Nickel clumps and light curve bumps: Light curves and spectra of models with macroscopic $^{56}$Ni clumps in the outer ejecta

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ABSTRACT

An excess of flux (i.e. a bump) in the early light curves of type Ia supernovae has been observed in a handful of cases. Multiple scenarios have been proposed to explain this excess flux. Recently, it has been shown that for at least one object (SN 2018oh) the excess emission observed could be the result of a large-scale clump of $^{56}$Ni in the outer ejecta of $\sim 0.03$ $M_\odot$. We present a series of model light curves and spectra for ejecta profiles containing $^{56}$Ni clumps of varying masses ($0.01, 0.02, 0.03,$ and $0.04$ $M_\odot$) and shapes. We find that even for our lowest mass $^{56}$Ni clump, an increase of $>2$ magnitudes is produced in the bolometric light curve at one day after explosion, relative to models without a $^{56}$Ni clump. We show that the colour evolution of models with a $^{56}$Ni clump differs significantly from those without, and shows a colour inversion similar to some double-detonation explosion models. Furthermore, spectra of our $^{56}$Ni clump models show that strong suppression of flux between $\sim 3700 – 4000$ Å close to maximum light appears to be a generic feature of this class of model. Comparing our models to observations of SNe 2017cbv and 2018oh, we show that a $^{56}$Ni clump of 0.02 – 0.04 $M_\odot$ can match shapes of the early light curve bumps, however the colour and spectral evolution are in disagreement. This would indicate that an alternative origin for the flux excess is necessary. In addition, based on existing explosion scenarios, producing a large-scale, macroscopic $^{56}$Ni clump in the outer ejecta as required to match the light curve shape, without the presence of additional short-lived radioactive material, may prove challenging. Given that only a small amount of $^{56}$Ni in the outer ejecta is required to produce a bump in the light curve, such a large clump in the outer ejecta must be rare, if it were to occur at all.

Key words. supernovae: general — radiative transfer

1. Introduction

Although there is general consensus that type Ia supernovae (SNe Ia) result from the thermonuclear explosions of white dwarfs in binary systems, there is currently little agreement on the types of systems required or the manner through which these systems explode as supernovae (see e.g. Livio & Mazzali 2018; Wang 2018; Jha et al. 2019; Soker 2019 for recent reviews of SNe Ia). Many of the proposed scenarios broadly reproduce observations surrounding maximum light, and therefore it is only through observations at either very late or very early times that differences between the various explosion and progenitor scenarios can be discerned. Particular attention has been paid to obtaining observations within hours to days of the explosion, as these times may show a ‘bump’ in the light curve indicating interaction with a companion star (Kasen 2010) or circumstellar material (Piro & Morozova 2016), or the presence of short-lived radioactive isotopes (Noebauer et al. 2017).

To date, only a handful of objects displaying such bumps have been observed, despite extensive observational effort. Although only a small number of examples are known, these objects show considerable diversity and subsequently multiple scenarios have been invoked to explain the flux excesses. Although peculiar in its own right, iPTF14atg was the first SN Ia discovered that showed a flux excess at early times – a strong ultraviolet pulse was observed within the first $\sim 4$ days following explosion. Based on the models of Kasen (2010), Cao et al. (2015) argue that this early UV emission was the result of interaction between the SN ejecta and companion star, and therefore iPTF14atg was produced via the single degenerate channel. In contrast, Kromer et al. (2016) argue that the spectral evolution of iPTF14atg is incompatible with this scenario and is instead more similar to the violent merger of two white dwarfs – however, they note that this scenario in itself does not explain the early UV emission. Since the discovery of iPTF14atg, additional objects have been claimed to show early excess emission, including SN 2012cg (Marion et al. 2016), SN 2016jhr (Jiang et al. 2017), and SN 2017cbv (Hosseinzadeh et al. 2017).

Hosseinzadeh et al. (2017) also compare their observations of SN 2017cbv to the interaction models of Kasen (2010) and find the models over-predict the UV luminosity at early times. Given this disagreement, they discuss the possibility that the early excess observed in SN 2017cbv is produced by a bubble of radioactive $^{56}$Ni, although they do not perform comparisons between models and observations. To date, this scenario of clumpy or irregular $^{56}$Ni distributions as the origin of early flux excesses has received little attention.

Recently, the exceptionally high cadence light curve of SN 2018oh provided another example of an early flux excess (Li et al. 2019). This bump is investigated in detail by both Shappee et al. (2019) and Dimitriadis et al. (2019), who consider multiple origins including companion/CSM interaction, the detonat-
tion of a thin helium shell on top of a carbon-oxygen white dwarf (the so-called double detonation scenario), and the possibility of an irregular $^{56}\text{Ni}$ distribution. Shappee et al. (2019) show that SN 2018oh is reasonably well matched up to $\sim 3$ days after explosion by a model with a well mixed $^{56}\text{Ni}$ distribution, while at later times less mixing is preferred. This would indicate that the $^{56}\text{Ni}$ distribution does not decrease monotonically towards the outer ejecta. Furthermore, Dimitriadis et al. (2019) show light curves from models for which there are two distinct $^{56}\text{Ni}$ regions within the ejecta – the majority of $^{56}\text{Ni}$ resides in the centre and powers the main light curve, while a separate clump ($0.03 \, M_\odot$) of $^{56}\text{Ni}$ in the outer ejecta powers the initial flux excess. Dimitriadis et al. (2019) find favourable agreement with the light curve shape of this scenario, however prefer an interpretation of interaction based on the colour evolution.

Further motivation for the study of irregular $^{56}\text{Ni}$ distributions comes from supernova remnants. For example, Tsebrenko & Soker (2015) find the structure of at least some remnants can be explained by a large clump of iron in the outer ejecta (at these late epochs, radioactive $^{56}\text{Ni}$ has decayed fully to stable $^{56}\text{Fe}$). The effect of similar clumps on the early light curve however has not been fully explored.

Here, we explore the spectra and light curves resulting from models with irregular $^{56}\text{Ni}$ distributions, containing a large clump of $^{56}\text{Ni}$ in the outer ejecta. We compare our radiative transfer models to SNe 2018oh and 2017cbv, for which irregular $^{56}\text{Ni}$ distributions have been considered as possible causes of the observed early excesses, and explore the parameter space that could provide reasonable agreement to both objects. In Sect. 2 we outline the construction of our models. We compare the effects of our irregular $^{56}\text{Ni}$ to models with a smoothly varying $^{56}\text{Ni}$ distribution in Sect. 3.1 and to models with extended $^{56}\text{Ni}$ distributions in Sect. 3.2. A comparison with observations is presented in Sect. 4 along with discussion in Sect. 5. Finally, we present our conclusions in Sect. 6.

