Wind-Driven Transients as A Unified Model for Peculiar Events AT2018cow and iPTF14hls

KOHKI UNO and KEIICHI MAEDA

1Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto, 606-8502, Japan

(Received March 13, 2020)
Submission to ApJ

ABSTRACT

We propose a wind-driven model for peculiar transients, and apply the model to AT2018cow and iPTF14hls. In the wind-driven model, we assume that a continuous outflow like a stellar wind is injected from a central system. While these transients have different observational properties, this unified model can explain their photometric properties which are not reproduced by a supernova-like instantaneous explosion. Furthermore, the model predicts characteristic spectral features and evolution, which are well in line with those of AT2018cow and iPTF14hls. Despite the different observational properties, the wind model shows that they have some common features; the large mass-loss rates (\(\sim 20 \, M_\odot \, \text{yr}^{-1}\) for AT2018cow and \(\sim 30 \, M_\odot \, \text{yr}^{-1}\) for iPTF14hls), the characteristic radii of \(\sim 10^{13} \, \text{cm}\) for the launch of the wind, and the kinetic energies of \(\sim 10^{51} \, \text{erg}\). It would indicate that both may be related to events involving a red super giant (RSG), in which the RSG envelope is rapidly ejected by an event at a stellar core scale. On the other hand, the main differences are time scales and the total ejected mass. We then suggests that iPTF14hls may represent a dynamical common-envelope evolution induced by massive binary systems (\(\sim 50 \, M_\odot\) each). AT2018cow may be either a tidal disruption event of a low-mass RSG by a black hole (BH), or a BH-forming failed supernova.

Keywords: stars: winds, outflows — supergiants — supernovae: individual (AT2018cow, iPTF14hls)

1. INTRODUCTION

In recent years, new classes of astronomical transients have been discovered, thanks to improvement in observational instruments and operation of new generation surveys such as Pan-STARRS (Kaiser et al. 2002), PTF (Law et al. 2009), ASSA-SN (Shappee et al. 2014), and ZTF (Kulkarni 2018). Some transients have peculiar light curves and/or spectral evolution, whose properties have not yet been explained by any existing models. AT2018cow (Prentice et al. 2018) and iPTF14hls (Arcavi et al. 2017) are among these enigmatic transients, whose origins have not been identified yet.

AT2018cow is a fast and luminous blue transient, discovered by ATLAS (Prentice et al. 2018). It showed a rapidly declining luminosity roughly following a power law, and a recessing photospheric radius from the beginning (Perley et al. 2019). These features are different from those seen in supernovae (SNe). Some models have been proposed, including an electron-capture collapse (Lyutikov & Toonen 2019), a Tidal Disruption Event (TDE, Kuin et al. 2019), and a common envelope jet (Soker et al. 2019). However, most, if not all, of the proposed models aim at explaining its energetics, luminosity, or time scale. The origin of the most peculiar observational features in the time evolution, as described above, remains unanswered.

iPTF14hls was classified as a typical Type IIP SN (Filippenko 1997) at the beginning (Arcavi et al. 2017). However, it turned out that it kept high brightness for almost 2 years. Although snapshot spectra of iPTF14hls were very similar to Type IIP SNe, its evolution was too slow. In addition, it showed line velocities (\(\sim 4000 \, \text{km/s}\)) and the color nearly constant over time. While its long timescale itself is peculiar, what is indeed the most difficult to understand is this combination of the (nearly) constant color (temperature) and the constant line velocities. Some models (e.g. Quataert et al. 2019; Liu et al. 2019; Gilkis et al. 2019) have been proposed, but mostly dealing with the light curve behavior.
Explosions like SNe produce homologously expanding ejecta, with monotonically increasing physical scale and decreasing density and optical depth. This combination never explain the peculiar time evolution seen in AT2018cow and iPTF14hls, as described above. The homologous expansion predicts that the photospheric radius increases initially (unlike AT2018cow). If the luminosity stays nearly constant (within a factor of a few), it must show either decreasing temperature or decreasing line velocities (unlike iPTF14hls).

These peculiar properties suggest that these systems might be described as a (stellar) wind (i.e., a continuous input of the mass and the energy from the inner engine) rather than an SN-like explosion (i.e. an instantaneous explosion). Indeed, Moriya et al. (2020) suggested such a model for iPTF14hls based on a phenomenological argument (§3.2 for more details). In this paper, we present a physically-motivated model for the ‘wind-driven’ explosion. We apply the model to AT2018cow and iPTF14hls, and show that their light curves and the evolution of the photosphere (i.e. color) can be explained within the same context. Furthermore, we investigate the details of the spectral line formation process, and find that the model predictions are perfectly in line with the characteristic line properties and the spectral evolution for both transients.

The paper is structured as follows. In §2, we introduce an analytical setup of the wind-driven model, under the assumption of the steady state. In §3, we apply the model to AT2018cow and iPTF14hls, and estimate the mass-loss rates and other wind properties using their photometric data. We further discuss the properties of spectral line formation and its evolution, and the model predictions here are compared with the spectroscopic properties of AT2018cow and iPTF14hls. Based on the derived properties of the wind, we discuss possible origins of these transients in §4. The paper is closed in §5 with conclusions.

