Evidence for a Pulsar Wind Nebula in the Type Ib Peculiar Supernova SN 2012au

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Received 2018 August 1; revised 2018 August 24; accepted 2018 August 28; published 2018 September 12

Abstract

We present an optical spectrum of the energetic Type Ib supernova (SN) 2012au obtained at an unprecedented epoch of 6.2 yr after explosion. Forbidden transition emission lines of oxygen and sulfur are detected with expansion velocities of $\approx 2300$ km s$^{-1}$. The lack of narrow H Balmer lines suggests that interaction with circumstumar material is not a dominant source of the observed late-time emission. We also present a deep Chandra observation that reveals no X-ray emission down to a luminosity of $L_X < 2 \times 10^{38}$ erg s$^{-1}$ (0.5–10 keV). Our findings are consistent with the notion that SN 2012au is associated with a diverse subset of SNe, including long-duration gamma-ray burst SNe and superluminous SNe, harboring pulsar/magnetar wind nebulae that influence core-collapse explosion dynamics on a wide range of energy scales. We hypothesize that these systems may all evolve into a similar late-time phase dominated by forbidden oxygen transitions, and predict that emission line widths should remain constant or broaden a few percent per year due to the acceleration of ejecta by the pulsar/magnetar bubble.

Key words: pulsars: general – stars: magnetars – supernovae: general – supernovae: individual (SN 2012au)

1. Introduction

Models of hydrogen-poor and energetic ($E_K \sim 10^{52}$ erg) broad-lined Type Ic (Ic-bl) core-collapse supernovae (SNe) associated with long-duration gamma-ray bursts (GRBs) often invoke central engine-driven mechanisms associated with the formation of compact objects that input energy into the explosion. The collapsar mechanism (MacFadyen & Woosley 1999), which involves a massive star collapsing directly to a black hole with accretion releasing energy in the form of a relativistic jet that can accrete the star, has long been a favored model (Woosley & Heger 2012). However, mounting evidence supports the view that these explosions may be powered by rapidly rotating magnetars, i.e., a neutron star with an exceptionally strong ($>10^{14}$ G) magnetic field (Thompson et al. 2004; Metzger et al. 2011, 2015; Mazzali et al. 2014).

Magnetars have also been used in models characterizing the diverse class of hydrogen-poor superluminous SNe (SLSNe-I; Inasera et al. 2013; Nicholl et al. 2013). SLSNe-I can radiate more than $10^{44}$ erg s$^{-1}$ at their peak luminosity and may be associated with extremely massive ($>100 M_\odot$) progenitor stars. Their slow-evolving light curves are consistent with those expected from the decay of tremendous amounts of radioactive $^{56}$Ni ($>3 M_\odot$), as might be synthesized by a pair-instability explosion. However, this scenario fails in numerous cases where the luminosity reaches levels requiring the nickel mass to be larger than the estimated ejecta mass.

Interaction between a SLSN-I and surrounding circumstellar material (CSM) is another possible energy source (Chatzopoulos & Wheeler 2012). However, SLSN-I events generally lack conspicuous spectroscopic features that support this interpretation at photospheric stages. SLSN–CSM interaction also requires an extreme mass-loss history of several $M_\odot$ of H-poor material shed in the last year before explosion in order to reproduce the observed light curves (Chevalier & Irwin 2011; Lunnan et al. 2018).

Discovery of SN 2011kl, which had a higher-than-average luminosity and was associated with the ultra-long-duration GRB 111209A, suggests that GRB and SLSN classifications are not necessarily distinct (Greiner et al. 2015). Understanding the SLSN–GRB connection is presently an area of active investigation (Margutti et al. 2017; Pian & Mazzali 2017; Coppens & et al. 2018). The connection was anticipated by earlier observations of the SLSN 2010gx (Pastorello et al. 2010), and the unusually energetic ($E_K \sim 10^{52}$ erg), slow-evolving Type Ib SN 2012au, which is believed to be a lower-luminosity counterpart to SLSNe (Milisavljevic et al. 2013; Kamble et al. 2014; Milisavljevic & Margutti 2018). Nebular phase observations of the SLSN 2015bn (Nicholl et al. 2016) and other SLSNe-I (Nicholl et al. 2018) have further strengthened the connection. Core angular momentum may be the key ingredient differentiating SLSNe and GRBs (Lunnan et al. 2014). However, other factors including the star formation rate and stellar mass may also be influential (Angus et al. 2016). Recent speculation that fast radio bursts may be magnetars in the remnants of SLSN explosions has heightened the significance of the SLSN–GRB connection (Metzger et al. 2017; Nicholl et al. 2017; Effekhari et al. 2018).