2. Models

2.1. Radiative transfer modelling

All model light curves and spectra presented in this work are calculated using TURTLS (Magee et al. 2018) and available on GitHub. In what follows we provide a brief overview of TURTLS. We refer the reader to Magee et al. (2018) for a full description of the code and Magee et al. (2020) for an application. TURTLS is a one-dimensional Monte-Carlo radiative transfer code designed for modelling the early time evolution of SNe Ia. The density and composition of the SN ejecta are taken as input parameters and freely defined by the user in a series of discrete cells. Monte-Carlo packets representing bundles of photons are injected into the model, tracing the decay of $^{56}\text{Ni}$. The propagation of these packets is followed throughout the model ejecta for a series of logarithmically separated time steps. For the models presented in this work, simulations are calculated between 0.5 and 30 days after explosion. We limit our simulations to 30 days after explosion due to the assumption of local-thermodynamic equilibrium. Packets are initially injected as $\gamma$-packets, representing $\gamma$-ray photons, and are followed assuming a $\gamma$-ray opacity of $\kappa/\rho = 0.3 \, \text{cm}^2 \, \text{g}^{-1}$. After an interaction with the ejecta, $\gamma$-packets are converted to $r$-packets, representing optical photons. To follow the propagation of $r$-packets, we use TARDIS (Kerzendorf & Sim 2014) to calculate the non-grey expansion opacities in each cell during each time step and also include the effects of electron scattering. Packets emerging from the model region are binned in terms of the time and frequency with which they escaped to construct synthetic observables. Light curves are constructed via a convolution of emerging packet luminosities and the desired set of filter functions.

In order to improve the signal-to-noise ratio of our synthetic observables during the crucial early phases, we have implemented into TURTLS the event-based technique (EBT) for spectrum extraction with virtual packets (see Long & Knigge 2002, Sim et al. 2010, Kerzendorf & Sim 2014, Bulla et al. 2015). Briefly, in the EBT, after a Monte Carlo packet performs an interaction with the model ejecta, a given number of ‘virtual packets’ ($v$-packets) are spawned. Each $v$-packet is emitted in a random direction with the same frequency in the fluid-frame as the real packets. Once injected, $v$-packets follow the same computational procedure as real packets, with the exception being that they do not interact with the ejecta. At time step $i$, an escaping $v$-packet contributes luminosity, $L_v$, to the spectrum, which is given by:

$$L_v = \frac{E}{N \Delta \lambda \Delta t} e^{-\tau},$$

where $E$ is the energy of the real packet that spawned the $v$-packet, $N$ is the number of $v$-packets created for each real packet, $\Delta \lambda$ is the filter bandwidth, $\Delta t$ is the time step, and $\tau$ is the optical depth of the ejecta.

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Fig. 1: Comparison of spectra calculated during different time steps (1.5 d, 11.0 d, and 18.7 d) for our fiducial SN 2018oh model (see Sect. 2). Virtual spectra (red) are calculated using the event-based technique, while real spectra (black) are calculated by directly counting the luminosities of escaping real packets.
Δt is the width of the time step, Δν is the width of the frequency bin, and τ is the total optical depth accumulated along the trajectory of the virtual packet. In this way, a ‘virtual’ spectrum is created from these packets for each time step in the simulation. The virtual light curve at this time is then calculated by integrating the convolution of this spectrum and the filter functions. This method has previously been shown to reproduce the synthetic observables calculated by direct binning of the real packets (see e.g. Fig. 4 of Kerzendorf & Sim 2014 or Fig. 8 of Bulla et al. 2015). In Fig. 1 we show the dramatic increase in the signal-to-noise ratio of our synthetic spectra using 2015). In Fig. 1 we show the dramatic increase in the signal-to-noise ratio of our synthetic spectra using v-packets compared to the direct counting of emerging r-packets.

2.2. Constructing models with \(^{56}\text{Ni}\) clumps

Dimitriadis et al. (2019) argued that the flux excess observed in the early light curve of SN 2018oh is consistent with a model containing two distinct regions of \(^{56}\text{Ni}\) in the ejecta. In this model, the main rise of the light curve is provided by the majority of \(^{56}\text{Ni}\), which is located within the centre of the ejecta. An additional 0.03 \(M_\odot\) of \(^{56}\text{Ni}\) is placed near the surface of the ejecta (above a mass coordinate of 1.3 \(M_\odot\)) and powers the initial excess. Following from Dimitriadis et al. (2019), we investigate the range of parameters that could plausibly reproduce the excess observed in SNe 2018oh and 2017cbv.

As a starting point, we use the models presented in Magee et al. (2020). One of the main limitations of these models is the composition, which uses a simplified three-zone structure (see Fig. 4 of Magee et al. 2018). As the models were designed to explore solely the effects of the \(^{56}\text{Ni}\) distribution on the light curve, \(^{56}\text{Ni}\) constitutes 100% of the iron-group element (IGE) zone (the centre of the ejecta) immediately after explosion. A small amount (~0.1 \(M_\odot\)) of carbon and oxygen is placed in the outer ejecta, while the remaining mass is filled-in with intermediate-mass elements (IME). Due to these limitations, spectra in particular do not provide perfect agreement with observations, as they are more sensitive to specifics of the ejecta composition. The relatively large fraction of IMEs at high velocities for the models presented here is typically reflected in the spectra, with the corresponding features being shifted to higher velocities. Nevertheless, the differences between all models still represent a useful point of comparison. More physical and detailed composition treatments will be explored in future work. Furthermore, all models presented as part of this work have a total ejecta mass of 1.4 \(M_\odot\).

Following the procedure outlined in Magee et al. (2020), we find the best matching models to SNe 2018oh and 2017cbv excluding observations earlier than approximately five days after explosion – in other words we do not include the bump when determining the best matching model. For both objects we find models that reproduce the later light curves, but are clearly discrepant at earlier times (see Sect. 4). We take these as our fiducial models and add macroscopic clumps of pure \(^{56}\text{Ni}\) into the outer ejecta at different locations, varying the total \(^{56}\text{Ni}\) mass contained within the clump and its width. Throughout this paper we refer to different \(^{56}\text{Ni}\) clump models, however we stress this is explicitly a singular, large-scale clump within each model with a mass of at least 0.01 \(M_\odot\). As our models are in one-dimension, this is essentially the same as a shell of \(^{56}\text{Ni}\).

Unlike some sub-Chandrasekhar mass explosions, Chandrasekhar-mass models do not predict shells of \(^{56}\text{Ni}\). In contrast, an excess of \(^{56}\text{Ni}\) along certain viewing angles could be produced in multi-dimensional Chandrasekhar-mass models due to deflagration plumes (see Sect. 5.1), which more closely resemble a clump, and not a shell, of \(^{56}\text{Ni}\) (e.g. Röpke et al. 2007b; Townsley et al. 2007; Seitenzahl et al. 2009). In addition, previous studies have used the terms ‘surface \(^{56}\text{Ni}\)’ or ‘an off-centre \(^{56}\text{Ni}\) distribution’ (Dimitriadis et al. 2019; Shappee et al. 2018) however neither term is appropriate. A model containing a large amount of \(^{56}\text{Ni}\) below the ejecta surface that increases monotonically towards the inner ejecta will not produce a light curve bump (Magee et al. 2020). Likewise an off-centre \(^{56}\text{Ni}\) distribution need not produce a bump and could...
refer to any model that does not contain $^{56}\text{Ni}$ in the ejecta centre. Therefore, clump is the most appropriate term for this context. An investigation of small-scale, microscopic clumps is beyond the scope of the work presented here.