When we were finalizing this manuscript, Piro & Lu (2020) presented their new work in which they independently derived the earlier work by Piro & Lu (2020). We note that additional processes (e.g., recombination and spectral formation) are newly discussed in the present work.

In the wind-driven model, we consider continuous outflows, which is analogous to stellar winds, characterized by the mass loss rate ($\dot{M}$) and the wind velocity ($v$). Under the assumption of steady states, the density structure of the system is given as follows;

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v}. \quad (1)$$

The innermost (equipartition) radius is described as $R_{eq}$, which can be regarded as the position where the wind is launched. In the inner region above $R_{eq}$, matters and photons are coupled up to the radius $R_{ad}$, where $\tau_s \approx c/v$ holds (where $\tau_s$ is the optical depth considering electron scattering, and $c$ is the speed of light). The temperature there is decreasing adiabatically. Above this region, the luminosity is roughly constant and the temperature there is determined by diffusion. Within the outer region, some characteristic radii, $R_c$, $R_{rec}$, $R_s$ and $R_{\text{H}_\alpha=1}$, are defined. $R_c$ is the color radius, where $\tau_{eff} \approx 1$ holds (where $\tau_{eff}$ is the effective optical depth). $R_{rec}$ is the recombination radius. $R_s$ is the scattering radius where $\tau_s \approx 1$ holds. $R_{\text{H}_\alpha=1}$ is the Hα forming radius (see Figure 1).

The optical depth for electron scattering is defined as follows;

$$\tau_{es} = \int_r^{R_{out}} \kappa_{es}\rho(r)dr = \frac{\kappa_{es} \dot{M}}{4\pi v} \left( \frac{1}{r} - \frac{1}{R_{out}} \right), \quad (2)$$

where $\kappa_s$ is the opacity considering electron scattering ($\kappa_s = 0.34 \text{ cm}^2 \text{g}^{-1}$ for the solar composition). $R_{out}$ is defined as the outermost radius, above which $\kappa_s = 0$. If $R_{out} \gg r$ holds, $\kappa_s$ is described as follows;

$$\tau_s = \frac{\kappa_{es} \dot{M}}{4\pi v} \frac{1}{r}. \quad (3)$$

The effective optical depth ($\tau_{eff}$), considering not only electron scattering but also absorption processes, is defined as follows;

$$\tau_{eff} = \int_r^{R_{out}} \kappa_{eff}\rho(r)dr, \quad (4)$$

where $\kappa_{eff}$ is the effective opacity, given as follows;

$$\kappa_{eff} = \sqrt{3(\kappa_{es} + \kappa_s)\kappa_s} \approx \sqrt{3\kappa_{es}\kappa_s} \quad (\kappa_{es} \gg \kappa_s). \quad (5)$$

2. WIND-DRIVEN MODEL

The basic formalism described here has been independently derived by the earlier work by Piro & Lu (2020). We note that additional processes (e.g., recombination and spectral formation) are newly discussed in the present work.

In the wind-driven model, we consider continuous outflows, which is analogous to stellar winds, characterized by the mass loss rate ($\dot{M}$) and the wind velocity ($v$). Under the assumption of steady states, the density structure of the system is given as follows;

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v}. \quad (1)$$

The innermost (equipartition) radius is described as $R_{eq}$, which can be regarded as the position where the wind is launched. In the inner region above $R_{eq}$, matters and photons are coupled up to the radius $R_{ad}$, where $\tau_s \approx c/v$ holds (where $\tau_s$ is the optical depth considering electron scattering, and $c$ is the speed of light). The temperature there is decreasing adiabatically. Above this region, the luminosity is roughly constant and the temperature there is determined by diffusion. Within the outer region, some characteristic radii, $R_c$, $R_{rec}$, $R_s$ and $R_{\text{H}_\alpha=1}$, are defined. $R_c$ is the color radius, where $\tau_{eff} \approx 1$ holds (where $\tau_{eff}$ is the effective optical depth). $R_{rec}$ is the recombination radius. $R_s$ is the scattering radius where $\tau_s \approx 1$ holds. $R_{\text{H}_\alpha=1}$ is the Hα forming radius (see Figure 1).

The optical depth for electron scattering is defined as follows;

$$\tau_{es} = \int_r^{R_{out}} \kappa_{es}\rho(r)dr = \frac{\kappa_{es} \dot{M}}{4\pi v} \left( \frac{1}{r} - \frac{1}{R_{out}} \right), \quad (2)$$

where $\kappa_s$ is the opacity considering electron scattering ($\kappa_s = 0.34 \text{ cm}^2 \text{g}^{-1}$ for the solar composition). $R_{out}$ is defined as the outermost radius, above which $\kappa_s = 0$. If $R_{out} \gg r$ holds, $\tau_s$ is described as follows;

$$\tau_s = \frac{\kappa_{es} \dot{M}}{4\pi v} \frac{1}{r}. \quad (3)$$

The effective optical depth ($\tau_{eff}$), considering not only electron scattering but also absorption processes, is defined as follows;

$$\tau_{eff} = \int_r^{R_{out}} \kappa_{eff}\rho(r)dr, \quad (4)$$

where $\kappa_{eff}$ is the effective opacity, given as follows;

$$\kappa_{eff} = \sqrt{3(\kappa_{es} + \kappa_s)\kappa_s} \approx \sqrt{3\kappa_{es}\kappa_s} \quad (\kappa_{es} \gg \kappa_s). \quad (5)$$
For the Kramars opacity, we use $\kappa = \kappa_0 \rho T^{-7/2} \text{cm}^2 \text{g}^{-1}$ with $\kappa_0 = 2 \times 10^{24}$ (Piro & Lu 2020), and $\rho$ and $T$ are given in the cgs unit.

