Persistent X-Ray Emission from ASASSN-15lh: Massive Ejecta and Pre-SLSN Dense Wind?

Yan Huang1,2 and Zhuo Li1,2

1 Department of Astronomy, School of Physics, Peking University, Beijing 100871, People’s Republic of China; hyan623@pku.edu.cn
2 Kawli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China

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Abstract

The persistent soft X-ray emission from the location of the most luminous supernova (SN) so far, ASASSN-15lh (or SN 2015L), with \( L \sim 10^{52} \text{ erg s}^{-1} \), is puzzling. We show that it can be explained by radiation from electrons accelerated by the SN shock inverse-Compton scattering the intense UV photons. The non-detection in radio requires strong free–free absorption in the dense medium. In these interpretations, the circumstellar medium is derived to be a wind \( (n \propto R^{-2}) \) with mass-loss rate of \( M \gtrsim 3 \times 10^{-5} M_{\odot} (v_{\text{w}}/10^{3} \text{ km s}^{-1}) \text{ yr}^{-1} \), and the initial velocity of the bulk SN ejecta is \( \lesssim 0.2c \). These constraints imply a massive ejecta mass of \( \gtrsim 60 (E_{0}/2 \times 10^{52} \text{ erg}) M_{\odot} \) in ASASSN-15lh, and a strong wind ejected by the progenitor star within \( \sim 8 (v_{\text{w}}/10^{3} \text{ km s}^{-1})^{-1} \) yr before explosion.

Key words: stars: mass-loss – supernovae: general – supernovae: individual (ASASSN-15lh)

1. Introduction

Superluminous supernovae (SLSNe) are a type of stellar explosion with a luminosity 10 or more times higher than standard supernovae (SNe; Gal-Yam 2012). SN 2005ap was the first discovered SLSN, with an absolute magnitude at peak around \(-22.7 \text{ mag} \) (Quimby et al. 2007). Over the past decade, due to rapid-cadence transient searches with a large field of view, more than a hundred SLSNe have been found (Quimby et al. 2007; Smith & McCray 2007; Gal-Yam 2012; Nicholl et al. 2014). SLSNe are likely associated with the deaths of the most massive stars, but the progenitors and the physics of the explosion are still not understood. Several power-input mechanisms have been proposed for SLSNe, including gamma-ray heating by the radioactive decays of \(^{56}\text{Ni}\) and \(^{56}\text{Co}\) (Gal-Yam et al. 2009), magnetar spin-down (Kasen & Bildsten 2010; Woosley 2010), SN shock interaction with dense material in the environment (Smith & McCray 2007; Chevalier & Irwin 2011), and pair-instability SNe (Woosley 2017; Woosley et al. 2007). Unveiling the progenitors and explosion mechanisms of SLSNe is crucial for our understanding of the evolution of massive stars.

ASASSN-15lh was discovered by the All-Sky Automated Survey for Supernovae (ASAS-SN) with an absolute magnitude of \(-23.5 \) and a peak bolometric luminosity of \( L_{\text{bol}} = (2.2 \pm 0.2) \times 10^{45} \text{ erg s}^{-1} \), more than twice the previously known SLSNe, making it the most luminous SN thus far (Dong et al. 2016). The temporary behavior showed a unique double-humped structure. It reached its primary peak several tens of days after explosion, and then decayed. However, a rebrightening began \( \sim 90 \) days after the primary peak and was followed by a long plateau (Godoy-Rivera et al. 2017). Persistent soft X-ray radiation with luminosity \( L \sim 10^{43} - 10^{45} \text{ erg s}^{-1} \) at the location of ASASSN-15lh was observed by Chandra during the follow-up campaign (Margutti et al. 2017). Radio follow-up of ASASSN-15lh was carried out by ATCA, 197 days after the first optical observation, but no radio emission was detected (Kool et al. 2015).

The major features characterizing ASASSN-15lh led it to be classified as a hydrogen-poor (type I) SLSN (Dong et al. 2016). There have been many discussions on the power input. Dong et al. (2016) suggested that the large radiation energy does not favor radioactive decay and a magnetar as the main energy sources, and the lack of spectral features also disfavors the model of interaction with a dense medium; however, Metzger et al. (2015) and Dai et al. (2016) suggested that updated magnetar models may still work. The later observed rebrightening posed new challenges for all the models. Chatzopoulos et al. (2016) explained the double-humped structure as a signature of the interaction of massive SN ejecta with an H-poor circumstellar shell of \( \sim 20 M_{\odot} \).