The general form of the $^{56}\text{Ni}$ mass fraction within each clump follows a Gaussian distribution, with the $^{56}\text{Ni}$ fraction at mass coordinate $m$ given by

$$X_{\text{Ni}}(m) = A \times e^{-(m-\mu)^2/2\sigma^2},$$  \hspace{1cm} (2)

where $\mu$ is the centre of the $^{56}\text{Ni}$ clump, $\sigma$ is the width of the clump, and $A$ is a scaling parameter used to control the total mass of $^{56}\text{Ni}$ in the clump. This mass fraction is then added to the underlying fiducial model to give a description for the entire ejecta. The choice of a Gaussian distribution for the $^{56}\text{Ni}$ clump is arbitrary, however we have also tested additional functional forms – such as those that are more similar to the inner regions of the ejecta (see Eqn. 11 of Magee et al. 2018). We find that the Gaussian distributions produce light curves that more closely resemble SNe 2018oh and SN 2017cbv, and therefore focus on these cases.

In Fig. 2 we show some of the model $^{56}\text{Ni}$ distributions explored as part of this work. As shown in Fig. 2, given that our models are in one dimension, the $^{56}\text{Ni}$ clumps effectively represent a shell of $^{56}\text{Ni}$ within the outer ejecta. As each of our models has a corresponding fiducial model (i.e. a model without a $^{56}\text{Ni}$ clump), we may consider the difference between the two to qualitatively reproduce the variation along different lines of sight. In this sense, our set of models broadly approximate the effect of a three-dimensional simulation with a large-scale clump of $^{56}\text{Ni}$ visible along a specific line of sight.

We have calculated light curves for $^{56}\text{Ni}$ clumps of 0.01, 0.02, 0.03, and 0.04 $M_\odot$, with widths ($\sigma$) of 0.06 and 0.18 $M_\odot$ and central locations of 1.35, 1.37, and 1.39 $M_\odot$. In general, we find that changing the central location of the $^{56}\text{Ni}$ clump has little effect on the overall light curve shape. Clumps located further out in the ejecta (e.g. at 1.37 or 1.39 $M_\odot$) produce earlier light curve bumps and redder colours beginning a few days after explosion, relative to clumps that are somewhat deeper inside the ejecta (e.g. at 1.35 $M_\odot$). The overall effect however is secondary to the mass and width of the clump. We therefore focus on models with $^{56}\text{Ni}$ clumps centred on 1.35 $M_\odot$ as these models produce the best agreement with observations (see Sect. 4) and are representative of the general trends.

As a further point of comparison, we also include models with extended $^{56}\text{Ni}$ distributions relative to the fiducial models. A key feature of our more extended $^{56}\text{Ni}$ distribution models is that the $^{56}\text{Ni}$ mass fraction is always monotonically decreasing towards the outer ejecta. This is clearly not the case for our $^{56}\text{Ni}$ clump models, which have decreasing $^{56}\text{Ni}$ mass fractions below 1.35 $M_\odot$ before increasing again around ~1 $M_\odot$.

### 3. Model observables

#### 3.1. Effects of $^{56}\text{Ni}$ clumps

In the following section we discuss generally the impact of $^{56}\text{Ni}$ clumps on the synthetic observables of the models. Here, we limit this discussion to a comparison between those models with $^{56}\text{Ni}$ clumps and those without. In Sect. 3.2, we discuss these models further alongside comparisons to a model with an extended $^{56}\text{Ni}$ distribution relative to our fiducial SN 2018oh model. In Sect. 4, we compare our clump models to observations of SNe 2018oh and 2017cbv and further discuss the implications for their specific explosion scenarios. We focus our discussion here on models in which clumps have been added to the fiducial model for SN 2018oh (EXP_Nio0.6_KE1.68_P9.7; see Magee et al. 2020 for further details on the model naming scheme). We find similar trends for models based on the SN 2017cbv fiducial model (EXP_Nio0.8_KE1.10_P9.7). Both of our fiducial models represent intermediate values for the density profile and $^{56}\text{Ni}$ distribution among the full parameter space explored in Magee et al. (2020).

Figures [3][a], (b), and (c) demonstrate the effect of $^{56}\text{Ni}$ clumps on the bolometric and $BR$ band magnitudes compared to models without clumps. We find that while the small increase in total $^{56}\text{Ni}$ mass does not strongly affect the peak absolute magnitude of the models, there are significant differences during the first few days after explosion. For all of the parameters investigated here, an excess of flux in the light curve (relative to the fiducial model) is produced during this time, however the duration and total amount of flux excess varies. Again, we note that although our simulations are all performed in one dimension, differences between models with clumps and our fiducial models are qualitatively similar to the variation in observables that may be expected along different lines of sight for a multi-dimensional model containing a clump only along a specific viewing angle.

We find that in all cases of $^{56}\text{Ni}$ clumps, the flux excess is most easily observed in the bluer bands – a natural consequence of the higher temperatures produced in the outer ejecta due to the presence of additional $^{56}\text{Ni}$ heating. For example, in the case of our models with a 0.03 $M_\odot$ $^{56}\text{Ni}$ clump, the $B$-band is ~2 mag. brighter relative to our fiducial model at approximately one day after explosion. The $R$-band shows a slightly more modest increase of ~3 magnitudes. Even for our lowest $^{56}\text{Ni}$ mass clump (0.01 $M_\odot$), the light curves are brighter relative to the fiducial model by ~3 – 3.5 mag. and ~2 – 2.5 mag. in the $B$- and $R$-bands, respectively. Aside from the total $^{56}\text{Ni}$ mass contained within the clump, the distribution also affects the shape and colour of the flux excess. As shown in Fig.[3][d] those models with narrower $^{56}\text{Ni}$ clumps ($\sigma = 0.06 M_\odot$) typically show larger and bluer excesses over those models containing broader $^{56}\text{Ni}$ clumps ($\sigma = 0.18 M_\odot$). In addition, they show a somewhat more well-defined peak or bump – broader $^{56}\text{Ni}$ clumps generally result in broader light curves with a ‘shoulder’ rather than a distinct bump.

For the models presented here, the duration of the flux excess ranges from ~4 – 5 days following explosion. Although the excess may have subsided at later times, the implications for the rest of the time evolution are profound and in particular the colour evolution for models with $^{56}\text{Ni}$ clumps differs significantly from those without, as shown in Fig.[3][d]. For our fiducial model, the initial colour at one day after explosion is quite red ($B - V \sim 0.8$ mag.) due to a lack of $^{56}\text{Ni}$ in the outer ejecta, but gradually becomes steadily bluer over the next week. Between 7 and 10 days after explosion, the $B - V$ colour has flattened and remains roughly constant at $B - V \sim 0.1$. In contrast, models with $^{56}\text{Ni}$ clumps show bluer colours (by ~0.3 – 0.5 mag.) within the first few days after explosion. By ~4 – 5 days following explosion, the $^{56}\text{Ni}$ clump models have become significantly redder than the fiducial model, by as much as ~0.6 mag. The $^{56}\text{Ni}$ clump models subsequently become bluer again, but remain consistently redder than the fiducial model – ranging from ~0.1 – 0.4 mag. redder around maximum light.