Here we present optical and X-ray data of SN 2012au obtained $>6$ yr post-explosion that offer fresh insight into the suspected link between SLSNe and GRB-SNe. In Sections 2 and 3 we present our optical spectroscopy and supporting X-ray observations, along with our analysis and results. In Sections 4 and 5 we discuss possible excitation mechanisms and outline numerous arguments in favor of the heating of ejecta by a pulsar wind nebula (PWN). Our discovery marks the first time a PWN signature has been detected in a verified extragalactic SN Ib at this extremely late epoch. We conclude...
in Section 6 with implications of our results and suggest future avenues of investigation. We adopt \(23.5 \pm 0.5\) Mpc as the distance to the host galaxy NGC 4790 (Theureau et al. 2007).

2. Observations

2.1. Optical Spectroscopy

A low-resolution optical spectrum of SN 2012au was obtained with the 6.5 m Magellan telescope at Las Campanas Observatory on 2018 June 8. The Inamori Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2011) was used with the f/4 camera in combination with the Mosaic3 array of eight thinned 2K × 4K × 15 μm E2V CCDs. A 300 line mm\(^{-1}\) grating and a 0°9 long slit were used. Exposures of 2 × 300 s were obtained and averaged. Resulting spectra have an effective wavelength range of 4520–10000 Å, with dispersion of 0.74 Å pixel\(^{-1}\) and FWHM resolution of 5 Å (measured at 6000 Å). The spectrum has interruptions in coverage between detector gaps. The seeing was \(0′.6\)

were obtained and averaged. Resulting spectra have an effective wavelength range of 4520–10000 Å, with dispersion of 0.74 Å pixel\(^{-1}\) and FWHM resolution of 5 Å (measured at 6000 Å). The spectrum has interruptions in coverage between detector gaps. The seeing was \(0′.6\) and conditions were generally clear but not photometric.

Standard procedures to bias-correct, flat-field, and flux-calibrate the data were followed using IRAF. LA-Cosmic (van Dokkum 2001) was used to remove cosmic rays in individual images. Some cosmetic defects introduced from hot pixels and imperfect background subtraction have been manually removed. Spectrophotometric standards Feige 56 and LTT 3864 were observed and used for absolute flux calibration (Hamuy et al. 2002), which is believed to be accurate to within 30%. The spectrum has been corrected for the redshift \(z = 0.004483\) of NGC 4790 (Theureau et al. 2007).

2.2. Chandra X-Ray Observations

We obtained a 20 ks observation of SN 2012au with the Chandra X-ray Observatory (CXO) in combination with ACIS-S on 2018 August 2 through Director’s Discretionary Time (PI: Patnaude; Observation ID 21660). Data have been reduced with the CIAO software v4.10 and corresponding calibration files. In a 2" radius region centered on the SN, we detect a count rate of \((3 \pm 3.5) \times 10^{-3}\) counts s\(^{-1}\) (0.5–10 keV), consistent with background. Thus, no X-rays are detected from SN 2012au. The neutral hydrogen column density in the direction of SN 2012au is \(3.8 \times 10^{20}\) cm\(^{-2}\) (Kalberla et al. 2005). For an assumed non-thermal spectrum with index \(\Gamma = 2\), we derive an unabsorbed flux limit of \(2.8 \times 10^{-15}\) erg s\(^{-1}\) cm\(^{-2}\), corresponding to luminosity \(L_X < 2 \times 10^{38}\) erg s\(^{-1}\) (0.5–10 keV).

