H\(\alpha\) emission in the nebular spectrum of the Type Ia supernova ASASSN-18tb

Juna A. Kollmeier, Ping Chen, Subo Dong, Nidia Morrell, M. M. Phillips, Doron Kushnir, J. L. Prieto, Anthony L. Piro, and Joshua D. Simon

1 Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA
2 Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Road 5, Hai Duan District, Beijing 100871, China
3 Las Campanas Observatory, Carnegie Observatories, Casilla 601, La Serena, Chile
4 Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel
5 Núcleo de Astronomía de la Facultad de Ingeniería y Ciencias, Universidad Diego Portales, Av. Ejército 441, Santiago, Chile
6 Millennium Institute of Astrophysics, Santiago, Chile

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ABSTRACT

As part of the 100IAS survey, a program aimed to obtain nebular-phase spectra for a volume-limited and homogeneous sample of Type Ia supernovae (SNe Ia), we observed ASASSN-18tb (SN 2018fhw) at 139 days past maximum light. ASASSN-18tb was a fast-declining, sub-luminous event that fits well within the observed photometric and spectroscopic distributions of the SN Ia population. We detect a prominent H\(\alpha\) emission line (\(L_{H\alpha} = 2.2 \pm 0.2 \times 10^{38}\) ergs s\(^{-1}\)) with FWHM \(\approx 1100\) km s\(^{-1}\) in the nebular-phase spectrum of this SN Ia. High luminosity H\(\alpha\) emission (\(L_{H\alpha} \geq 10^{40}\) ergs s\(^{-1}\)) has previously been discovered in a rare class of SNe Ia-like objects showing CSM interactions (SNe Ia-CSM). They predominantly belong to over-luminous (\(M_{\text{max}} < -19\) mag) SN Ia, and are exclusively found in star-forming galaxies. By contrast, ASASSN-18tb is a sub-luminous SN Ia (\(M_{\text{B,max}} \sim -17.7\) mag) found in an early-type galaxy dominated by old stellar populations. We discuss possible origins for the observed hydrogen. Out of 75 SNe Ia for which we have so far obtained nebular spectra in 100IAS, no other SN shows a \(\sim 1000\) km s\(^{-1}\) H\(\alpha\) emission line with comparable line luminosity as ASASSN-18tb, emphasizing the rarity of such emission in the nebular phase. Based on preliminary results from our survey, the rate for ASASSN-18tb-like nebular H\(\alpha\) emission could be as high as \(\sim 10\)\% level among sub-luminous SNe Ia.

Key words: supernovae: general – supernovae: individual (ASASSN-18tb/SN2018fhw) – techniques: spectroscopic

1 INTRODUCTION

Although Type Ia supernovae (SNe Ia) are fundamentally important to many areas of astrophysics and cosmology, the explosion mechanism and nature of their progenitors remains elusive. It is generally agreed upon that SNe Ia result from the thermonuclear explosions of C/O white dwarfs (WDs, Hoyle & Fowler 1960; Nugent et al. 2011), but there are unsolved questions about which systems this occurs in and how the explosions proceed. Broadly speaking, the progenitor scenarios can be grouped into the single degenerate (SD) and double degenerate (DD) classes (e.g., see reviews by Maoz et al. 2014; Wang 2018), but even among these there are fundamental differences between the models (e.g., see a review by Livio & Mazzali 2018).

In the “classic” SD scenario, the WD gains material from a non-degenerate companion, such as a main-sequence, supergiant, or red giant star. A chief prediction of these models is the stripping of \(\sim 0.1 – 0.5\) M\(_{\odot}\) of material from the donor (Marietta et al. 2000; Pan et al. 2012; Boehner et al. 2017),
which should be revealed at late times as the ejecta expands and becomes optically thin (Mattila et al. 2005; Botyánzski et al. 2018). This basic expectation has motivated extensive observational efforts to find spectral evidence of companion material in the nebular phases of SNe Ia, notably hydrogen emission (Mattila et al. 2005; Leonard 2007; Lundqvist et al. 2013, 2015; Maguire et al. 2016; Graham et al. 2017; Sand et al. 2018; Shappee et al. 2018; Holmbo et al. 2018; Tucker et al. 2018; Dimitriadis et al. 2019), which have so far not detected the predicted signature.