In Fig. 3 we show spectra for our models at 1.50d and 18.75d after explosion. These phases correspond to approximately near the peak of the early flux excess and close to maximum light. We focus here on the case of our fiducial SN 2018oh model, models with $^{56}\text{Ni}$ clumps of 0.01 and 0.03 $M_\odot$, clump
Fig. 3: Light curves for models with and without clumps of $^{56}$Ni in the outer ejecta. Panels (a), (b), and (c) show the bolometric, $B$-, and $R$-band magnitudes, respectively. The $B - V$ colour evolution is shown in Panel (d). We determine our fiducial model for SN 2018oh by finding the best match to the later light curve (excluding the early bump) among the models of Magee et al. (2020). This is shown as a black solid line. Coloured lines show light curves resulting from models with added clumps of $^{56}$Ni in the outer ejecta, of varying $^{56}$Ni masses. Each clump is centred on a mass coordinate of 1.35 $M_\odot$ and has a width of either 0.06 or 0.18 $M_\odot$.

Dashed black lines show a model that has a more extended $^{56}$Ni distribution relative to our fiducial model, but is otherwise identical (i.e. the same density profile and $^{56}$Ni mass in each case). Our models demonstrate that bumps in the early light curves, of varying sizes and lengths, can be generated by different clumps of $^{56}$Ni in the outer ejecta.

In order to determine which elements are responsible for producing the features observed in the spectra, we track the opacity bin with which each packet experienced its last interaction and the contribution of each element to the total opacity within this bin. When packets are then binned in frequency to produce the spectrum, this gives the contribution of each element to the total luminosity at a given wavelength (see e.g. Fig. 2 of Kromer & Sim 2009 and Fig. 8 of Magee et al. 2016). This is shown in Fig. 5 for our 1.50 d spectra, where each element is denoted by a different colour. Fig. 5 shows that the feature around $\sim$4800 Å could likely be attributed to Mg ii. At all other wavelengths there does not appear to be a dominant source of opacity, hence the last element with which a packet experienced an interaction is approximately random and there is a lack of features in the spectrum. For our model with a 0.03 $M_\odot$ $^{56}$Ni clump, Fig. 5 shows that Ni is the dominant source of opacity at all wavelengths. This is unsurprising given that most packets escaping at this time will have originated from the $^{56}$Ni clump.
Closener to maximum light, at 18.75 d after explosion, differences in spectra between the models are more subtle, as demonstrated by Fig. 4. We again note that limitations in the composition of our models can result in velocities of IMEs that are too high. For the models shown in Fig. 4, the Si II 6355 velocity is \(~\sim 15000\) km s\(^{-1}\) at maximum light, while the velocity in SN 2018oh is \(~\sim 10300\) km s\(^{-1}\) (Li et al. 2019). In Fig. 5 we also show the contribution of each element to the luminosity at every wavelength for our fiducial model and model with a 0.03 M\(_\odot\) 56Ni clump. For all models, we find that the Si II 6355 feature is unaffected by the presence of 56Ni clumps. Indeed, wavelengths longer than \(~\sim 4500\) Å show only small variations at this time. A prominent exception to this is the S II ‘W’ feature around \(~\sim 5400\) Å. Figure 5 indicates that this feature has become affected by the presence of additional Fe in all but our fiducial model. The most noticeable differences for our model spectra around maximum light occur at wavelengths \(~\sim 4500\) Å. Figure 5 shows that the strong Ca II H&K features are either significantly weakened or completely removed by the presence of additional IGEs.

Even for relatively small 56Ni clumps of 0.01 M\(_\odot\) (representing \(~\sim 2\%) of the total 56Ni mass for the models in Fig. 4), a dramatic increase in luminosity at early times can be achieved. Such signatures should be easily detected in observations of SNe Ia, provided they are discovered sufficiently early (within \(~\sim 3\) days of explosion).

3.2. 56Ni clumps vs. extended 56Ni distributions

In Fig. 4 we also show comparisons of our 56Ni clump models to a model with a more extended 56Ni distribution relative to our fiducial model. In this case, the 56Ni distribution in the outer \(~\sim 0.1\) M\(_\odot\) is comparable to our 0.01 M\(_\odot\) clump model with \(\sigma = 0.18\). Deeper inside the ejecta however, the 56Ni distributions differ significantly. Figure 5 clearly shows the consequences of these differences in 56Ni distributions.

Our extended 56Ni distribution model shows a broad light curve that smoothly increases in brightness towards maximum light. For our 0.01 M\(_\odot\) clump model with \(\sigma = 0.18\), the light curve is similar to that of the extended 56Ni distribution model until \(~\sim 1.5\) days after explosion. After this point, the two models clearly diverge. The clump model shows a somewhat flattening of the rise between \(~\sim 1.5 – 3\) days, before subsequently rising more sharply again until maximum light. The colour evolution also differs significantly for both models, as shown in Fig. 5(d). The clump model is easily distinguished based on the sudden shift towards redder colours following explosion, while our extended 56Ni distribution model shows a relatively flat colour evolution during the first 10 days post-explosion.

The spectra of our extended 56Ni distribution model are also shown in Fig. 4. At both early times and close to maximum light, the extended 56Ni distribution model appears similar to our 0.01 M\(_\odot\) 56Ni. This further highlights the need for continuous follow up as both models are reasonably indistinguishable without observations towards the end of the bump phase (\(~\sim 2 – 4\) d after explosion).

As discussed in Magee et al. (2020), a light curve bump can not be produced solely by having a large fraction of 56Ni in the outer ejecta. Our models clearly demonstrate that a bump in the light curve requires the 56Ni distribution to vary non-monotonically. A smoothly decreasing 56Ni fraction towards the outer ejecta will only vary the width and colours of the light curve, but does not produce a flux excess resembling those of models with 56Ni clumps. If the clump is extended over a relatively large region of the ejecta (\(~\sim 0.18\) M\(_\odot\)), a broader light curve can be produced, however even in this case the model is clearly distinguished from a monotonically decreasing extended 56Ni distribution based on the colour evolution.

4. Comparisons with observations of SNe Ia

4.1. SN 2018oh

In the following section, we compare our model light curves and spectra to observations of SN 2018oh. We find the best agreement when assuming an explosion date of MJD = 58144.1 and distance modulus of \(\mu = 33.66\) mag. and adopt these values throughout this work. We note that the explosion date found here is 0.2 d earlier than the first-light time derived by Li et al. (2019) and the distance modulus is fully consistent. The spectrum of
SN 2018oh has been corrected for galactic extinction only (host reddening is estimated to be negligible; Li et al. 2019) and was obtained from WISeREP (Yaron & Gal-Yam 2012). In order to ensure accurate flux calibration, we calculate synthetic magnitudes from the spectrum. We then calculate the offset relative to co-temporal photometric magnitudes and apply this across all bands using a third-order polynomial. The observed spectrum is then scaled to match the photometry in each band.