Here we focus on the origin of the X-ray emission, but not the UV emission, which is assumed to be produced from a region inside the SN shock. If the X-ray emission is really produced by ASASSN-15lh, one may expect it to vary with time, rather than keeping a constant luminosity, so the interpretation of X-ray emission from the host galaxy is favored (Margutti et al. 2017). Here we show that the persistent behavior can be explained by radiation from the SN shock, i.e., the shock-accelerated electrons upscattering the incoming UV photons from the SN photosphere. In this way, the ejecta mass and the density of the medium can be derived, and they give a hint of the progenitor of ASASSN-15lh. In Section 2, we give the main observational results on ASASSN-15lh. Our model is provided in Sections 3 and 4 gives the results of modeling, followed by discussion and conclusion (Section 5). Notice that we use the convention \( q_{e} = q/10^{4} \) and cgs units in the following unless stated otherwise.

2. Observations

ASASSN-15lh was discovered on 2015 June 14 (UT) by the ASAS-SN survey (Dong et al. 2016). The redshift is \( z = 0.2326 \), corresponding to a luminosity distance of \( d_{L} \simeq 1171 \text{ Mpc} \). At

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3 See, however, Leloudas et al. (2016) and Krühler et al. (2018), who suggested that ASASSN-15lh was a tidal disruption event from a supermassive Kerr black hole.
the primary peak of the light curve the absolute magnitude is $M_{V,AB} = -23.5 \pm 0.1$, and the bolometric luminosity is $L_{\text{bol}} = (2.2 \pm 0.2) \times 10^{45}$ erg s$^{-1}$. Because of similarities in the evolution of temperature, luminosity, and radius between ASASSN-15lh and the other SLSNe-I, ASASSN-15lh was characterized as a hydrogen-poor SLSNe-I (Dong et al. 2016). The host galaxy of ASASSN-15lh is a luminous galaxy ($M_K \simeq -25.5$) with little star formation.

The time of the primary peak is JD2457179 (2015 June 5). Godoy-Rivera et al. (2017) reported a UV rebrightening starting 90 days (observer frame) after the primary peak, followed by a plateau $\simeq$120 days long in the bolometric light curve, and further fading since $\simeq$210 days after explosion. Over $\sim$550 days since detection, ASASSN-15lh has radiated $E_{\text{rad}} \sim (1.7-1.9) \times 10^{52}$ erg.

Margutti et al. (2017) presented the detection of persistent soft X-ray emission, with a luminosity $L \sim 10^{41}-10^{42}$ erg s$^{-1}$, at the location of ASASSN-15lh by Chandra. They obtained four epochs of deep X-ray observations with Chandra on 2015 November 12, 2015 December 13, 2016 February 20, and 2016 August 19, corresponding to 129.4 days, 154.6 days, 201.5 days, and 357.8 days (rest frame) since optical maximum light on 2015 June 5. Table 1 shows the X-ray flux observed by Chandra.

Kool et al. (2015) used ATCA to observe the radio emission on 2015 November 21.1 UT, i.e., 197 days after the first optical observation (MJD 57150.5). No radio emission was detected at the SN location. 3$\sigma$ upper limits of 23 $\mu$Jy at 5.5 GHz and 21 $\mu$Jy at 9 GHz were given.

### Table 1

| Date (MJD) | Exposure (ks) | Unabsorbed Flux (erg s$^{-1}$ cm$^{-2}$) |
|-----------|--------------|-----------------------------------------|
| 57338     | 10           | $\leqslant 2.0 \times 10^{-15}$          |
| 57369     | 10           | $\leqslant 4.4 \times 10^{-15}$          |
| 57438     | 40           | $\leqslant 3.6 \times 10^{-15}$          |
| 57619     | 30           | $\leqslant 4.9 \times 10^{-15}$          |

3. Model

3.1. Hydrodynamic Evolution

Consider that the SN ejecta of ASASSN-15lh drives a shock propagating into the circumstellar medium (CSM). The hydrodynamic evolution of the shock depends on the density structure of the freely expanding SN ejecta and the structure of the CSM. Consider the CSM to be a steady stellar wind released from the progenitor star of ASASSN-15lh. For a free wind with constant mass-loss rate $M$ and wind speed $v_w$, one has the wind density as a function of the radius $R$,

$$n = \frac{M}{4\pi R^2 m_p v_w} \equiv AR^{-2}. \quad (1)$$

So $A$ is a parameter representing the density of the wind-like CSM. For a high wind mass-loss rate of $M = 10^{-2} M_\odot$ yr$^{-1}$ and a wind speed of $v_w = 10^4 v_w, c$ cm s$^{-1}$, $A$ should be normalized as $A = 10^{38} A_{38}^2$ cm$^{-2}$.