By definition, SNe Ia lack signs of hydrogen in the ejecta, but should the explosion occur in a hydrogen-rich medium that, too, would reveal itself in nebular hydrogen emission. Indeed, there does exist a rare class of Ia-like objects that exhibit evidence for circumstellar interactions (the prototype being SN 2002jc; studied first by Hamuy et al. 2003; Wood-Vasey et al. 2004). The spectra of these so-called “SNe Ia-CSM” are often dominated by highly luminous \( \left( L_{H_\alpha} \approx 10^{40} - 10^{41} \text{ ergs s}^{-1} \right) \) Hz emission lines at FWHM \( \sim 500 - 2000 \text{ km s}^{-1} \) (Silverman et al. 2013). Most of the known SNe Ia-CSM, however, show Hz lines even in the very early phases of spectral evolution, although two of them, PTF11kx (Dilday et al. 2012) and SN 2015cp (Graham et al. 2018), show a delayed CSM interaction. One speculation is that the progenitors of the SNe Ia-CSM are binary systems with a C/O WD and an asymptotic giant branch star (Hamuy et al. 2003) such as the symbiotic nova RS Oph (Dilday et al. 2012). Whether these are interactions with a dense interstellar medium, the long-sought “smoking gun” of the classic SD models, or evidence for alternate progenitor models remains uncertain. What is clear is that, for a variety of reasons, we might expect hydrogen emission in the late-time nebular spectra for SNe Ia, but it has been difficult to find.

Here we report nebular-phase spectroscopy of ASASSN-18tb, where we find clear evidence of hydrogen in emission. This observation was obtained as part of the 100 type IA Supernova (“100IAS”) survey, where we aim to systematically obtain nebular spectra of 100 SNe Ia from a volume-limited sample of nearby SNe Ia (Dong et al. 2018). In \( \S \) 2, we describe our observations and data analysis. In \( \S \) 3, we discuss possible interpretations and implications of this result. We conclude in \( \S \) 4 with a discussion of future work.

2 OBSERVATIONS AND DATA ANALYSIS

ASASSN-18tb (SN 2018fhw) was discovered by the All-Sky Automated Survey for Supernovae (ASAS-SN, Shappee et al. 2014 Brimacombe et al. 2018) and was classified as a SN Ia based on a SALT spectrum taken on UT 2018-08-23 (Eweis et al. 2019). The publicly-available spectrum of the SN on the Transient Name Server (https://wis-tns.weizmann.ac.il/object/2018fhw) was obtained at a phase of \(-4\) days with respect to the epoch of maximum light in the \( B \) band. We show in Figure 1 a Branch Diagram (Branch et al. 2006) to place ASASSN-18tb in context with other SNe. Pseudo equivalent widths of the Si II \( \lambda 5072 \) and \( \lambda 6355 \) absorption features measured from the SALT spectrum and corrected to maximum light using the relations given in Table 7 of Folatelli et al. (2013) indicate that ASASSN-18tb was of the “Cool” (CL) subtype in the Branch classification system.