In Fig. 5, we show a comparison between our models and observations of SN 2018oh. As demonstrated by Fig. 6, our fiducial model provides good agreement with the light curve beginning approximately one week after explosion, but is clearly significantly fainter than the observations at early times. Extending the $^{56}$Ni distribution of our fiducial model, such that $^{56}$Ni is present throughout the ejecta (see Fig. 2), does not reproduce the shape of the light curve and instead results in a broader light curve that passes through the early flux excess. As in Magee et al. (2020), this indicates that the early excess is not simply due to a large fraction of $^{56}$Ni in the outer ejecta.

Rather than a simple extended $^{56}$Ni distribution, Fig. 6 shows that models with $^{56}$Ni clumps can broadly reproduce the light curve shape of SN 2018oh throughout its evolution to maximum light. The mass of the $^{56}$Ni clump required to match the flux excess of SN 2018oh is between 0.02 – 0.03 $M_{\odot}$. This is consistent with the value found by Dimitriadis et al. (2019), although we note that differences in the total $^{56}$Ni mass and distribution, and density profile compared to our models likely accounts for differences in the overall light curve shapes. Smaller $^{56}$Ni clumps (0.01 $M_{\odot}$) do not reach the required luminosities to match the flux excess around ~2 days after explosion.

Aside from the mass of the $^{56}$Ni clump, there is some tension between the g- ($3 800 \text{ Å} \leq \lambda \leq 5 400 \text{ Å}$) and Kepler- ($4 200 \text{ Å} \leq \lambda \leq 9 000 \text{ Å}$) bands over the shape of the clump that is required. We find that our model with a narrow ($\sigma = 0.06 \ M_{\odot}$) 0.03 $M_{\odot}$ clump produces the best match to the g-band light curve of SN 2018oh, while in the Kepler-band the model is somewhat too bright (by ~0.5 mag.) during the excess phase. For the other models shown in Fig. 6 we find broad clumps ($\sigma = 0.18 \ M_{\odot}$) generally produce better agreement with the shape of the the Kepler light curve, but are slightly fainter than the g-band observations. We note however that the g-band light curve of SN 2018oh is much less well constrained, having significantly fewer observations and larger uncertainties. In addition, our models with $^{56}$Ni clumps are systematically brighter than the V-band observations around maximum light, while our fiducial model shows better agreement.

These discrepancies are further highlighted by the colour (Fig. 7) and spectral evolution (Fig. 8). Figure 8 shows that even for our fiducial model there is disagreement between the model and observed spectra. This can be attributed to the simplified

Fig. 5: Contribution of individual elements within the model ejecta to the flux at each wavelength. Element fluxes are calculated based on their contribution to the opacity bin with which escaping Monte Carlo packets experienced their last interaction. Spectra are shown for our fiducial model (left) and our model that included an additional $^{56}$Ni clump of 0.03 $M_{\odot}$ and width of 0.06 $M_{\odot}$ (right). Spectra are also shown for 1.50 d after explosion, binned to $\Delta \lambda = 15 \text{ Å}$ (top), and 18.75 d after explosion, binned to $\Delta \lambda = 10 \text{ Å}$ (bottom).
Our fiducial model shows good agreement with the light curve excluding the initial early bump. A model with an extended 56Ni distribution relative to our fiducial SN 2018oh model is shown as a dashed line. Based on comparisons to our models, we infer an explosion date of MJD = 58144.1, which is shown as a vertical dash-dot line. Our fiducial model shows good agreement with the light curve excluding the initial early bump. A model with an extended 56Ni distribution relative to our fiducial SN 2018oh model is shown as a dashed line. The epoch of our spectral comparison is shown as a vertical dotted line.

Fig. 7: Colour evolution of SN 2018oh compared to models with and without 56Ni clumps in the outer ejecta. From left to right, panels shown the g-, V-, and Kepler-bands. Observations of SN 2018oh are shown as black points. Non-detections and detections of <3σ are shown as downward triangles. Our fiducial model is shown as a grey solid line, while models with 56Ni clumps are shown as coloured lines. Based on comparisons to our models, we infer an explosion date of MJD = 58144.1, which is shown as a vertical dash-dot line. Our fiducial model shows good agreement with the light curve excluding the initial early bump. A model with an extended 56Ni distribution relative to our fiducial SN 2018oh model is shown as a dashed line. The epoch of our spectral comparison is shown as a vertical dotted line.

Fig. 6: Comparison of SN 2018oh to models with and without 56Ni clumps in the outer ejecta. Observations of SN 2018oh are shown as black points. Non-detections and detections of <3σ are shown as downward triangles. Our fiducial model is shown as a grey solid line, while models with 56Ni clumps are shown as coloured lines. Based on comparisons to our models, we infer an explosion date of MJD = 58144.1, which is shown as a vertical dash-dot line. Based on comparisons to our models, we infer an explosion date of MJD = 58144.1, which is shown as a vertical dash-dot line.

This difference in colour is further reflected in the spectrum at approximately 11.5 d after explosion. For our fiducial model, although the region around ∼3500 – 4000 Å (shaded in Fig. 8) is fainter than SN 2018oh, the overall shapes of the features are quite similar – with the exception being that the Ca II H&K and Si ii λ3858 lines are blended in our model (dotted lines in Fig. 8). This is clearly not the case in all of our other models however, which show a significant amount of line blanketing. As discussed in Sect. 3 for all models with 56Ni clumps there is a strong suppression of flux at wavelengths <∼ 500 Å, which can be attributed to the presence of additional IGEs. In addition, all models with 56Ni clumps show a relatively flat feature between ∼3 700 – 4 000 Å that is not seen in SN 2018oh, or indeed even the model with an extended 56Ni distribution.

Following the colour evolution to maximum light, our clump models reach an inversion shortly before two weeks after explosion. At this point, the colour flattens before gradually becoming increasingly red. Again, this can be attributed to the presence of the 56Ni clump causing an increasing amount of blanketing as more flux emerges from the inner regions of the ejecta. Conversely, our fiducial model does not become as red as the shortcoming used which, as discussed in Sect. 2 and Sect. 3.1 results in IME velocities that are too high. Regardless of these shortcomings, Fig. 4 shows that spectral features at longer wavelengths are largely unaffected by the presence of clumps, while shorter wavelengths are much more sensitive. Therefore comparisons between our clump and fiducial models, and SN 2018oh, are still useful for inferring the effect of 56Ni clumps on spectra, and investigating whether any specific signatures they might have at shorter wavelengths are present in SN 2018oh.

Shortly after explosion, Fig. 7 shows that our fiducial model is significantly redder than SN 2018oh, in addition to being fainter. The presence of the 56Ni clump provides an additional heating source in those models, and hence their bluer colours are more similar to SN 2018oh at this time (although we note the large uncertainties). Unfortunately, g-band observations are unavailable for the period MJD = 58148 – 58151 (∼3.8 – 6.8 d post-explosion), which coincides with the largest discrepancies in colour between our fiducial and 56Ni clump models.
clump models, although it remains redder than SN 2018oh by ~0.05 mag.