Consider a spherical SN ejecta to be homogeneous with a constant velocity $\beta_0 c$ and a bulk kinetic energy $E_0$. Initially the shock expands with the initial velocity $\beta_0 c$, transferring the ejecta energy into the swept-up medium. The shock energy when the shock expands to radius $R$ is

$$E = (\beta_0 c)^2 \int_0^R n m_p 4\pi r^2 dr = 4\pi A m_p R (\beta_0 c)^2. \quad (2)$$

Later on, when half of the initial energy has been transferred into the shocked medium, $E = \frac{1}{2} E_0$, the shock starts to decelerate significantly. This occurs at a radius defined as the deceleration radius,

$$R_{\text{dec}} = \frac{E_0}{8\pi m_p A c^2 \beta_0^2} \approx 2.7 \times 10^{10} \text{ cm} \ E_{52} A_{38}^{-1} \beta_{0.2}^{-2}. \quad (3)$$

For ASASSN-15lh, we normalize the initial energy to be $E_0 = 10^{52} E_{52}$, since the radiated energy is of the order of $10^{52}$ erg. The corresponding deceleration time since the SN explosion is

$$t_{\text{dec}} = \frac{R_{\text{dec}}}{c\beta_0} \approx 2.8 \times 10^3 \text{ yr} \ E_{52} A_{38}^{-1} \beta_{0.2}^{-3.2}. \quad (4)$$

Thus, at time $t < t_{\text{dec}}$, the shock propagates at a constant velocity, $\beta = \beta_0$, and the shock radius is $R = c t / \beta_0$. At $t > t_{\text{dec}}$, the shock dynamics transits into the self-similar Sedov–Taylor solution; then we have the shock velocity $\beta = \beta_0^{2/3} (ct/R_{\text{dec}})^{-1/3}$. Note that the sensitive dependence of $t_{\text{dec}}$ on $\beta_0$ implies that in our case of a non-relativistic shock in ASASSN-15lh, $\beta_0 \ll 1$, $t_{\text{dec}}$ is much larger than the relevant observation time. So we only need to consider the freely expanding phase of $t < t_{\text{dec}}$ where $\beta = \beta_0$.

It should be noted that in a more realistic model one may consider a uniformly expanding ejecta with a steep power-law density profile on the outside, for which the numerical simulations show that the outflow energy is as a function of velocity, $E_\text{eq}(>\beta) \propto \beta^{-k}$. Since the shock energy is provided by the kinetic energy of the ejecta that catch up with the shock, the dynamical evolution is determined by $E_\text{eq}(>\beta) = E(\beta)$, which gives $\beta \propto t^{1/(k+3)}$. Numerical simulations show that the velocity profile of the SN ejecta is $\beta \propto M_\infty(>\beta)^{-\beta_1/(n+1)}$, with $\beta_1 \sim 1/5$ and $n = 3/(2)$ for radiative (convective) envelopes of the progenitor stars (Matzner & McKee 1999), thus $k \sim 14/3$ (19/3) correspondingly. The large $k$ values make $\beta = \text{constant}$ a good assumption.

3.2. Shock Radiation

Given the hydrodynamic evolution of the SN shock, we next discuss the radiation from the shock. The swept-up CSM electrons will be accelerated by the shock, via, e.g., diffusive shock acceleration processes, and the postshock magnetic field is also amplified, hence the accelerated electrons will give rise to synchrotron and inverse-Compton (IC) radiation in the downstream region (e.g., Chevalier & Fransson 2006). We discuss the IC and synchrotron components separately below, focusing on their contributions to X-ray and radio emission, respectively.

3.2.1. IC Radiation

We first show that for ASASSN-15lh, IC is the dominant cooling process other than synchrotron radiation for the accelerated electrons. The synchrotron cooling time of electrons with Lorentz factor (LF) $\gamma_e$ is $\tau_{\text{syn}} = 3m_e c/4\pi^2 \sigma_T U_B \gamma_e^3$.\]
depending on the energy density of the postshock magnetic field, \( U_B = 4\epsilon_B m_n c^2 \), where \( \epsilon_B \) is the equipartition parameter for magnetic field. On the other hand, the electrons will also lose energy by upscattering the ambient photons. Given the intense UV photon emission from the inner photosphere of the newly exploded SN, a dominant contribution to the seed photons for IC scattering is the UV photons (Björnsson & Fransson 2004). For a UV luminosity of \( L_{UV} \), the photon energy density at the shock region is \( U_{ph} = L_{UV}/4\pi R^2 c \), then the electron cooling time due to IC scattering of UV photons can be derived as \( t_{IC} = 3m_e c / 4\sigma_T U_{ph} \gamma_e c \). So the ratio of synchrotron to IC cooling time is