Light curves in \( BVri \) obtained at the Las Cumbres Observatory were fit using the “SNooPy” (Burns et al. 2011) package to yield a time of \( B \) maximum of JD 2458357.3±0.4, a maximum-light magnitude of \( B = 16.66 \pm 0.04 \), and decline rate parameters of \( \Delta m_{15}(B) = 2.0 \pm 0.1 \) (Phillips 1993) and \( s_{BV} = 0.5 \pm 0.04 \) (Burns et al. 2014). The absolute \( B \) magnitude at maximum (assuming zero host galaxy reddening and \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \)) was \(-17.7 \pm 0.06 \) mag, placing ASASSN-18tb on the sub-luminous portion of the \( s_{BV} \) vs. \( M(B_{\text{max}}) \) relationship for SNe Ia (see Figure 4 of Burns et al. 2018). Shown in Figure 2a is an image of the host galaxy, 2MASX J04180508-6336523, an apparent dwarf elliptical galaxy (\( M_V = -17.4 \) at \( \text{helio} \) = 0.0170 ± 0.0001 (Eweis et al. 2019). The \( g - r \) and \( r - i \) colors of the host measured by the Dark Energy Survey (Abbott et al. 2018) are consistent with a dwarf elliptical (Schombert 2018), and our optical spectrum shows no obvious emission lines. We note that this classification is in line with the well-known association of sub-luminous SNe Ia with early-type galaxies (Hamuy et al. 1996, 2000).

The nebular spectrum presented here was obtained with LDSS3 (Low Dispersion Survey Spectrograph 3) on UT 2019-01-13 at the 6.5m Magellan Clay telescope as part of 100IAS. The post-maximum phase at the time of observation was \( +139 \) days. We obtained three 1800 s exposures of ASASSN-18tb with spectral resolving power \( R \approx 700 \). We had sub-arcsecond seeing throughout our exposure sequence with the final seeing settling to 0.65′′. To avoid as much host galaxy contamination of the spectrum as possible, instead of aligning the slit along the parallactic angle (which had an average value of 24° during the observations), we rotated it to a position angle of 90.5°. We employed routine calibration and reduction procedures using IRAF tasks.

We show the flat-fielded, rectified, and wavelength-calibrated two-dimensional spectrum in Figure 2b, where the \( H_\alpha \) line is clearly apparent (and indicated with an arrow). Note that in the 2D spectrum shown in Figure 2b there is no evidence of spatially extended narrow \( H_\alpha \) emission, indicating that the SN exploded in a region of low star formation. The extracted 1D spectrum of ASASSN-18tb is displayed in Figure 3, with an inset showing the strong \( H_\alpha \) emission line detection. We also include the spectrum (scaled and shifted in flux) of the sub-luminous Type Ia SN 1986G (Phillips et al. 1987) obtained at 103 days after \( B \)-band maximum (Cristiani et al. 1992), showing similar features and line ratios compared to the nebular-phase spectrum of ASASSN-18tb.

The emission line profile of the \( H_\beta \) feature is reasonably well fit by a Gaussian with a FWHM of 26 Å. Taking into account the resolution of the spectrum and the redshift of the host galaxy, this corresponds to a FWHM of 1085 km s\(^{-1}\). The peak of the emission is blueshifted by \(-300 \text{ km s}^{-1}\) with respect to the redshift of the host galaxy, and the total measured flux is \(3.5 \times 10^{-16} \text{ ergs s}^{-1} \text{ cm}^{-2}\), with an estimated uncertainty of \(+10\%\). Assuming a distance of 70.7 Mpc implies a luminosity of \(2.2 \pm 0.2 \times 10^{38} \text{ ergs s}^{-1}\).

No other emission features with similar width as the \( H_\alpha \) line are detectable in our spectrum of ASASSN-18tb. In particular, no obvious emission is observed at the expected position of \( H_\beta \). From Equation 1 of Leonard (2007), we calculate a 3\( \sigma \) upper limit for the equivalent width of \( H_\beta \).
emission of 3.4 Å. Given the continuum flux at the wavelength of \( H\beta \) after correcting for slit losses from differential atmospheric refraction (following Shappee et al. 2017), this value translates to an upper limit to the flux of \( \beta \) of \( 2.6 \times 10^{-17} \) ergs s\(^{-1}\) cm\(^{-2}\), and \( F(H\alpha)/F(H\beta) \geq 14 \). However, visually comparing a Gaussian emission line with this flux to the observed spectrum at \( H\beta \) suggests that such a feature would not, in fact, be detected at 3\( \sigma \) significance, and this limit is therefore insufficiently conservative. By shifting and scaling the observed H\( \alpha \) profile to the wavelength of H\( \beta \), we estimate that a more realistic lower limit on the Balmer decrement is \( F(H\alpha)/F(H\beta) \geq 6 \). We further discuss this Balmer decrement in relation to the origin of this hydrogen emission next.\(^1\)