3. Analysis and Results

3.1. Spectral Properties

In Figure 1, we present our day 2270 spectrum of SN 2012au. Forbidden oxygen transitions [O I] \(\lambda\lambda6300, 6364\), [O II] \(\lambda\lambda7319, 7330\), and [O III] \(\lambda\lambda4959, 5007\) are clearly observed. All forbidden line profiles exhibit a clear asymmetry toward blueshifted wavelengths, peaking at \(-700 \pm 50\) km s\(^{-1}\) (Figure 2). We measure the expansion velocity of [O III], [O I], [O II], and [S III] using the half-width-zero-intensity shortward of 4959 Å, 6300 Å, 7325 Å, and 9531 Å, respectively. All measurements extend to approximately 2300 ± 100 km s\(^{-1}\). The weakly detected O I 7774 has no clear peak in emission and does not appear to have the same emission line profile as the forbidden transitions.

Excess flux is observed between 5100 and 5400 Å. This could potentially be the remnant of the plateau of emission observed in the day 321 spectrum (Milisavljevic et al. 2013; Figure 3). However, contaminating flux from the host galaxy cannot be ruled out. The fall-off in flux below 4800 Å is attributed to rapid loss of instrument sensitivity at these shorter wavelengths.

No narrow (FWHM < 200 km s\(^{-1}\)) features are observed in the spectrum. Particular attention was made to possible emission in the region of Hα, which would be indicative of interaction with H-rich CSM. The 2D spectrum shows narrow emission lines of [O I] 6300, 6364, [N II] 6548, 6583, and Hα extended spatially across the slit but nothing conspicuous and specific to the SN location (Figure 1, bottom). After careful subtraction of the local background we estimate an upper limit of Hα emission to be \(<4.1 \times 10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\).

3.2. Emission Line Diagnostics

The emission line intensity ratios of our spectra can be used with atomic rates from CHIANTI (Del Zanna et al. 2015) to constrain properties of the ejecta. The intensity ratio O I/[O II] is a sensitive temperature diagnostic and the measured ratio of \(\approx 0.27\) indicates a temperature of \(T \approx 5000\) K. However, this should be viewed as an average temperature of the O\(^+\) zone. Because the line profile of O I does not closely follow those of the other lines (Section 3.1), some emission may originate from a different region of the ejecta and include cool gas that does not emit in the collisionally excited lines.

The [O III]/[S III] ratio reflects a higher temperature of the O\(^++\)/S\(^++\) zone. If we assume that \((S^{++}/S) = (O^{++}/O)\), then the measured ratio of [S III]/[O III] = 0.146 can be used in the expression

\[ [S\ III]/[O\ III] = 5.98 \times [S/O] \times \exp(12800/T) \]

to give

\[ S/O = 0.024 \times \exp(-12800/T). \]

The assumption of equal ionization fractions for S and O is plausible, but it potentially introduces an uncertainty of a factor of 2.

Notably, [S III] \(\lambda\lambda9531\) line emission is observed, but [S II] \(\lambda\lambda6717, 6731\) is absent. This suggests electron densities above \(10^4\) cm\(^{-3}\). Using the ratio of S/O from the equation above at \(10^4\) K, assuming \((S^{++}/S) = (O^{++}/O)\) in the singly ionized zone, and that log \(T\) is at least 3.7, then the ratio of [S II]/[O II] as a function of density can be determined. Estimating the upper limit to emission centered around the [S II] \(\lambda\lambda6716, 6731\) lines to be \(\approx 0.2 \times I\) ([O II]), we find that log \(T = 3.8\) and log \(n \geq 6.0\).

We thus conclude a sulfur to oxygen ratio \(\approx 0.01\) and a density of \(\log n \geq 6.0\). The high density is likely associated with significant clumping of ejecta, because a uniform sphere at that density with the radius \(R = 4.3 \times 10^{16}\) cm given by the time since explosion and observed expansion velocity would produce far more than the observed luminosity. The line profiles of all the forbidden oxygen lines are roughly the same.
Notes.

- In units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$.
- In units of $10^{38}$ erg s$^{-1}$.
- Estimated from $4/3 \times$ [S III] 9531 line flux.