Based on comparisons with observations of SN 2018oh, our models indicate that while $^{56}$Ni clumps of ~0.02 – 0.03 $M_\odot$ can reproduce the early light curve shape there is an overall negative effect on the spectra closer to maximum light. While some differences in features between our models and observations can be attributed to the simple composition used, a strong suppression of flux in the region ~3 700 – 4 000 Å appears to be a generic feature of models with relatively large $^{56}$Ni clumps (large enough to match the early flux excess in the light curve). A similar feature is not observed in SN 2018oh and therefore would suggest that such clumps are not present in the outer ejecta. Figure 7 also clearly demonstrates the need for continuous and well-sampled multi-band follow-up of SNe Ia, as the shape of the colour evolution can provide a key diagnostic between the different ejecta structures.

4.2. SN 2017cbv

We now look to compare our models to observations of SN 2017cbv. Here we assume an explosion date of MJD = 57821.2 and distance modulus of $\mu = 30.74$. The distance modulus used in this work is consistent with that of Hosseinzadeh et al. (2017), while the explosion date is 0.7 days earlier. Spectra of SN 2017cbv have been corrected for galactic extinction only (host reddening is estimated to be negligible; Hosseinzadeh et al. 2017) and were obtained from WISEREP (Yaron & Gal-Yam 2012) and originally published in Hosseinzadeh et al. (2017). Spectra are flux calibrated in the same manner as described for SN 2018oh (see Sect. 4.1).

A comparison between the light curves of SN 2017cbv (Hosseinzadeh et al. 2017) and our models is shown in Fig. 9. Figure 9 demonstrates that our fiducial model generally provides reasonable agreement with SN 2017cbv close to maximum light. The $U$-band light curve is clearly an exception to this, as our fiducial model peaks earlier and fainter than the observations. As mentioned previously, we have assumed $^{56}$Ni constitutes 100% of the total IGE immediately following explosion. The presence of additional elements could result in an increased opacity and slower evolution for the $U$-band in particular, with other bands affected to a lesser degree. This would however, also lead to a decrease in near-UV flux.

Figure 10 shows that models with $^{56}$Ni clumps in the outer ejecta can also provide reasonable agreement with the early light curve shape of SN 2017cbv. We find models with $^{56}$Ni clumps of 0.03 – 0.04 $M_\odot$ provide the best match to the shape of the $BVgri$ band light curves within the days following explosion. The overall level of agreement in these bands is generally insensitive to the width of the $^{56}$Ni clump, however this is clearly not the case for the $U$-band. Models with narrow $^{56}$Ni clumps ($\sigma = 0.06$) reproduce the shape of the $U$-band flux excess better than those with broader $^{56}$Ni clumps ($\sigma = 0.18$), however even in these cases our models show an overall flatter flux excess than observed in SN 2017cbv. Around maximum light, our $^{56}$Ni clump models show significant differences compared to our fiducial model and show a much closer resemblance to the extended $^{56}$Ni distribution model.

Unlike SN 2018oh, SN 2017cbv has well sampled multi-band observations and spectra extending from explosion to after maximum light and therefore provides a better opportunity to determine which models can be excluded. Here, we consider spectra at three important epochs during the evolution of SN 2017cbv – shortly after explosion (~1.5 d), towards the end of the flux excess phase (~3.5 d), and close to maximum light (~18.5 d). As with SN 2018oh, we find that our fiducial model does not provide perfect agreement at maximum light. We again note that the effect of the clump is most pronounced at shorter wavelengths, while longer wavelengths are less affected (such as the Si II λ6355 feature). We therefore focus our spectral comparisons on investigating signatures of the clumps at shorter wavelengths.

In Fig. 11 we show the colour evolution ($B - V$ and $g - r$) of SN 2017cbv compared to our models. Immediately following explosion, our fiducial model is clearly significantly redder than SN 2017cbv, and also shows no prominent features in its spectra (Fig. 11). Those models with narrow $^{56}$Ni clumps ($\sigma = 0.06$ $M_\odot$) provide better agreement with the colour evolution during these epochs. Figure 11 shows that at 1.5 d after explosion the features around ~3.600 and 4.200 Å in SN 2017cbv are reasonably well matched by our narrow $^{56}$Ni clump models, although the models show a velocity that is too low. By 3.5 d, we also find that the colours and spectroscopic features of some of our clump models are similar, although again the velocities of IGE features are too low in the model. Better agreement may be achieved if the density profile was altered such that the $^{56}$Ni clump was shifted to higher velocities.

After these early phases, the initial light curve bump has subsided and the colour evolution of SN 2017cbv shows a small in-
Fig. 9: Comparison of SN 2017cbv $UBVgri$ light curves to models with and without $^{56}$Ni clumps in the outer ejecta. SN 2017cbv is shown as black points. The fiducial model for SN 2017cbv is shown as a solid grey line. Models with $^{56}$Ni clumps added to the fiducial model are shown as coloured lines. Based on comparisons to our models, we infer an explosion date of MJD = 57821.2, which is shown as a vertical dash-dot line. Our fiducial model shows good agreement with the light curve excluding the initial early bump, from $\sim$5 days after explosion. A model with an extended $^{56}$Ni distribution relative to our fiducial SN 2017cbv model is shown as a dashed line. The epochs of our spectral comparisons are shown as vertical dotted lines.

Fig. 10: Comparison of the $B - V$ (left) and $g - r$ (right) colour evolution in SN 2017cbv (black points) to models with (coloured lines) and without $^{56}$Ni clumps (grey lines) in the outer ejecta. A model with an extended $^{56}$Ni distribution relative to our fiducial SN 2017cbv model is shown as a dashed line. The epochs of our spectral comparisons are shown as vertical dotted lines.
The region showing strong flux suppression at maximum light in our clump models is given by a shaded grey region.

crease to redder colours until approximately one week after explosion. At this point, the evolution turns towards bluer colours again. Our fiducial and extended $^{56}$Ni distribution models (i.e. those models without $^{56}$Ni clumps) clearly do not match the shape of this colour evolution. Initially their colours are very red and become increasingly blue, and then steadily becoming redder again from approximately one week after explosion. In contrast, our $^{56}$Ni clump models show a similar colour inversion as in SN 2017cbv, although the colours are systematically shifted redder by $\sim 0.2$ mag. Models with narrower $^{56}$Ni clumps also typically show more dramatic changes in colour than SN 2017cbv. For example, over approximately five days, SN 2017cbv shows a shift of $\Delta(B-V) \sim 0.1$ mag. This is similar to the colour change in our broader $^{56}$Ni clump models, but significantly smaller than that of our narrow $^{56}$Ni clump models where $\Delta(B-V) \gtrsim 0.2$ mag. This is clearly in disagreement with the $U$-band light curve shape and the early spectral comparisons, for which we find better agreement with narrow $^{56}$Ni clumps.

We note that the $g-r$ colour of SN 2017cbv does not show a similar colour evolution as in the $B-V$ colour during the early epochs. Instead the colour gradually becomes bluer before flattening. In contrast, our $^{56}$Ni clump models still show a slight colour inversion. Additionally, the $g-r$ colours of these models are significantly bluer than SN 2017cbv beginning approximately one week after explosion. Instead, the shape of the colour evolution in our fiducial model is more similar to that of SN 2017cbv (although the colours are systematically redder in the model), excluding the initial few days during the flux excess phase.