3 DISCUSSION

The search for hydrogen emission in SNe Ia has been ongoing for many decades. As mentioned above, the presence of hydrogen and/or helium-rich material in the CSM is regarded as a generic prediction of models that favor single degenerate binary systems as SNe Ia progenitors. Hydrogen stripped from a non-degenerate companion embedded in the SN ejecta at velocities of \( \sim 1000 - 2000 \) km s\(^{-1}\) is expected to be observable at epochs \( \gtrsim 200 \) days after explosion (see Botyánszki et al. 2018, and references therein). However, the search has proven elusive, with non-detections being the rule (e.g. Mattila et al. 2005; Leonard 2007; Lundqvist et al. 2013; Shappee et al. 2013, 2018). A single tentative detection of H\( \alpha \) emission for SN 2013ct has been reported by Maguire et al. (2016), who also reported 17 non-detections. In the remainder of this section, we discuss possible scenarios for explaining the H\( \alpha \) emission in ASASSN-18tb.

3.1 Comparison with SNe Ia-CSM Objects

Comparison of ASASSN-18tb with the class of “SNe Ia-CSM” is instructive. At maximum light, the spectrum of SN 2002ic (the prototype Ia-CSM) showed absorption features typical of a luminous, slow-declining 1991T-like event (Phillips et al. 1992; Filippenko et al. 1992), but diluted in strength by the CSM interaction with the SN ejecta. Since then, several further examples of SNe Ia-CSM objects have been identified (Silverman et al. 2013), the best-observed one being PTF11kx, which showed temporally variable Na\( i \), Fe\( ii \), Ti\( ii \), and He\( i \) absorption lines and a 1991T-like spectrum at maximum before developing strong hydrogen and calcium emission lines approximately a month after maximum which was interpreted as due to the interaction of the SN ejecta with a shell of CSM at a distance of \( \sim 10^{16} \) cm (Dilday et al. 2012). Recently, the detection of hydrogen and calcium emission 664 days after maximum in the 1991T-like SN 2015cp has provided a second case of a delayed CSM interaction in a SN Ia-CSM event (Graham et al. 2018).

Our detection of H\( \alpha \) emission in the spectrum of the sub-luminous SN Ia ASASSN-18tb adds a new element to the puzzle. The Balmer decrement we observe is similar to the SNe Ia-CSM, which is consistent with what might be expected from shock excitation. But how do the spectral and photometric properties of ASASSN-18tb compare to the SNe Ia-CSM? The early epochs of the best-observed examples of the SNe Ia-CSM resemble those of the luminous, slow-declining SN 1991T. Figure 1 shows the positions of SN 1991T and the SN Ia-CSM PTF11kx in the Branch diagram. These objects are members of the “Shallow-Silicon” (SS) subtype, and thus are quite different in their spectral and photometric characteristics compared to the fast-declining, sub-luminous ASASSN-18tb which belongs to the “Cool” (CL) region of the Branch diagram. Furthermore, all previous SNe Ia-CSM were found in star-forming galaxies, while the host of ASASSN-18tb is an early-type galaxy dominated by old stellar populations. Finally, the H\( \alpha \) luminosity of ASASSN-18tb is two orders of magnitude smaller than the H\( \alpha \) luminosities of SNe Ia-CSM (Silverman et al. 2013; Graham et al. 2018).

The evidence is thus mixed as to whether ASASSN-18tb should be considered similar to the SN Ia-CSM objects or not. It is possible that ASASSN-18tb reveals a much broader variety within the SNe Ia-CSM class. It is also possible that ASASSN-18tb is something distinctive altogether. Definitively answering this question will require follow up observations, which we discuss in further detail below.