### Table 1

| Line       | Flux$^a$ | Luminosity$^b$ |
|------------|----------|----------------|
| [O III] $\lambda\lambda$4959, 5007 | 2.10 ± 0.04 | 1.4 ± 0.05 |
| [O I] $\lambda$6300, 6364 | 0.99 ± 0.02 | 0.65 ± 0.02 |
| [O II] $\lambda\lambda$7319, 7330 | 0.96 ± 0.03 | 0.64 ± 0.03 |
| O I $\lambda$7774 | 0.26 ± 0.03 | 0.17 ± 0.02 |
| [S III] $\lambda\lambda$9069, 9531 | 0.62 ± 0.06$^c$ | 0.41 ± 0.04 |

![Figure 1. Magellan+IMACS optical spectrum of SN 2012au obtained 2018 June 8. Top: entire 1D spectrum as extracted (gray) and data smoothed using 5 Å boxcar (black). The phase is with respect to the $v$-band maximum on 2012 March 21. Bottom: 2D spectrum in the region of [O I] and H$\alpha$. No conspicuous narrow emission lines local to the SN are observed.](image)

(Night 4), that they are likely colocated, but with O$^{+7}$ associated with a lower density, higher temperature zone.

### 4. Discussion

Our $t = 6.2$ yr spectrum of SN 2012 au is markedly different from the last published spectrum at $t \sim 1$ yr (Milisavljevic et al. 2013; Figure 3). At that time SN 2012au exhibited [O I], [Ca II], and Mg I] emissions typical of stripped-envelope core-collapse SNe, and unusually strong emissions from Ca II H&K, Na I D, and O I 7774. It also showed persistent P-Cyg absorptions attributable in part to Fe II at 2000 km s$^{-1}$. None of these features are observed in the new spectrum, with the exception of [O I] that has a radically different emission line profile (Figure 2) and the weakly detected O I.

Figure 3 also shows examples of objects that share late-time emission properties of SN 2012au. The recently reported optical spectrum of iPTF15dtg (Taddia et al. 2018) that we identify as a member of this grouping is included as well. Milisavljevic et al. (2013) noted that asymmetries between the emission line profiles of ions in these objects are consistent with moderately aspherical explosions. They also highlighted the O I $\lambda 7774$ line of width $\approx 2000$ km s$^{-1}$ as being indicative of a jetted explosion and a defining feature of these objects. Nicholl et al. (2016) later interpreted the O I feature to be the signature of the heating of a shell by a central engine.

Below we discuss possible excitation mechanisms for the late-time spectrum of SN 2012au and utilize multiwavelength data that further constrain properties of the ejecta and CSM.

#### 4.1. Radioactivity and SN–CSM Interaction

Typically, late-time spectra of SNe I at stages reaching 1 yr are still powered by radioactive $^{56}$Co in the $^{56}$Ni $\rightarrow$ $^{56}$Co $\rightarrow$ $^{56}$Fe decay chain. However, radioactivity is not a plausible heating source for the oxygen-rich ejecta at $t = 6.2$ yr considering $\approx 0.3 M_\odot$ of $^{56}$Ni was produced in SN 2012au (Milisavljevic et al. 2013; Takaki et al. 2013) and $^{56}$Co has a half-life of 77.3 days (Albarger et al. 1989). Furthermore, radioactivity is typically associated with neutral and singly ionized lines (see, e.g., Matheson et al. 2001), and yet our 6.2 yr spectrum exhibits a larger range of ionization levels.

SN–CSM interaction is the most common late-time emission mechanism for objects observed $>3$ yr post-explosion (see Milisavljevic et al. 2012; Chevalier & Fransson 2017, and references therein). Optical emission principally originates from a reverse shock that propagates upstream into outward expanding ejecta that gets heated and ionized. Such late-time detections all have clear signatures of interaction with an H-rich CSM including development of narrow emission lines and/or high-velocity H-rich ejecta (Milisavljevic & Fesen 2017; Figure 4). SNe Ib/c examples include SN 2001em (Chugai & Chevalier 2006), SN 2014C (Milisavljevic et al. 2015), and SN 2004dk (Mauerhan et al. 2018). A few SLSNe-I have
exhibited hydrogen emission several hundred days after explosion (Yan et al. 2017). This contrasts with SN 2012au, which shows no spectral features indicative of SN–CSM interaction.

If SN 2012au was indeed interacting with H-rich material, then H Balmer line emission would be expected. Certain H-rich CSM distributions could potentially inhibit optical emission at the time of observation, but such configurations are considered to be unlikely. It is also possible that SN 2012au is interacting with an H-poor environment. This scenario has been discussed in the context of SLSNe-I (Chatzopoulos & Wheeler 2012), but the detailed spectroscopic properties predicted for helium/carbon/oxygen-rich CSM interaction at these extremely late epochs is poorly explored.