\[
\frac{t_{syn}}{t_{IC}} = \frac{U_{ph}}{U_b} \approx 4.4 \times 10^2 L_{UV,45}^{-1} \gamma_e^{-1} B_{-0.2}^{-2} \beta_0^{-2}.
\]  

(5)

For ASASSN-15lh, given the large UV luminosity (Godoy-Rivera et al. 2017) we normalize the UV luminosity as \( L_{UV} = 10^{45} L_{UV,45} \) erg. For \( \beta \ll 1 \) and a wide range of A, one has \( t_{syn} \gg t_{IC} \), hence we assume that IC cooling dominates synchrotron cooling.

By diffusive shock acceleration theory, the CSM electrons swept up by the SN shock are accelerated to follow a power law in momentum \( dN_e/dp \propto p^{-\gamma_e} \) with \( \epsilon_e > \epsilon_{min} \) and the power-law index. For relativistic electrons we have \( \epsilon_e > \epsilon_r \), thus the electron distribution at \( \gamma_e \gg 2 \) can also be approximated as a power law in the electron’s LF with the same index, \( dN_e/d\gamma_e \propto \gamma_e^{-\gamma_e} \). Radio observations of Type Ib/c SNe indicate \( p \approx 3 \) (Chevalier & Fransson 2006), thus we take \( p = 3 \) here. This is also consistent with the poorly constrained X-ray spectrum of ASASSN-15lh (Margutti et al. 2017).

Suppose that the accelerated shock electrons carry a fraction \( \epsilon_e \) of the postshock internal energy \( U = n_e m_p c^2 \), with \( n_e \) the postshock proton number density. We will take the typical value \( \epsilon_e = 0.1 \). If the bulk electrons are relativistic, then using the approximation of a power law in LF, the minimum LF can be derived to be \( \gamma_e = [(p - 2)/(p - 1)](m_p/m_e)\epsilon_e \beta_0^2 \) (e.g., Piran et al. 2013). The minimum LF is a constant initially when the shock does not decelerate, \( \gamma_e = \beta_0^2 \). However, if the initial shock velocity \( \beta_0 \) is low enough, the bulk electrons may be non-relativistic, \( \gamma_e \ll 2 \). Since we are only interested in the electrons that emit synchrotron and IC radiation, the relevant electrons should be relativistic, \( \gamma_e \gg 2 \). Thus, for the characteristic frequencies in the synchrotron and IC spectra, we should take

\[
\gamma_{min} = \frac{p - 2 m_p}{p - 1} \epsilon_e \beta_0^2, 2.
\]  

(6)

If the bulk accelerated electrons are non-relativistic, the electron energy is, for \( p \ll 3 \), dominated by electrons with \( \gamma_e \gg 2 \) (Sironi & Giannios 2013), i.e., relativistic electrons. Thus, we can approximate \( \epsilon_e U \approx \int \gamma_e n_e c^2 (dN_e/d\gamma_e) d\gamma_e \). Moreover, the postshock electron number density for \( \gamma_e \gg 2 \) is \( n_{rel} \approx \int \gamma_e n_e c^2 (dN_e/d\gamma_e) d\gamma_e \). Combining these two equations gives the fraction of the total electrons that are relativistic, \( \gamma_e \gg 2 \),

\[
f_{rel} = \frac{n_{rel}}{n_e} = \min \left( 1, \frac{p - 2 m_p}{p - 1} \epsilon_e \beta_0^2 \right). \]  

(7)

So given the total number of the electrons swept up by the shock \( N_e = 4\pi AR \), the number of relativistic electrons that give rise to synchrotron and IC radiation is only \( f_{rel} N_e \).

The radiative cooling changes the electron distribution. By letting the electron cooling time, dominated by IC cooling, be equal to the age of the SN shock, \( t_{IC} = t \), we obtain the cooling LF \( \gamma_e = 3m_e c / 4\sigma_T U_{ph} t \). For electrons with \( \gamma_e > \gamma_c \), the electrons cool significantly and the distribution deviates from the injection power law, with the index changed to \( p + 1 \). Given the bright UV emission of ASASSN-15lh, we find that at the beginning \( \gamma_c < \gamma_{min} \), all electrons are in the fast cooling regime. Later \( \gamma_c > \gamma_{min} \) may happen, thus we should consider both fast cooling and slow cooling regimes in deriving the electron distribution and radiation spectrum.