3.2 Stripped Mass Estimates in the SD Model

As described above, broad \( (\sim 1000 \text{ km s}^{-1}) \), nebular-phase H\( \alpha \) emission due to stripped material from a non-degenerate

\(^1\) We note that while the observed limit on the Balmer decrement is not uncommon in astrophysical plasmas, the deviation from the standard recombination value requires explanation, e.g. dust or an alternate power source.
Figure 2. (a) gri image of the host galaxy of ASASSN-18tb, 2MASX J04180598-6336523, taken from Data Release 1 of the Dark Energy Survey (Abbott et al. 2018). The image is 1′ on a side (21 kpc at the distance of the SN) and the position of the SN is marked by the white ticks. (b) Two-dimensional Magellan/LDSS3 spectrum of ASASSN-18tb near the wavelength of Hα. The narrow Hα emission line we detected is indicated with an arrow. The faint emission observed at λ ~ 640 nm and ~7 arcsec to the right of the SN is due to [O II]λ3727 from an unrelated faint galaxy at z ~ 0.7.

Figure 3. The rest-frame nebular-phase spectrum of ASASSN-18tb. The full ≈ 139 days Magellan spectrum is shown in black. The inset shows a zoom-in on the strong Hα 6562.8 Å line detection. We also show a spectrum (scaled and shifted in flux) of the sub-luminous Type Ia SN 1986G at 103 days in red for comparison.

Finally, we raise the possibility that the observed Hα has an entirely different origin. One alternative explanation is that the companion is a longstanding prediction of SD models (e.g. Mattila et al. 2005; Botyánszki et al. 2018). While the full multi-dimensional radiation transfer calculations required to model this process accurately do not exist in the literature, for illustrative purposes, we simply translate the Hα luminosity of ASASSN-18tb into a stripped hydrogen mass according to a series of MS38 models (Botyánszki & Kasen 2017) with reduced density using the simplified radiation transfer modeling by Botyánszki et al. (2018). We obtain ~ 2 × 10^{-3} M_⊙. This value is significantly lower than the ≥ 0.1 M_⊙ typically expected from SD models, and whether much lower stripped masses are possible (e.g., at a large binary separation) is under debate (Liu et al. 2012; Botyánszki & Kasen 2017). It is curious, however, that the ratio of the peak flux of Hα to that of the [FeIII]λ4658 feature in the nebular spectrum observed in ASASSN-18tb is similar to that predicted by Botyánszki et al. (2018, see their Figure 2), despite the fact that our mass estimate is considerably lower than their prediction. Note that the Botyánszki et al. calculations are for a Chandrasekhar-mass WD with 0.6 solar masses of 56Ni, whereas ASASSN18-tb was a sub-luminous event, possibly sub-Chandrasekhar-mass WD (e.g., Mazzioli et al. 1997; Piro et al. 2014; Scalzo et al. 2014; Wyrzosa et al. 2019), with a Ni mass likely in the range of ~ 0.1 – 0.2 M_⊙. Accounting for the lower Ni mass is likely to increase the stripped-mass estimate to ~ 0.01 M_⊙. We look forward to future models more appropriate to sub-luminous SNe.

A separate and distinct prediction of the SD scenario is the appearance of excess radiation during the first ~ 1 – 2 days following explosion due to the interaction of the SN ejecta with its non-degenerate companion (Kasen 2010). Fortuitously, when ASASSN-18tb was discovered, it was located within the Camera 4 field of the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014) Sector 1 observations (Brimacombe et al. 2018). The precise TESS light curves from this SN may provide an important probe of these models, such as whether such a collision occurs or if there is additional emission at early times from dense CSM interaction (Piro & Morozova 2016).

3.3 Other Possibilities

Finally, we raise the possibility that the observed Hα has an entirely different origin. One alternative explanation is that...
the H$\beta$ emission is the result of fluorescent UV pumping. This would naturally produce a high Balmer decrement (as observed). The cartoon picture is that of an expanding hydrogen shell being pumped by the soft UV photons from the SNe itself. In general, weak Paschen lines would indicate a non-recombination source and the H$\alpha$ flux would scale with the UV source flux. This highlights the important role UV and IR observations play in understanding these systems.