4.2. Pulsar Wind Nebula

Another late-time emission mechanism is pulsar interaction with expanding SN gas. A PWN is generated by the spin-down power of a central pulsar. In this scenario, photoionization of the inner regions of the expanding shell of ejecta can be the dominant source of optical line emission, especially at early times (<10 yr) when the expanding ejecta absorb much of the PWN-emitting ionizing radiation.

The Chevalier & Fransson (1992) model is based on the young Crab Nebula and has been widely used for pulsar and magnetar nebulae (e.g., Kasen & Bildsten 2010). The freely expanding SN density profile is approximated by an inner, flatter power law density profile surrounded by a steeper one. The inner profile has an index of $m = 1$ and the outer $n = 9$ (Chevalier & Soker 1989; Matzner & McKee 1999). For the SN 2012au parameters $E_k \sim 10^{52}$ erg and $M_{ej} \approx 4 M_\odot$, the transition between these power laws occurs at $18,000 \text{ km s}^{-1}$. Thus the SN 2012au PWN is well within the inner, flatter region of the freely expanding gas. From Equation (2.11) of Chevalier & Fransson (1992), the velocity $V$ of the PWN is

$$V = 289 E_{39}^{0.25} E_{k51}^{-0.25} M_{ej1}^{-0.5} t_{yr}^{0.25} \text{ km s}^{-1},$$

where $E_{39}$ is in units of $10^{39}$ erg s$^{-1}$, $E_{k51}$ in 10$^{51}$ erg, $M_{ej1}$ in 10 $M_\odot$, and $t_{yr}$ in years. With $V = 2300 \text{ km s}^{-1}$ (assuming the emission is coming from close to the shell), $E_{k51} = 10$, $M_{ej1} = 0.4$, and $t_{yr} = 6.2$, we have $\dot{E} = 10^{40}$ erg s$^{-1}$. The Crab pulsar currently has $\dot{E} \approx 4 \times 10^{38}$ erg s$^{-1}$ (e.g., Condon & Ransom 2016) and extrapolating back with constant braking index gives an initial $\dot{E} \approx 4 \times 10^{39}$ erg s$^{-1}$, quite close to what is needed for SN 2012au. The Crab magnetic field is $B \approx 4 \times 10^{12}$ G (e.g., Condon & Ransom 2016), well below the magnetar field $B > 10^{15}$ G. Hence, the pulsar in SN 2012au is potentially more Crab-like than magnetar-like.

The Chevalier & Fransson (1992) model includes line estimates for an O zone. It predicts an [O III] luminosity at 1500 days to be $0.46 \times 10^{38}$ erg s$^{-1}$, which is close to the $1.4 \times 10^{38}$ erg s$^{-1}$ observed in SN 2012au. [O I] is weak because a thermal instability cools the gas, but somewhat different parameters could increase [O I]. [O II] is weak because of low temperature and high density, but that could also change. The high energy of SN 2012au should result in a considerably lower density that the PWN is moving into than that in the Crab.
Chevalier & Fransson (1992) assumed that the swept up shell would be broken up by instabilities so the ionizing radiation from the PWN photoionizes freely expanding gas ahead of the shock front. In that case, there are different layers of ionized and neutral O in the O zone. However, the similar radiation from the PWN photoionizes freely expanding gas shell would be broken up by instabilities so the ionizing efficiency of this process is low, $E \approx 10^{41} \text{ erg}$. The energetic of the shell depends on the mass, which can be found from the freely expanding density profile, and velocity $V$, yielding $E_k = 2.5 \times 10^{48} \text{ erg}$. The energy of freely expanding gas is $1.3 \times 10^{48} \text{ erg}$, which implies that the initial rotational energy of the pulsar, $E_0$, was $1.3 \times 10^{48} \text{ erg}$, corresponding to a rotation period of 0.13 s. This is longer than the millisecond periods found in the magnetar models for SLSNe and is due to the $V^4$ dependence of $E_k$ (Equation (1)); line widths in the magnetar model approach $\sim 12,000 \text{ km s}^{-1}$ and remain constant.