We define the innermost radius ($R_{\text{eq}}$) as the radius below which equipartition is realized between the internal energy (dominated by radiation) and the kinetic energy; $aT^4 = \rho v^2 / 2$ where $a$ is the radiation constant. The temperature there, $T_{\text{eq}} = T(R_{\text{eq}})$, is then described as follows;

$$T_{\text{eq}} = \left( \frac{1}{8\pi a} \right)^{1/2} \frac{M}{\rho v^2} R_{\text{eq}}^{1/2}. \quad (6)$$

Above $R_{\text{eq}}$, the temperature first decreases adiabatically as a function of radius, following the advection by the wind. The outermost radius of this region is defined as $R_{\text{ad}}$. It is defined by $\tau_s \approx c/v$, and thus

$$R_{\text{ad}} = \frac{\kappa_s}{4\pi c} \frac{M}{\rho} \tau_s. \quad (7)$$

The temperature structure at $R_{\text{eq}} < r < R_{\text{ad}}$ is given as follows;

$$T(r) = T_{\text{eq}} \left( \frac{r}{R_{\text{eq}}} \right)^{-\frac{7}{4}}. \quad (8)$$

Above $R_{\text{ad}}$, the temperature is determined by diffusion. The temperature structure is then described as follows;

$$T(r) = T_{\text{ad}} \left( \frac{r}{R_{\text{ad}}} \right)^{-\frac{7}{4}}, \quad (9)$$

where $T_{\text{ad}} = T(R_{\text{ad}})$ is given as follows;

$$T_{\text{ad}} = T_{\text{eq}} \left( \frac{R_{\text{ad}}}{R_{\text{eq}}} \right)^{-\frac{7}{4}} = \left( \frac{2\pi^3 \pi^2 R_{\text{ad}}^4}{\alpha^2 \kappa_s^4} \right)^{1/2} \frac{M}{\rho v} v^{1/2} R_{\text{eq}}, \quad (10)$$

Using the distribution of density and temperature, we estimate the color (thermalization) radius $R_c$;

$$R_c = \left( \frac{2\pi^3 \pi^2 R_{\text{ad}}^4}{\alpha^2 \kappa_s^4} \right)^{1/2} \frac{M}{\rho v} v^{1/2} R_{\text{eq}}^{1/3}, \quad (11)$$

in case $R_c \ll R_{\text{rec}}$ (the recombination radius is described bellow). When $R_c < R_{\text{ad}}$ holds, $R_{\text{ad}}$ becomes the photospheric radius ($R_{\text{ph}}$). On the other hand, if $R_c > R_{\text{ad}}$ holds, $R_c$ becomes $R_{\text{ph}}$.

An additional physical scale is introduced by the ionization structure. We consider the recombination radius $R_{\text{rec}}$, as defined by $T(R_{\text{rec}}) = T_{\text{rec}}$, where $T_{\text{rec}}$ is the recombination temperature. In the present work, $T_{\text{rec}}$ is taken as 6000 K and 12000 K for H and He, respectively. In general $T_{\text{ad}} > T_{\text{rec}}$ holds, and thus $R_{\text{rec}}$ is determined as follows;

$$T_{\text{rec}} = T_{\text{ad}} \left( \frac{R_{\text{rec}}}{R_{\text{ad}}} \right)^{-\frac{7}{4}}. \quad (12)$$

The luminosity is given by the diffusion. Above $R_{\text{ad}}$, the flux $F(r)$ must be nearly constant;

$$L(r) = -\frac{4\pi r^2 c}{3\kappa_s \rho} \frac{\partial}{\partial r} T^4 \approx \text{constant}. \quad (13)$$

Therefore,

$$L(r) = 8.92 \times 10^{43} \text{ erg s}^{-1} \times \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{v}{0.1c} \right)^2 \left( \frac{R_{\text{eq}}}{1 \times 10^{13} \text{ cm}} \right)^{1/2}. \quad (14)$$

For most of the cases, the photosphere is formed above $R_{\text{ad}}$. So that this formula can be used.
If the color temperature and $T_{\text{rad}}$ are close to the recombination temperature, we are not able to use the approximation $R_{\text{rec}} \gg R_c$ and $R_{\text{rec}} \gg R_{\text{ad}}$. Then, we need to take the effects of the recombination radius into account. Then we need to solve the following three relations. First, the relation $\tau_{\text{eff}}(R_{\text{ad}}) = c/v$ must be satisfied. With the temperature structures, it is described as follows:

$$R_{\text{ad}} = (8\pi a)^{3/2} T_{\text{rec}}^{11/2} \left( \frac{1}{R_{\text{rad}}} - \frac{4\pi c}{\kappa_s M} \right)^{-9} \times M^{-3/2} R_{\text{eq}}^{-2/3}.$$  (15)

Second, $\tau_{\text{eff}}(R_c) = 1$ is described as follows:

$$1 = \frac{8}{11} \sqrt{3\kappa_s a} \frac{2}{T_{\text{rec}}^{11/2} - T_{\text{obs}}^{11/2}} \times M^{1/2} v^{-13/2} R_{\text{eq}}^{-4/3} R_{\text{ad}}^{-2/3}.$$  (16)

Third, the luminosity is given as follows:

$$L = \frac{2\pi c}{\kappa_s} v^2 R_{\text{eq}}^{13/2} R_{\text{ad}}^{1/2}.$$  (17)

In the wind-driven model, we can compute two observables (luminosity and color temperature) from three input parameters ($R_{\text{eq}}$, $M$, and $v$). Conversely, from observational data of luminosity and color temperature, we can estimate (or give constraints on) these parameters. However, using only two observables would not give a unique solution. Practically, we can use another observational information (e.g., line velocity) to close the relations, the examples of which are given in §3.

