Hα Luminosity of ATLAS18qtd Does Not Plateau in the Nebular Phase

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ABSTRACT

We present new spectroscopic and photometric observations of ATLAS18qtd/SN 2018cqj, a fast-declining Type Ia supernova with variable Hα emission in previously-published nebular phase spectra. ATLAS18qtd is undetected in both spectroscopic and photometric observations which occurred at $\sim 540$ d after maximum light and $\sim 230$ d after the last Hα detection. With these new non-detections, we place an upper limit on the Hα luminosity of $\lesssim 1.1 \times 10^{36}$ erg s$^{-1}$ indicating the Hα flux decreased by a factor of $\gtrsim 4$ since the previous detection. This upper limit excludes Hα emission that plateaus or increases since the previous detection but cannot confirm that the Hα emission decay rate is equivalent to the supernova decay rate.

Keywords: supernovae: individual (2018cqj)

INTRODUCTION

Type Ia supernovae (SNe Ia) are key cosmological probes (e.g., Riess et al. 1998; Perlmutter et al. 1999), yet their progenitor systems are still widely debated. The two main theories for SNe Ia progenitors are the single- and double-degenerate scenarios, where ‘single’ and ‘double’ refer to the number of degenerate objects (i.e., white dwarfs, hereafter WDs) in the system (see Jha et al. 2019 for a review). While searches for observational signatures from the single-degenerate scenario have mostly returned non-detections, the double-degenerate scenario struggles to explain SNe Ia interacting with nearby circumstellar material (CSM), referred to as SNe Ia-CSM, (Silverman et al. 2013a).

ATLAS18qtd (SN 2018cqj) is a faint, fast-declining SN Ia (Prieto et al. 2020) in IC 550 ($z = 0.0165$) discovered by the Asteroid Terrestrial-impact Last Alert System (ATLAS, Tonry et al. 2018). Variable Hα emission in nebular-phase spectra was discovered by Prieto et al. (2020) and the uncertain origin of the Hα emission prompted our follow-up observations.

OPTICAL IMAGING AND SPECTROSCOPY

New optical spectroscopy and r-band imaging data were acquired on Dec 27 & 28, 2019 UT with the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004). Initial data reduction procedures roughly follow the Gemini Data Reduction Cookbook\textsuperscript{1}. Additionally, we implement LACOSMIC (van Dokkum 2001) to reject cosmic rays.

The r-band image has a total exposure time of $\approx 1200$ s and has a measured FWHM of $\approx 0.75'' (= 4.6$ pixels). The final WCS solution is verified with 162 PanSTARRS objects and has an RMS of $\sim 1.5$ pixels. We compute aperture photometry of stars in the image and derive a photometric zeropoint of 32.71 $\pm$ 0.03 mag. With this photometric zeropoint, we place a 3$\sigma$ upper limit at the location of ATLAS18qtd of $r > 25.2$ mag.

The spectroscopic observations total 8100 s of exposure time split across 2019 Dec. 28 & 29 UT. On both nights nearby objects fall within the slit and are used to anchor the trace location for ATLAS18qtd. We extract the non-

\textsuperscript{1} http://ast.noao.edu/sites/default/files/GMOS_Cookbook/
Figure 1. **Top panel:** $r$-band image of ATLAS18qtd. Thin rectangles represent 1″-wide slit orientations from each night when observations were conducted (cyan=Dec. 27; magenta=Dec. 28; 2019 UT). **Middle panel:** Non-detection spectrum of ATLAS18qtd at $\sim$ 540 days after maximum. **Bottom left panel:** Spectral region around H$\alpha$ showing no evident emission and our $10\sigma$ flux limit in blue. **Bottom right panel:** H$\alpha$ evolution including our new $10\sigma$ upper limit. The dashed black line represents the expected flux if the H$\alpha$ emission decays at the same rate as the V-band light curve.
detection spectrum for each observation and provide the final spectrum in Fig. 1. A spectrophotometric standard star was used to correct the extracted spectrum for instrumental throughput and atmospheric attenuation.

ATLAS18qtd is undetected in both the photometric and spectroscopic observations, yet the spectrum must be on an absolute flux scale to place a useful limit on Hα emission. Three slit-coincident point sources are used to estimate the reliability of the flux scale from the spectrophotometric standard star. After correcting for slit losses we calculate synthetic magnitudes from the flux-calibrated spectra and compare these results to magnitudes derived from the r-band image. The flux calibration is accurate to within a factor of ∼ 2 without additional corrections, attributable to the excellent observing conditions (mean airmass < 1.2, seeing ∼ 0.8″, and little-to-no cloud cover).

RESULTS

The new observations occurred ≈ 541 days after maximum light using the $t_{\text{max}}$ from Prieto et al. (2020). Utilizing Eq. 3 from Tucker et al. (2020), the 10σ upper limit on Hα emission is $F_{\text{Hα}}(10\sigma) < 1.6 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, or equivalently $L_{\text{Hα}}(t_{\text{max}}) < 1.1 \times 10^{36}$ erg s$^{-1}$ (Fig. 1). The conservative 10σ upper limit is chosen to better reflect the inherent uncertainties in our analysis, such as imprecise flux calibration and neglecting any uncertainty in the redshift-derived distance.

The nebular spectra of ATLAS18qtd at +193 and +307 days after maximum have measured Hα luminosities of $L_{\text{Hα}}(+193d) = 3.8 \times 10^{37}$ erg s$^{-1}$ and $L_{\text{Hα}}(+307d) = 4.6 \times 10^{36}$ erg s$^{-1}$ (Prieto et al. 2020). Additionally, the nebular V-band decline rate for ATLAS18qtd was measured to be ∼ 0.015 mag day$^{-1}$. If $L_{\text{Hα}}$ decays similarly to the SN bolometric luminosity, which is in turn nearly proportional to the $V$-band decline rate (e.g., Shappee et al. 2017; Dimitriadis et al. 2017), the predicted Hα luminosity during our spectroscopic observations is $L_{\text{Hα}}(+550d) \sim 3 \times 10^{35}$ erg s$^{-1}$, a factor of ∼ 3.5 lower than our Hα upper limit (Fig. 1).

Our new upper limit on Hα constrains some CSM scenarios. SNe In-CSM typically exhibit Hα luminosities that plateau in the nebular phase and the emission lasts out to 500 days after maximum (e.g., PTF11kxx, Silverman et al. 2013b) although observations at these epochs are scarce. Any continuation or increase in $L_{\text{Hα}}$ would be detectable in our spectrum, indicating the Hα must decline by a factor of $\gtrsim 4$ between the prior spectrum at +307 d and our later observations. Thus, we can place a lower limit on the Hα decline rate of $\gtrsim 0.007$ mag/day. This limit is consistent with the V-band decline rate of ∼ 0.015 mag/day but cannot confirm that these decay rates are equivalent. Another possible explanation for the Hα emission that does not invoke the presence of CSM is material stripped from a companion star during the explosion (e.g., Marietta et al. 2000). However, the inferred stripped mass values are an order of magnitude lower than expected from models in the literature (Prieto et al. 2020; Dessart et al. 2020).

ACKNOWLEDGMENTS

We thank Aaron Do for assisting with the SNIFS/UH88 acquisition imaging. M.A.T. acknowledges support from the DOE CSGF through grant DE-SC0019323. B.J.S. is supported by NSF grants AST-1908952, AST-1920392, and AST-1911074.

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