We favor the long spin-down model because it implies a current pulsar power that is roughly consistent with that needed to produce the observed luminosity. A prediction of this model is increasing PWN velocities, as opposed to constant velocities in the short spin-down case. Deceleration is not expected in a PWN model.

5. X-Ray Emission from the PWN

We considered the viability of detecting X-rays from the candidate PWN. Assuming a dipole model for the central source, with a spin period of 1 ms, the spin-down luminosity is given as

$$L_p \approx 2 \times 10^{42} B_{14}^2 (t/\text{year})^{-2} \text{ erg s}^{-1},$$

where $B_{14}$ is the magnetic field in units of $10^{14} \text{ G}$. At the time of our CXO observation ($t = 2325 \text{ days}$) $L_p \lesssim 10^{41} \text{ erg s}^{-1}$. If only 1% of that is converted into X-rays, the expected luminosity of the central source is $\sim 10^{39} \text{ erg s}^{-1}$. This would
be the most favorable situation, and a less energetic PWN would have a lower luminosity.

We can estimate the optical depth to 1 keV X-rays as

$$\tau = (\sigma/16\ m_p) \times 3/(4\pi) \times M_{\odot}/(v_{ej})^2,$$

where $\sigma$ is the cross-section for 1 keV X-rays, $m_p$ is the proton mass, $v_{ej}$ is the initial ejecta velocity, and $t$ is the age in years. Assuming a cross-section of $10^{-19}$ cm$^2$, appropriate for oxygen-rich ejecta, and $v_{ej}$ upwards of $\sim 3 \times 10^4$ km s$^{-1}$, the optical depth to 1 keV X-rays is $\gg 1$. Thus, the CXO nondetection is consistent with our estimate that the candidate PWN of SN 2012au is presently optically thick to 1 keV X-rays.

Notably, SN–CSM interaction (see Chevalier & Fransson 2017) is a possible alternative source of late-time X-ray emission. However, adopting parameters estimated in Kamble et al. (2014): progenitor mass-loss rate $M \approx 4 \times 10^{-6}M_{\odot}$ yr$^{-1}$, with a wind speed of $v_w = 1000$ km s$^{-1}$ extending out to a radius of at least $10^{17}$ cm), the expected thermal X-ray emission associated SN–CSM interaction would only be $\lesssim 10^{32}$ erg s$^{-1}$. This translates to a 0.5–10 keV X-ray flux of $\sim 10^{-20}$ erg cm$^{-2}$ s$^{-1}$, which is well below our detection limit.

6. Conclusions

We have presented optical and X-ray observations of the energetic, slow-evolving Type Ib SN 2012au obtained >6 yr post-explosion that provide direct evidence of a newly formed PWN exciting O-rich ejecta. Our findings support the notion that SN 2012au and a subset of SLSNe, GRB-SNe, and SNe Ib/c have been relatedly influenced by magnetized compact objects on a wide range of energy scales. It remains unclear what key aspects of the progenitor systems unite these SNe that span absolute magnitudes of $-22 < M_B < -17$.

We anticipate that, like SN 2012au, SNe harboring influential pulsar/magnetar wind nebulae will evolve into a late-time phase dominated by forbidden oxygen transitions. Furthermore, we predict that optical emission line widths should remain constant or broaden upwards of a few percent per year due to acceleration of ejecta by the pulsar/magnetar bubble. In the specific case of SN 2012au, we estimate velocity broadening at the rate of $4\% \text{yr}^{-1}$. Measurements are potentially achievable with return visits from 8 to 10 m class telescopes using $R \gtrsim 10,000$ spectroscopy over the next several years, although the best opportunities for distant events await the arrival of next-generation extremely large telescopes.

We thank the referee for a very helpful reading of the Letter and suggestions that significantly improved its content and presentation. This Letter includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile. D.J.P. acknowledges support from NASA Contract NAS8-03060. We thank the Chandra X-ray Observatory for the Director’s Discretionary Time which made possible the X-ray observations cited in this Letter. Data for SNe 1997dq 2007bi, and 2015bn were retrieved from the Weizmann interactive supernova data repository (http://wiserep.weizmann.ac.il). J. Mauerhan kindly shared spectra of SN 2014C. R.A.C. acknowledges support from NSF grant AST-1814910.

Facilities: Magellan:Baade (IMACS), CXO.

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