3. APPLICATIONS TO THE OBSERVED TRANSIENTS

3.1. AT2018cow

Using the relations we derived in §2, we can calculate $R_{\text{eq}}(t)$, $M(t)$ and $v(t)$ under the wind-driven model from the observational data (Perley et al. 2019), luminosity $L(t)$ and temperature $T_{\text{obs}}(t)$. From the observationally inferred photospheric radius (from $L$ and $T$), the initial velocity of AT2018cow must be $\sim 0.1c$. This constraint can be used to derive a unique solution for $R_{\text{eq}}$, $M$, and $v$, at the initiation of the outflows. However, after that, the evolution of $v$ in not clear. As a rational approximation, we assume that $R_{\text{eq}}$ is constant over time, which is then fixed by the above information.

At the initiation of the event, $L = 3.4 \times 10^{44}$ erg s$^{-1}$, $T_{\text{obs}} = 31390$ K, and $v = 0.1c$. $R_{\text{eq}}$ is then derived as $1.7 \times 10^{13}$ cm, and this radius is fixed for subsequent evolution. In addition, $R_c < R_{\text{ad}}$ holds in the early phase and thus $R_{\text{ph}} = R_{\text{ad}}$. Then, using the relations, (10) and (14), $\dot{M}(t)$ and $v(t)$ are described as follows;

$$v(t) = 3.00 \times 10^9 \text{ cm s}^{-1} \times \left( \frac{T_{\text{obs}}(t)}{31390 \text{ K}} \right)^{\frac{4}{7}} \times \left( \frac{L(t)}{3.4 \times 10^{44} \text{ erg s}^{-1}} \right)^{\frac{5}{7}},$$  (18)

and

$$\dot{M}(t) = 19.4 M_\odot \text{ yr}^{-1} \times \left( \frac{v(t)}{3 \times 10^9 \text{ cm s}^{-1}} \right)^{-\frac{3}{2}} \left( \frac{T_{\text{obs}}(t)}{31390 \text{ K}} \right)^{-2} \times \left( \frac{L(t)}{3.4 \times 10^{44} \text{ erg s}^{-1}} \right)^{\frac{3}{2}}.$$  (19)

After a few days, the relation between the radii turns out to change to $R_c > R_{\text{ad}}$. Then, using expressions, (11) and (14), $\dot{M}(t)$ and $v(t)$ are described as follows;

$$v(t) = 9.86 \times 10^8 \text{ cm s}^{-1} \times \left( \frac{T_{\text{obs}}(t)}{21200 \text{ K}} \right)^{\frac{4}{7}} \times \left( \frac{L(t)}{3.6 \times 10^{43} \text{ erg s}^{-1}} \right)^{\frac{2}{7}},$$  (20)

and

$$\dot{M}(t) = 18.0 M_\odot \text{ yr}^{-1} \times \left( \frac{v(t)}{9.86 \times 10^8 \text{ cm s}^{-1}} \right)^{\frac{10}{11}} \left( \frac{T_{\text{obs}}(t)}{21200 \text{ K}} \right)^{-\frac{6}{11}} \times \left( \frac{L(t)}{3.6 \times 10^{43} \text{ erg s}^{-1}} \right)^{\frac{2}{7}}.$$  (21)

Figure 2 shows the evolution of $\dot{M}$, $v$, and $R_{\text{ph}}$ as we derived. In the wind-driven model, $\dot{M}$ is roughly constant for $\sim 10$ days after the initiation. After that, $\dot{M}$ decreases following a power law as a function of time (see Figure 2). Interestingly, the power law behavior with the index of $-5/3$ is found, which is the typical mass accretion rate evolution for fallback of materials onto a central compact object (e.g., TDE or failed SN). Therefore, it points to a possibility that a power source of AT2018cow may be accretion onto a compact object (see §4).

By a rough application of a similar (basically the same) model to AT2018cow, Piro & Lu (2020) reached the similar conclusion, as we confirm here. Note that the behavior in the first $\sim 10$ days is different. This is due to a difference in the detail of the model. While Piro
Figure 2. The top panel shows the bolometric light curve of AT2018cow (left axis) from Perley et al. (2019) and the evolution of the derived mass-loss rate (right axis). The black dashed line shows a power law with the index of $-5/3$. The middle panel shows the estimated photospheric radius evolution. The bottom panel shows the estimated velocity evolution.

& Lu (2020) assumed that $v$ is constant, we allow the evolution of $v$ under the constraint given by the initial condition.