Although the early colour and spectral evolution are reasonably well reproduced in our $^{56}$Ni clump models, it is clear that at maximum light there is significant disagreement, as shown in Fig. 11. As in SN 2018oh, we find that close to maximum light, our models do not reproduce the Ca ii H&K and Si ii 1538 lines. Instead, our models show strong flux suppression in this region due to the presence of additional IGEs. In contrast to earlier times, our fiducial model provides the best agreement at this epoch. As in the case of SN 2018oh, our models show that the flux suppression in the near-UV appears to be a generic feature of models with $^{56}$Ni clumps. Those models with clumps large enough to match the light curve shape all exhibit this feature, which is not observed in the spectra of SN 2017cbv. Therefore, we argue that while a $^{56}$Ni clump could explain the observed light curve shape, it is inconsistent with the spectral evolution.

5. Discussion

Our models show that $^{56}$Ni clumps in the outer ejecta can produce an excess of flux during the first few days after explosion – the strength and duration of which depend on both the mass and shape of the clump. Comparing our models to observations of SNe 2018oh and 2017cbv, we find that large ($\sim 0.02 – 0.04 M_\odot$) $^{56}$Ni clumps can in general reproduce the shape of the optical light curve bumps and colours within the first few days of explosion. Such large clumps produce strong flux suppression at near-UV wavelengths however, which is not seen in the spectra of either object. In Sect. 5.1 we first discuss predictions of $^{56}$Ni clumps from existing explosion models, while in Sect. 5.2 we discuss alternative scenarios for producing early light curve bumps and how they compare to those produced by $^{56}$Ni clumps.

5.1. Sources of $^{56}$Ni clumps

Many of the models proposed for SNe Ia invoke deflagrations to some degree, which could provide one method of producing $^{56}$Ni clumps (Khokhlov et al. 1993; Höflich & Khokhlov 1996; Gamezo et al. 2005; Bravo & García-Senz 2006; Jordan et al. 2008). Generally, in such models the interior of the white dwarf is initially burned by a sub-sonic deflagration. As the burning front propagates, it will eventually become subject to Rayleigh-Taylor instabilities that wrinkle and deform the flame (Khokhlov 1994, 1995). At the same time, buoyancy of the hot, burned ash...
accelerates the deflagration plumes towards the surface of the white dwarf (Reinecke et al. 2002). The overall effect of the deflagration is irregular or uneven burning, and deflagration plumes could therefore potentially create $^{56}\text{Ni}$ clumps in the outer ejecta. Multi-dimensional simulations in general however, do not show strong variations in the light curves as a function of viewing angle, which may be expected if there were significant differences in composition along certain directions (see e.g. Röpke et al. 2007a; Seitenzahl et al. 2013; Sim et al. 2013; Fink et al. 2014; Long et al. 2014).

One potential scenario for producing large $^{56}\text{Ni}$ clumps in the outer ejecta lies in gravitationally-confined detonations (GCD; Plewa et al. 2004). This scenario does produce an excess that is qualitatively similar to SNe 2018oh and 2017cbv, although much less extreme. Here, the deflagration plumes reach the surface of the white dwarf before burning transitions to a detonation. As the plumes travel along the surface, they eventually converge on the stellar point opposite that of the initial breakout and it is this convergence that triggers the detonation. The result is a highly asymmetric ejecta composition in which clumps of deflagration ash are present at high velocities. Seitenzahl et al. (2016) present light curves and spectra for one realisation of the GCD scenario, which shows a strong dependence on viewing angle. When viewed close to the direction of the deflagration ignition, a small bump ($\lesssim 0.5$ mag. and lasting $\sim 3$ days) in the $U$-band light curve is observed (see Fig. 7 of Seitenzahl et al. 2016), resulting from the presence of the deflagration ash. Whether the GCD scenario could produce larger $^{56}\text{Ni}$ clumps similar to those studied here remains to be seen, but warrants further investigation.

We note it has also been argued that the GCD scenario may not be robustly achieved (Röpke et al. 2007a) and while initial models designed to mimic the GCD scenario could reproduce observables of SNe Ia (Kasen & Plewa 2005, subsequent multi-dimensional explosion simulations have shown good agreement with neither normal nor 91T-like SNe Ia (Seitenzahl et al. 2016). In addition, the abundance distribution appears dissimilar to that inferred for normal SNe Ia based on late-time spectra (Maguire et al. 2018), as much of the stable material produced in the high density core would be carried to the outer ejecta through buoyancy.

Aside from models invoking deflagrations, the double-detonation scenario is another possibility for producing large $^{56}\text{Ni}$ mass fractions in the outer ejecta (Livne 1990; Woosley & Weaver 1994; Bildsten et al. 2007). In these models, a thin helium shell builds up on the surface of the WD. Depending on certain conditions (e.g. mass of the WD, mass of the helium shell, etc.), the shell may ignite and create a secondary detonation that leads to the complete disruption of the star (Fink et al. 2007). In general, burning in the helium shell can produce a large amount of $^{56}\text{Ni}$, qualitatively similar to the $^{56}\text{Ni}$ clumps included in this work (Fink et al. 2010; Shen et al. 2010; Moll & Woosley 2013). Similar to our models, the presence of a $^{56}\text{Ni}$ shell produces an excess of flux within the days following explosion. Although some double-detonation models predominantly produce $^{56}\text{Ni}$ during the shell burning, other short-lived radioactive isotopes are also synthesised — in particular $^{48}\text{Cr}$ and $^{52}\text{Fe}$ (Woosley & Weaver 1994). In addition to affecting the light curves, the presence of these additional isotopes also produces a distinctive Ti (at $^{48}\text{Ti}$ is a daughter product of the $^{48}\text{Cr}$ decay chain) trough between $\sim 4000$ – 4 300 Å. Even for models in which the helium shell products are dominated by $^{56}\text{Ni}$, a strong Ti feature is produced (Polin et al. 2019). The presence of such a feature could therefore provide one method for distinguishing a $^{56}\text{Ni}$ excess produced by helium shell detonations and other methods.

Even relatively small $^{56}\text{Ni}$ clumps in the outer ejecta (0.01 $M_\odot$ of $^{56}\text{Ni}$ above a mass coordinate of 1.35 $M_\odot$) can have a significant effect on the light curve, producing a light curve bump that increases the bolometric magnitude by $>2$ magnitudes at one day after explosion. Given that such bumps are not observed for the majority of SNe Ia, this would indicate that $^{56}\text{Ni}$ clumps (at least those large enough to reproduce the light curve shapes of SN 2018oh and SN 2017cbv) must be relatively rare phenomena, if indeed they occur at all.

5.2. Alternative sources of flux excesses

While our models show that $^{56}\text{Ni}$ clumps in the outer ejecta can produce an excess of flux at early times, similar behaviour is found for other scenarios that do not invoke the presence of additional $^{56}\text{Ni}$ — in particular, interaction between the SN ejecta and companion star or circum-stellar material (CSM). In both cases, this material is shock heated by the SN ejecta and gradually cools, providing an additional source of luminosity.