Given the ubiquity of hydrogen in the universe and plethora of mechanisms to power H$\alpha$ (e.g., stellar winds/mass losses, common envelope/Roche lobes, planetary nebulae, interstellar media interactions, shock interactions, to name a few), there are many other possible scenarios that we have not interpreted to understand this rare discovery. Indeed, it is perhaps the persistent rarity of finding nebular hydrogen emission in these systems that may be the biggest clue to solving the Type Ia progenitor puzzle.

3.4 Statistical Preview

The 100IAS survey was constructed precisely for the purpose of obtaining a complete, nearly volume-limited sample of Type Ia SNe, in order to gauge nebular-phase demographics for these objects. By construction, we sample broadly across the Type Ia luminosity function, and notably, we aim to be unbiased with respect to sub-luminous events. Over the course of 100IAS, we have thus far obtained nebular-phase spectra for 75 SNe Ia. For all objects except ASASSN-18tb, H$\alpha$ emission with a FWHM $\approx 1100$ km s$^{-1}$ and a luminosity of $2 \times 10^{48}$ ergs s$^{-1}$ can be confidently ruled out. A few examples are shown in Figure 4. Therefore, the luminous H$\alpha$ emission seen in ASASSN-18tb must be rare, with an occurrence rate of ~ few % of all SNe Ia. Its rarity is also consistent with the nondetections of such H$\alpha$ emission lines for several dozen SNe Ia with well-observed nebular-phase spectra published in the literature (see references in Section 1). With a peak luminosity of $M_{\alpha,max} = -17.7 \pm 0.06$ mag, ASASSN-18tb is at the low-luminosity end of the SNe Ia luminosity function (see, e.g., Burnes et al. 2014), and nebular spectra for sub-luminous SNe Ia are dramatically under-represented in the literature. In the 100IAS sample, there are ~ 10 objects with comparable or lower luminosity to ASASSN-18tb, and so the fraction of SNe Ia with luminous H$\alpha$ at nebular phase for this population could be as high as ~ 10%.

4 CONCLUSIONS

We present an unambiguous detection of H$\alpha$ emission in the nebular-phase spectrum of the Type Ia SNe ASASSN-18tb as part of the 100IAS survey. We find some similarities with the rare class of SNe Ia-CSM, but also highlight some striking differences, such as the photometric and spectral properties of ASASSN-18tb and the relatively low luminosity of its H$\alpha$ emission in comparison to this class. With our data alone, we cannot definitively rule out a CSM-interaction interpretation for this feature as opposed to alternate hypotheses such as the long-sought stripped material from a non-degenerate companion, or other potential scenarios with which we have not compared. In any case, ASASSN-18tb is worthy of significant follow up.

Figure 4. A sample of nebular spectra from the 75 SNe Ia of the 100IAS survey. Except for ASASSN-18tb (red; upper right), no other object in 100IAS show FWHM $\geq 1000$ km s$^{-1}$ H$\alpha$ detected at $2 \times 10^{48}$ ergs s$^{-1}$, shown as simulated signals with red dashed lines. The rest-frame wavelength of H$\alpha$ is shown by the solid cyan lines and at $\pm 500$ km s$^{-1}$ by blue dashed lines in each sub panel.

Such follow up observations will be key for discriminating between the possible origins of the H$\alpha$ emission. For example, the UV/X-ray emission may prove critical. This has indeed been observed for at least one SN Ia-CSM (Bochenek et al. 2018), although we note that this is one of the most extreme members of this class. CSM interaction also results in a larger bolometric luminosity that declines more shallowly than cobalt decay (Silverman et al. 2013), and infrared observations should be sought to construct a late time light curve. Further spectra as the SN fades may reveal additional emission lines as the shock interaction increases. We look forward to further comprehensive theoretical and observational analysis of this system to decode the physical origin of this H$\alpha$ emission and thereby gain further insights into the elusive progenitors of SNe Ia.

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