Within the wind-driven model, very strong outflows (over $20 M_\odot \,yr^{-1}$) immediately after the initiation of the explosive event are required. After $\gtrsim 10$ days, the estimated mass-loss rate decreases to a few $M_\odot \,yr^{-1}$, and the wind velocity becomes as low as 4000 km s$^{-1}$. Integrating the estimated mass-loss rate and the kinetic power over time, we estimate that the total ejected mass is $0.68 M_\odot$ and total kinetic energy ($E_{\text{kin}}$) is $1.7 \times 10^{51}$ erg. Note that the cumulative kinetic energy exceeds $10^{51}$ erg already at $\sim 4$ days (see Figure 3). Thus, the outflows immediately after the initiation contain most of the total kinetic energy.

The model has a monotonically decreasing velocity evolution. Therefore, the outflows launched at later epochs never catch up with those ejected at earlier epochs. This means that the steady-state solution is a good approximation, as long as the effect of the infinite time interval is taken into account. This can be partly accounted for, by examining a history of each Lagrangian element. Besides, a time delay for each Lagrangian element to reach $R_{\text{ph}}$ is sufficiently small ($t \lesssim 10$ days). Therefore our procedure to estimate $\dot{M}$ and $v$ from the observational data at the photosphere ($L$ and $T$) without including this time delay would not introduce a large error. The history of each element is shown in Figure 4, with characteristic physical scales (e.g. $R_{\text{rad}}$) encountered by each fluid element.

Figure 4 allows to extract general features in spectral line formation expected for this model. Using the recombination temperature of helium, $T_{\text{rec(He)}} \approx 12000$ K, we can derive the recombination radius of helium $R_{\text{rec(He)}}$ for each fluid element, below which helium is singly ionized and create no HeI lines by resonance scattering. The initial outflow ($v \approx 0.1c$) injected from $R_{\text{eq}}$ at 3.44 days approaches $R_{\text{rec(He)}}$ on $\sim 20$ days (see Figure 4). Given that it takes $\sim 5$ days for the initial wind element to reach to $R_{\text{ph}}$ and start emitting photons, the wind-driven model predicts that the HeI lines start to emerge.
Figure 5. A schematic picture (not scaled) for the line formation in AT2018cow, where an observer is placed on the left side of the figure. It is assumed that the wind in the right side is stronger, to explain the redshift observed in the early phase. The change in the relative size of the photosphere to the recombination radius results in the change in the line profile (see the main text). (Left: ) At $t \lesssim 35$ days, the photospheric radius is much smaller than the recombination radius of helium. (Right: ) At $t \gtrsim 35$ days, both of the photosphere and the recombination front move inward. The shrink of the recombination radius is more substantial, leading to the large photospheric radius relative to the recombination radius.

$\sim 15 - 20$ days after the discovery. This result is consistent with the observation (Perley et al. 2019) which shows the emergence of the HeI lines at $\sim 15$ days.

The recombination temperature of hydrogen, $T_{\text{rec}(H)}$, is taken as 6000 K. Similarly to the case for the helium recombination, we consider that hydrogen is fully ionized below $R_{\text{rec}(H)}$. The hydrogen line forming region, $R_{\tau_{H_\alpha}=1}$ (see Appendix A), closely follows $R_{\text{rec}(H)}$ up to $\sim 60$ days. The epoch we estimate for the hydrogen lines to emerge is $\sim 40$ days, which is later than the observation by a factor of two. However, we note that the temperature decrease will be accelerated, once additional cooling effect is considered. Especially, the helium recombination would cool the outflow efficiently, which might decrease $R_{\text{rec}(H)}$ and $R_{\tau_{Ha}=1}$, leading to the formation of the H lines immediately after the He line formation.

The hydrogen line forming radius, $R_{\tau_{H_\alpha}=1}$, is larger than $R_{\text{ph}}$ by more than an orders of magnitude. Even if we assume the hydrogen lines are formed at $R_{\text{rec}(He)}$ (see above), it is so by a factor of $\gtrsim 3$ in the first $\sim 40$ days. When the line forming region is far above the photosphere, the spectra must be characterized by emission lines (see Figure 1). This result is consistent with the observation of AT2018cow, which shows emission lines, not absorption.

The observed hydrogen and helium lines show redshifts of $+3000$ km s$^{-1}$ at the time of the first detection of the lines. They evolve blueward as time goes by, and change the profile at $\sim 30 - 40$ days, after which they show a sharp peak around the rest wavelength, with the bluer flux suppressed (Perley et al. 2019). This behavior is explained naturally within a context of the wind-driven model (Figure 5). The possible explanation of the (initial) redshift here is phenomenological, but it can be explained if we consider aspherical winds and we observed the event from the ‘weaker’ side. The peculiar time evolution is, on the other hand, predicted by our wind model irrespective of the wind geometry (note that the spectral information is not used in constructing the model). Figure 4 shows that the recombination radius of helium is sufficiently larger than the photospheric radius until $\sim 35$ days after the discovery. In this phase, the emission line is expected, and the line profile follows the geometrical distribution of the wind. Around $\sim 35$ days, the recombination radius of helium suddenly decreases and becomes close to the photospheric radius. Afterward, the red-shift lines from the rear region are efficiently blocked by the photosphere, and the profile we
observe should evolve blueward. In addition, the line profile is affected by the absorption for the approaching side, and the blue-shift emission component will be suppressed by this effect. Therefore, we expect to observe a sharp profile at the rest-frame wavelengths, with the blue-shifted side substantially suppressed.