Kasen (2010) shows how the total luminosity produced during the light curve bump varies depending on the nature of the companion, with larger mass and more evolved companions producing larger flux excesses. For red giant companions, the $B$-band flux excess is approximately one magnitude fainter than peak, while in the ultraviolet it is approximately one magnitude brighter. This is unlike our $^{56}\text{Ni}$ clump models, in which the flux excess is always $\gtrsim 2$ mag. fainter than peak. In contrast, less evolved main sequence stars show flux excesses covering a similar range in magnitude to that of our $^{56}\text{Ni}$ clump models, however they are generally shorter lived. For example, when assuming interaction occurs with a 6 $M_\odot$ MS companion, the $B$-band light curve has already plateaued within $\sim 1$ day of explosion. The companion interaction scenario has been proposed for the light curve bumps in SNe 2018oh and 2017cbv, and is the favoured interpretation in both cases (Hosseinzadeh et al. 2017; Dimitriadis et al. 2019; Shappee et al. 2019). We note however, that both SNe show a fainter UV luminosity than predicted by this model and show no signs of hydrogen, which is expected to be swept up during the interaction and produce strong emission at late times (Sand et al. 2018; Tucker et al. 2019).

Similarly, Piro & Morozov (2016) investigate interaction with CSM and show that various light curve bumps can be produced depending on the mass and radial extent of the material. Piro & Morozov (2016) also demonstrate that the distribution of $^{56}\text{Ni}$ within the ejecta plays an important role in shaping the light curve bump, as those models with more extended $^{56}\text{Ni}$ distributions can mask the signatures of interaction. In all cases, those CSM models without mixed $^{56}\text{Ni}$ distributions produce pronounced bumps in the $V$-band light curve that differ significantly from the bumps in our models. For those models with more extended $^{56}\text{Ni}$ distributions, the CSM mass must be relatively large ($\sim 0.3$ $M_\odot$) to produce a flux excess as long lived as our $^{56}\text{Ni}$ clump models. In the case of SN 2017cbv however, the presence of CSM was investigated by Ferretti et al. (2017), who found no evidence for significant amounts of material.

Finally, Levanon & Soker (2019) present an alternative scenario to explain the flux excess of SN 2018oh — interaction between the SN ejecta and disk-originated matter (DOM). During the violent merger of two white dwarfs, the disruption of the less massive secondary can lead to the formation of an accretion disk around the more massive primary that launches a wind or jet (Levanon et al. 2015). Based on analytical models, Levanon & Soker (2017) show that following the explosion this DOM is shock heated and produces early UV emission in a similar man-
ner as the interaction between SN ejecta and companion star or CSM. One of the benefits of this scenario is that, as it originates from the double degenerate scenario, it naturally explains the absence of hydrogen features in late time spectra – as is the case for SN 2018oh and SN 2017cbv. The timescale and luminosity of the flux excess produce by the DOM interaction scenario is also similar to some of $^{56}$Ni clump models, and therefore warrants further investigation with full radiative transfer calculations.

6. Conclusions

Following from the works of Dimitriadis et al. (2019) and Shappee et al. (2019), we investigated $^{56}$Ni clumps in the outer ejecta as a source of the flux excess observed in SNe 2018oh and 2017cbv. For each object, we took a fiducial model that reproduces the later light curve (i.e. ignoring the early flux excess) and added $^{56}$Ni clumps to investigate the changes relative to a model without clumps. We presented light curves and spectra for models containing $^{56}$Ni clumps of 0.01 – 0.04 $M_\odot$. In all cases, we find that models with $^{56}$Ni clumps produce an excess of flux during the first few days after explosion. Even a relatively small $^{56}$Ni clump of 0.01 $M_\odot$ can have a profound effect on the early light curve and produce an increase in the bolometric magnitude > 2 mag. at one day after explosion. The appearance of the flux excess is also affected by the shape of the $^{56}$Ni clump, with narrower clumps producing excesses with a more well-defined peak than broader clumps. In addition, our models show that the effects of the $^{56}$Ni clumps are most prominent at shorter wavelengths and the colour evolution of models with $^{56}$Ni clumps differs significantly. All models with $^{56}$Ni clumps show an inversion in the $B$ – $V$ colour evolution between ~3 – 6 days after explosion and are clearly distinguished from the fiducial models and even models with more extended $^{56}$Ni distributions.

We compared the light curves of our models with $^{56}$Ni clumps to observations of SNe 2018oh and 2017cbv and find improved agreement compared to the fiducial models – our $^{56}$Ni clump models can produce the overall light curve shape in both objects. Similar to Dimitriadis et al. (2019), we find that a $^{56}$Ni clump of 0.02 – 0.03 $M_\odot$ is required to reproduce the shape of SN 2018oh, while for SN 2017cbv a slightly higher mass of 0.03 – 0.04 $M_\odot$ is required. Although our $^{56}$Ni clump models can reproduce the early light curve bumps of both objects, there are noticeable differences in the colours and spectral evolution. Our models are systematically redder and show more extreme changes in colour than the observations. A strong suppression of flux in the region of ~3 700 – 4 000 Å also appears to be a generic feature in the maximum light spectra of our $^{56}$Ni clump models. Neither SN 2018oh nor SN 2017cbv show a similar feature, indicating that while models with $^{56}$Ni clumps could match the light curve shapes, the spectra are in disagreement. Overall, this would suggest that $^{56}$Ni clumps are not the source of the early excess flux in either object.

Based on existing explosion models, producing such clumps in the outer ejecta as required also appears challenging. The GCD scenario can produce $^{56}$Ni clumps in the outer ejecta for certain viewing angles, and hence can also produce a small bump in the light curve. Such clumps however, are not as extreme as would be required to match the light curve shapes of SNe 2018oh and 2017cbv. Whether this scenario could produce larger $^{56}$Ni clumps and good agreement with observations remains to be seen, but warrants further investigation. Alternatively, the double detonation scenario can also produce large $^{56}$Ni fractions in the burned ash of the accreted helium shell. Again, this scenario can also produce light curve bumps, however the picture is complicated by the presence of short-lived isotopes providing an additional powering source for the early light curve. In addition, the helium shell ash produces distinct spectroscopic features, such as strong Ti absorption. The presence of such a feature could therefore provide one method of distinguishing between $^{56}$Ni clumps produced by either deflagration or helium shell ash.

Studies of SNe Ia have shown that early light curve bumps are rare. Only a handful of objects displaying bumps are currently known, despite extensive searches. Based on a sample of 35 SNe Ia with sufficiently early light curves, Magee et al. (2020) find ~20 – 30% of objects show evidence for a flux excess when compared against their model light curves. Given that even a relatively small $^{56}$Ni clump can significantly alter the light curve shape, this would indicate that $^{56}$Ni clumps (at least those as large as required to match the light curves of SNe 2018oh or 2017cbv) must also be relatively rare – if they occur naturally at all. Future surveys dedicated to the discovery and follow-up of SNe at early times will help to shed light on the nature of flux excesses in SNe Ia.

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