dominant source of optical line emission. *Top*: entire 1D spectrum as extracted (gray) and data smoothed using 5 Å boxcar (black). *Bottom*: 2D spectrum in the region of [O I] and Hα.

Notes and References. [1] MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262; [2] Mazzali, P., et al. 2014, MNRAS, 443, 67; [3] Nicholl, M., et al. 2016, ApJL, 828, L18; [4] Grainer, J. et al. 2015, Nature, 523, 189; [5] Jerkstrand, A., et al. 2017, ApJ, 835, 13; [6] Milisavljevic, D., et al. 2013, ApJL, 770, L38; [7] Takaki, K., et al. 2013, ApJ, 772, 17; [8] Results originally presented in **Milisavljevic, D. et al., 2018, ApJL, 864, L36**; [9] Chevalier, R. A., & Fransson, C. 1992, ApJ, 395, 540; [10] Blondin, J. M., & Chevalier, R. A. 2017, ApJ, 845, 139; [11] Gal-Yam, A., et al. 2009, Nature, 462, 624; [12] Milisavljevic, D., et al. 2019, arXiv:1904.05897

Abstract

Theoretical modeling of H-poor and energetic core-collapse supernovae (SNe), long-duration gamma-ray bursts (GRBs), and super-luminous supernovae (SLSNe) often invoke engine-driven scenarios associated with the formation of compact objects that input energy into the explosion [1-2]. The true nature of the suspected central engines and the energy scales that they may participate in and influence their diverse parent explosions remains poorly constrained by observations. However, growing evidence supports the notion that subsets of SNe, SLSN and GRB–SN may a share a common magnetar central engine [3-5].

SN 2012au in NGC 4790 (Fig. 1) was originally found to be a slow-evolving and energetic ($E_K \sim 10^{52}$ erg) Type Ib supernova (SN) exhibiting a rarely observed combination of late-time emission properties that bridge various types of H-stripped SNe and SLSNe consistent with a SN-GRB-SLSN connection (Fig. 2) [cf. 6,7]. In this poster we present new optical and X-ray observations of SN2012au obtained more than six years post-explosion [8] that offer fresh insight into this remarkable event. Our optical spectra show forbidden transition emission lines of oxygen and sulfur with expansion velocities of 2300 km/s that are dramatically different from those observed in spectra obtained one year post explosion when the principal heating mechanism is radioactive ^{56}Co (Fig. 3). H Balmer lines are not detected and Chandra X-ray Observatory observations reveal no X-ray emission down to a luminosity of < 2×10^{38} erg/s (0.5–10 keV), together suggesting that interaction with circumstellar material does not contribute significantly to the emission.

We conclude that the dominant source of the observed late-time emission is photoionization of O zone gas that has been shocked by a high-pressure pulsar wind nebula (PWN) and subjected to instabilities, similar to the Crab Nebula [9,10]. Our discovery marks the first time a PWN signature has been detected in a verified extragalactic SN Ib and support the notion that SN 2012au belongs to a subset of SLSNe, GRB-SNe, and SNe Ib/c that are relatedly influenced by magnetized neutron stars that participate in explosion dynamics on a wide range of energy scales.

We anticipate that other members of this family of SNe harboring influential pulsar/magnetar wind nebulae will evolve into a late-time phase dominated by forbidden oxygen transitions, if observed long enough after explosion and with sufficient depth (Fig. 4). We also predict that optical emission line widths in these objects observed post-transformation should remain constant or broaden upwards of a few percent per year due to acceleration of ejecta by the pulsar/magnetar bubble (Fig. 5). It remains unclear what key aspects of the progenitor systems unite these SNe that span absolute magnitudes of $-22 < M_B < -17$.