3.2. iPTF14hls

For iPTF14hls, $T_{\text{obs}} \sim 7000$ K has been derived, which does not evolve much over time (Moriya et al. 2020). This is close to the recombination temperature of hydrogen ($T_{\text{rec}(\text{H})} \approx 6000$ K). Therefore, the effect of the recombination radius must be taken into account. In addition, the velocity of FeII lines stayed constant, $v \approx 4000$ km $s^{-1}$, over time (Arcavi et al. 2017). This velocity should represent the outward velocity around the photosphere. The number of the observational constraint is enough to derive a unique solution (equation 15, 16, and 17). For the conditions appropriate for iPTF14hls, it turns out that $R_c$ is always larger than $R_{\text{ad}}$, therefore $R_{\text{ph}} = R_c$. Accordingly, $\dot{M}$ is described as follows:

$$\dot{M}(t) = 32.3 M_\odot \text{ yr}^{-1} \times \left(\frac{v(t)}{4.00 \times 10^8 \text{ cm s}^{-1}}\right)^{\frac{3}{5}} \times \left(\frac{L(t)}{9.99 \times 10^{42} \text{ erg s}^{-1}}\right)^{\frac{4}{5}}. \quad (22)$$

Figure 6 shows the evolution of $\dot{M}$, $R_{\text{ph}}$, and $R_{\text{eq}}$.

At the maximum luminosity, the mass-loss rate in the model is over $30 M_\odot$ yr$^{-1}$. The large mass-loss rate here is qualitatively consistent with that suggested by Moriya et al. (2020) based on a phenomenological approach, where they assumed the density at the photosphere while we derive it by using other constraints. Indeed, the quantitatively derived mass-loss rate in this work is larger by a factor of $\sim 3$. To explain the observational properties of iPTF14hls, outflows (winds) should keep its strength for almost 2 years. The total ejected mass is $\sim 25 M_\odot$ and the total kinetic energy is $\sim 4.4 \times 10^{51}$ erg in the wind-driven model (see Figure 7).

Figure 8 shows the evolution of some characteristic radii, overplotted with the histories of selected fluid elements. Below $R_{\text{rec}(\text{H})}$, hydrogen is fully ionized. The hydrogen recombination occurs when the fluid element reaches $R_{\text{rec}(\text{H})}$. For iPTF14hls, typical time delay for each fluid element to move from $R_{\text{eq}}$ to $R_{\text{ph}}$ (and $R_{\text{H}2(\alpha)=1}$) is $\sim 100$ days. Given the overall slow evolution of iPTF14hls until $\sim 450$ days, the steady-state approximation is justified. Note that the initial $\sim 100$ delay in our model is an artifact, as our model is constructed only through the observational data after $\sim 140$ days since the discovery.

Considering the Sobolev approximation (see Appendix A) as we have done for AT2018cow, we estimate the line-forming radius for Hα ($R_{\text{H}2(\alpha)=1}$). We find that $R_{\text{H}2(\alpha)=1}$ is larger than $R_{\text{ph}}$ by only a factor of at most two (note that this is at least $\sim 3$ or even more than an order of magnitude for AT2018cow). In this case, we expect...
The dynamical time scale (free-fall time) of an RSG is common envelope (CE) evolution as the energy source. As one possibility, we consider a binary system including an RSG, specifically the mass ejection derived by a common envelope (CE) evolution as the energy source. The dynamical time scale (free-fall time) of an RSG is given by

\[ t_{\text{dyn}} = \sqrt{\frac{3\pi}{32G\rho}} \]

\[ \approx 20 \text{ days} \left( \frac{M}{25M_\odot} \right)^{-\frac{1}{2}} \left( \frac{R}{2 \times 10^{13} \text{ cm}} \right)^{\frac{3}{2}}, \]  

(23)

where \( G \) is the Newtonian constant of gravitation. The dynamical time scale shown here would set a minimal response time in which the mass ejection reacts to the change in the energy input from the central system (a merged core or a close binary within an RSG envelope). This would then give the time scale of the variability in its luminosity. Indeed, the time scale of the variability seen in iPTF14hls is roughly on the same order. Given the mass ejection of \( \sim 25M_\odot \) in iPTF14hls, we may consider a CE where the primary’s core mass is \( \sim 30M_\odot \) (i.e. \( \sim 55M_\odot \) as a whole) and a companion star is \( \sim 50M_\odot \). If the orbital separation between the core and the companion shrinks to \( \sim 10^{11} \text{ cm} \) (i.e. the core size), the orbital energy release is estimated as follows;

\[ E_{\text{grav}} = 4.0 \times 10^{51} \text{ erg} \]

\[ \times \left( \frac{M_1}{30M_\odot} \right) \left( \frac{M_2}{50M_\odot} \right) \left( \frac{R_1}{1 \times 10^{11} \text{ cm}} \right)^{-1}, \]  

(24)

where \( M_1 \) is the primary’s core mass, \( R_1 \) is the core radius, and \( M_2 \) is the companion mass. This explains the estimated total kinetic energy for iPTF14hls. In summary, we suggest the dynamical CE evolution induced by massive binary systems (\( \sim 50M_\odot \) each) as a promising scenario for iPTF14hls.

This CE scenario is, however, not suitable to AT2018cow. The dynamical time scale of a putative RSG companion is too long for AT2018cow; given the smaller mass ejection, we might consider a less massive companion RSG which leads to even larger time scale. Furthermore, the evolution of the mass-loss rate (\( \propto t^{-5/3} \)) suggests that it is probably driven by a fallback accretion to a BH. Also, the fast ejecta (\( \sim 0.1c \)) indicates an event related to a compact object.

We suggest two scenarios that could satisfy these constraints; a BH-forming failed SN or a TDE of an RSG. For the BH-forming failed SN of a massive RSG, only the outermost layer, thus \( \lesssim 1M_\odot \), is ejected (Kashiyama & Quataert 2015). The energy scale of the fallback accretion is given by \( E = \epsilon Mc^2 \), where \( \epsilon \sim 10^{-3} \) (Dexter & Kasen 2013). If we consider \( 1M_\odot \) as the accreted mass, then it is \( \sim 1 - 2 \times 10^{51} \text{ erg} \). Another possibility is a TDE of a low-mass RSG. The energy budget will be similar to the case of the failed-SN scenario.

4. DISCUSSION

In this paper, we have shown that peculiar properties of AT2018cow and iPTF14hls, which have not been explained by the existing models like a supernova explosion, can be naturally explained by the wind-driven model. Furthermore, although AT2018cow and iPTF14hls have very different observational properties, we have shown that they can be explained within the same context of the wind-driven model. Interestingly, there are a few physical properties shared by the two objects. First, both events have almost the same inner radii, \( \sim 10^{13} \text{ cm} \). Second, their kinetic energies are both \( \sim 10^{51} \text{ erg} \). The main differences in the derived properties are time scales and total ejected mass.

The physical scale where the equipartition takes place, \( R_{\text{eq}} \sim 10^{13} \text{ cm} \), is a typical radius of a red super giant (RSG). This result implies that the progenitor (system) may involve an RSG. The energy budget, \( \sim 10^{51} \text{ erg} \), indicates that it may be powered by the release of the gravitational energy at \( \sim 10^{10} - 11 \text{ cm} \), if this is powered by a stellar object (i.e. \( 10 - 100M_\odot \)). Interestingly, this is the size of a core of an RSG. Except for SNe, phenomena which could release such a large amount of kinetic energy are limited.

As one possibility, we consider a binary system including an RSG, specifically the mass ejection derived by a common envelope (CE) evolution as the energy source. The dynamical time scale (free-fall time) of an RSG is

Figure 8. The same as Figure 4 but for iPTF14hls.
Peculiar transients AT2018cow and iPTF14hls showed peculiar observational properties, a combination of which defies straightforward explanations by existing models (e.g., an SN-like explosion). AT2018cow showed a rapidly decreasing luminosity and a recessing photosphere. iPTF14hls showed a long-lasting luminosity for almost 2 years, constant line velocities, and too slow spectral evolution. Most of the existing models aimed at explaining only their light curves and energetics, without addressing these peculiarities. In the present work, we have proposed a unified model, the wind-driven model, to explain these two peculiar transients with totally different observational features. We have shown that the model can explain the light curves and spectral evolution for both of AT2018cow and iPTF14hls.

Under the wind-driven model, we have estimated the evolution of the mass-loss rate, $\dot{M}$. Both transients are explained by (initially) strong outflows exceeding a few $M_\odot$ yr$^{-1}$ ($\sim 20M_\odot$ yr$^{-1}$ for AT2018cow and $\sim 30M_\odot$ yr$^{-1}$ for iPTF14hls). In addition to this similarity in the mass-loss rates, they share common properties in important physical scales; the innermost (equipartition) radius of $\sim 10^{13}$ cm and the kinetic energy of $\sim 10^{51}$ erg.

The model does not use the information on the spectral line features in its construction. Therefore, we can provide ‘prediction’ for the spectral features. We have shown that the model can explain the characteristic spectral feature; emission in AT2018cow while absorption (or P-Cygni) in iPTF14hls. We can also explain the evolution and related time scales seen in AT2018cow: emergence of HeI lines at $\sim 15$ days, the blueward shift toward the rest wavelength in the red component, as well as suppression in the blue wing, in time scale of $\sim 30$ days.

The radius of $\sim 10^{13}$ cm suggests that both events likely involve an RSG. The kinetic energy of $\sim 10^{51}$ erg then matches to the gravitational energy release if the system would shrink to $\sim 10^{11}$ cm. This is the typical size of a He core of an RSG, and we speculate this may be related to a common-envelope event involving an RSG as a primary for iPTF14hls. AT2018cow has a much shorter time scale than iPTF14hls, and we speculate that the companion star here is a BH. This can then be a TDE involving a low-mass RSG, or a BH-forming failed SN from a massive RSG.

In the present work, we have restricted ourselves for the steady-state solution (see Piro & Lu (2020) for discussion of the effect of a non-steady-state wind). While we have shown that it is a good approximation and also have taken into account the effect of the time delay in the spectral formation analysis, detailed and accurate investigation will require radiation-hydrodynamic simulations. Also, spectral synthesis simulations are required to address further details of the spectral evolution. We plan to tackle these issues in our future work.