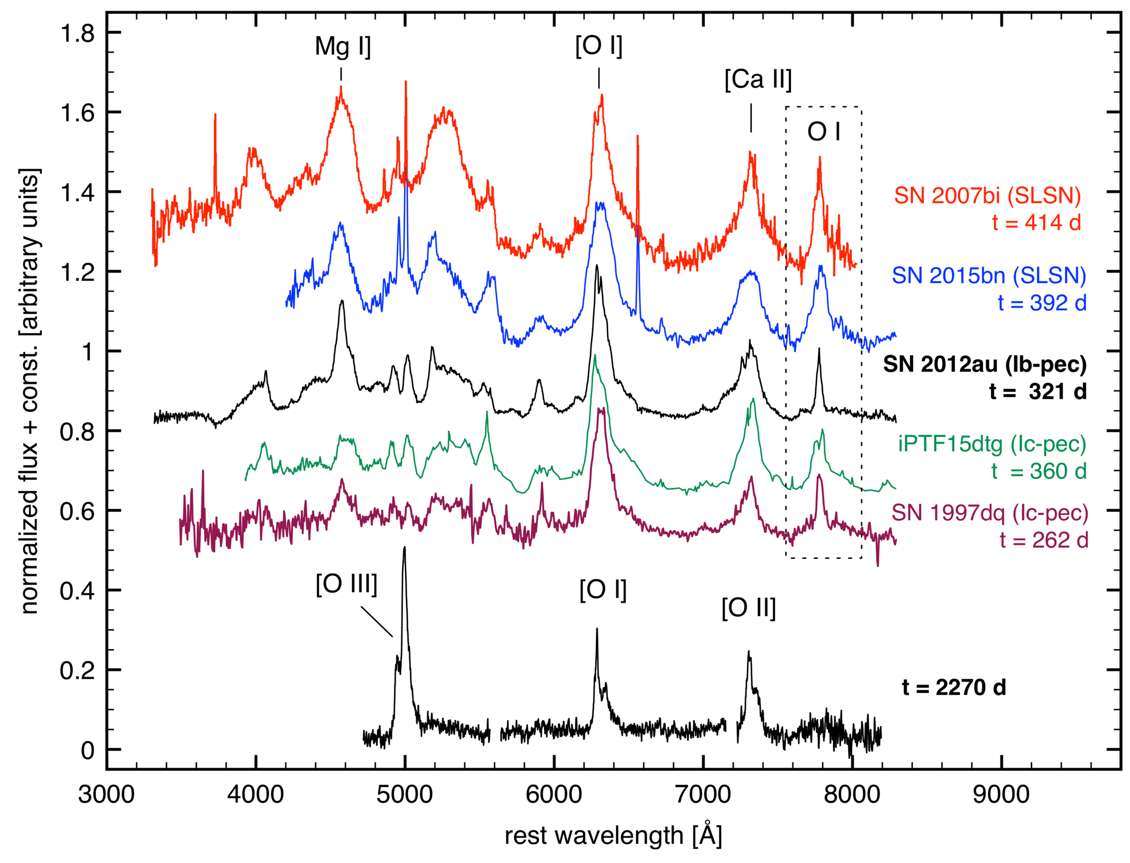
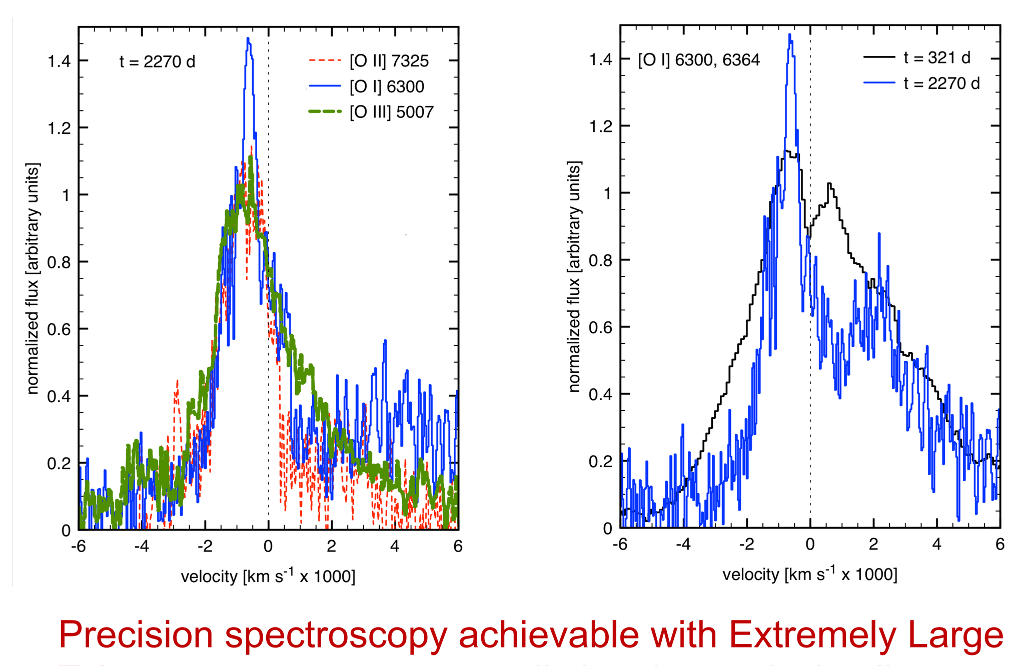


Fig. 4. Late-time transformation: Earlier nebular spectrum (t ≈ 1 yr) of SN 2012au compared to our t = 6.2 yr spectrum. Also shown is a subset of related SLSNe and SNe Ic that all exhibit slow light curve evolution and similar late-time emissions. The O I λ7774 line is a defining feature of these related objects [6], and has been interpreted to be potentially associated with heating of a shell by a central engine [3]. **We hypothesize that all of these events may evolve to a similar late-time emission phase that we are now observing in SN 2012au.**

Fig. 5. Emission line profiles: All forbidden line profiles exhibit a clear asymmetry toward blueshifted wavelengths, peaking at −700 ± 50 km/s and with expansion velocities of 2300 km/s. *Left*: modified [O I], [O II], and [O III] emission line profiles of SN 2012au. Companion doublet lines [O I] λ6364 and [O III] λ4959 have been modeled and subtracted from the profiles, and the [O II] λλ7319, 7330 blend has been treated as a single line with Doppler velocities with respect to 7325 Å. Right: unmodified [O I] emission line profiles for days 321 and 2270.



Precision spectroscopy achievable with Extremely Large Telescopes can test our prediction that emission line widths should remain unchanged or increase with time if influenced by a pulsar/magnetar wind nebula [12].