ACKNOWLEDGMENTS

K.M. acknowledges support provided by Japan Society for the Promotion of Science (JSPS) through KAKENHI grant (17H02864, 18H04585, and 18H05223).

APPENDIX

A. SOBOLEV APPROXIMATION

We use the Sobolev approximation to compute the line optical depth, neglecting the stimulated emission. In general, it is given as follows:

$$\tau_{\nu_0} = \frac{\pi e^2}{m_e c} f_l \lambda_{\nu_0} n_l \frac{1}{\left\{ \frac{dv}{dr} \cos^2 \theta + \frac{v(r)}{r} \right\} (1 - \cos^2 \theta)}; \quad (A1)$$

where $m_e$ is the mass of electron, $f_l$ is the line oscillation strength, $n_u$ and $n_l$ is the number density in the upper level and the lower level, $\lambda_{\nu_0}$ is the line rest wavelength, and $\theta$ is the between the flow direction and the line of sight.

For Hα, $n_l = n_2$, where $n_2$ is the number density of hydrogen in second level. For the steady state wind, $dv/dr = 0$. We could estimate the line optical depth by setting $\theta = 90^\circ$, $f_2 \approx 0.64$ and $\lambda_{\text{H}\alpha} = 656.3$ nm. To estimate $n_2$, we use the density and temperature computed for the wind-driven model. Assuming $n_1 \approx n_H$ and the Boltzmann distribution, where $n_H$ is the number density of hydrogen, and $n_1$ is that of hydrogen in the ground level, $n_2$ is given by

$$n_2 \approx \frac{Y_H}{\mu m_p} \frac{g_2}{g_1} \rho \exp \left( \frac{-\Delta E_{1.2}}{kT} \right); \quad (A2)$$
where $Y_H \approx 0.9$ is the number fraction of hydrogen for the solar composition, $\mu \approx 1.34$ is the mean atomic mass, $m_p$ is the proton mass, $g_1 = 2$ and $g_2 = 8$ are the statistical weights, $E_{1,2} = 10.2$ eV is the energy difference, and $k = 8.62 \times 10^{-5}$ eV K$^{-1}$ is the Boltzmann constant. Therefore, the line optical depth of Hα is derived as follows:

$$\tau_{H\alpha} \approx 1.79 \times 10^{18} \rho \exp \left( -\frac{\Delta E_{1,2}}{kT} \right) \frac{r}{v}, \quad (A3)$$

where $\rho$, $r$, and $v$ are expressed in the cgs unit. The line forming radius is evaluated by $\tau_{H\alpha} \approx 1$.

REFERENCES

Arcavi, I., Howell, D. A., Kasen, D., et al. 2017, Nature, 551, 210, doi: 10.1038/nature24030

Dexter, J., & Kasen, D. 2013, ApJ, 772, 30, doi: 10.1088/0004-637X/772/1/30

Filippenko, A. V. 1997, ARA&A, 35, 309, doi: 10.1146/annurev.astro.35.1.309

Gilkis, A., Soker, N., & Kashi, A. 2019, MNRAS, 482, 4233, doi: 10.1093/mnras/sty3008

Kaiser, N., Aussel, H., Burke, B. E., et al. 2002, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4836, Pan-STARRS: A Large Synoptic Survey Telescope Array, ed. J. A. Tyson & S. Wolff, 154–164, doi: 10.1117/12.457365

Kashiyama, K., & Quataert, E. 2015, MNRAS, 451, 2656, doi: 10.1093/mnras/stv1164

Kuin, N. P. M., Wu, K., Oates, S., et al. 2019, MNRAS, 487, 2505, doi: 10.1093/mnras/stz053

Kulkarni, S. R. 2018, The Astronomer’s Telegram, 11266, 1

Law, N. M., Kulkarni, S. R., Dekaney, R. G., et al. 2009, PASP, 121, 1395, doi: 10.1086/648598

Liu, T., Song, C.-Y., Yi, T., Gu, W.-M., & Wang, X.-F. 2019, Journal of High Energy Astrophysics, 22, 5, doi: 10.1016/j.jheap.2019.02.001

Lyutikov, M., & Toonen, S. 2019, MNRAS, 487, 5618, doi: 10.1093/mnras/stz1640

Moriya, T. J., Mazzali, P. A., & Pian, E. 2020, MNRAS, 491, 1384, doi: 10.1093/mnras/stz3122

Perley, D. A., Mazzali, P. A., Yan, L., et al. 2019, MNRAS, 484, 1031, doi: 10.1093/mnras/sty3420

Piro, A. L., & Lu, W. 2020, arXiv e-prints, arXiv:2001.08770. https://arxiv.org/abs/2001.08770

Prentice, S. J., Maguire, K., Smartt, S. J., et al. 2018, ApJL, 865, L3, doi: 10.3847/2041-8213/aadd90

Quataert, E., Lecoanet, D., & Coughlin, E. R. 2019, MNRAS, 485, L83, doi: 10.1093/mnrasl/slz031

Shappee, B., Prieto, J., Stanek, K. Z., et al. 2014, in American Astronomical Society Meeting Abstracts, Vol. 223, American Astronomical Society Meeting Abstracts #223, 236.03

Soker, N., Grichener, A., & Gilkis, A. 2019, MNRAS, 484, 4972, doi: 10.1093/mnras/stz364