Next we discuss the radiation spectrum from IC scattering of UV photons, considering both fast and slow cooling cases like Sari et al. (1998). On average, the IC radiation power of a single electron with \( \gamma_e = \beta_0^2 \) is \( P_{IC} = (4/3) \sigma_T c \gamma_e^4 U_{ph} \). For simplicity, we assume that the seed photons are isotropic, neglecting the correction of order unity from anisotropic incoming photons. The UV photons are in a blackbody-like spectrum, thus the energy distribution is narrow, and we can approximate them as monochromatic, with a frequency of \( \nu_0 = 3k_{B} T / h \). Observations show that the rest-frame temperature of the UV photons is \( T_{ph} \approx 2 \times 10^8 \) K (Dong et al. 2016).

Typically, the UV photons will be scattered by electrons with \( \gamma_e \) up to a frequency of \( \nu_0 = (4/3) \gamma_c^2 \nu_0 \). The specific power at \( \nu_0 \) is \( P_{IC} / \nu_0 = \sigma_T c U_{ph}/\nu_0 \), independent of \( \gamma_e \). The number of relativistic electrons is \( f_{rel} N_e \), and the observed IC flux at the spectral peak is

\[
F_{m,IC} = 163 \mu Jy A_{38} L_{UV,45}^{-1} d_L^{-2} \gamma_e^{-1/2} - \gamma_0^{-2} f_{rel},
\]  

(8)

where \( t_0 = t/(1 \text{ day}) \). We take a broken power-law approximation for the radiation spectrum (Ghisellini 2013) for the fast cooling case \( \gamma_e < \gamma_m \)

\[
F_{m,IC} = \begin{cases} \frac{F_{m,IC} \left( \frac{\nu}{\nu_{c,c}} \right)}{\nu_{c,c}}, & \nu < \nu_{c,c} \\ \frac{F_{m,IC} \left( \frac{\nu}{\nu_{c,m}} \right)^{-p/2}}{\nu_{c,m}}, & \nu \leq \nu_{c,m} \end{cases}
\]  

(9)

whereas, for the slow cooling case \( \gamma_m < \gamma_e \).

\[
F_{m,IC} = \begin{cases} \frac{F_{m,IC} \left( \frac{\nu}{\nu_{c,m}} \right)}{\nu_{c,m}}, & \nu < \nu_{c,m} \\ \frac{F_{m,IC} \left( \frac{\nu}{\nu_{c,c}} \right)^{-p/2}}{\nu_{c,c}}, & \nu \leq \nu_{c,c} \end{cases}
\]  

(10)

The break frequencies in the spectrum relevant to the characteristic electron LFs are \( \nu_{c,c} = (4/3) \gamma_c^2 \nu_0 = 1.4 \times 10^{17} \text{ Hz} L_{38}^{-1} A_{38}^{-1} \) and \( \nu_{c,m} = (4/3) \gamma_m^2 \nu_0 = 1.7 \times 10^{15} \text{ Hz} \).
3.2.2 Synchrotron Radiation

Consider the synchrotron radiation emitted by the shock-accelerated electrons, although this is not the dominant process of electron energy loss. In particular, we are interested in the contribution from synchrotron radiation to the radio emission from SNe Ib/Ic (Chevalier 1998; Björnsson & Fransson 2004). We define \( \nu_{\Delta} \) as the frequency at which the optical depth of synchrotron absorption is unity, and the electron LF of emitting photons at \( \nu_{\Delta} \) as \( \gamma_{\Delta} \). It should be noted, and confirmed later, that we are facing the problem of the minimum injection LF \( \gamma_{\Delta} \) and the cooling LF \( \gamma_{\mathcal{C}} \) being close to unity, and far smaller than \( \gamma_{\Delta} \), i.e., \( \gamma_{\Delta} \gg 1 \) and \( \gamma_{\mathcal{C}} \sim \gamma_{\mathcal{C}} \sim 1 \). We still take a broken power-law approximation for the synchrotron spectrum.

The frequency range of interest for gigahertz radio emission would be the spectral segments around \( \nu_{\Delta} \), which, as derived in the Appendix, is

\[
\nu_{\Delta} \approx 343 \text{ GHz } t_{\Delta}^{\nu_{\Delta}} L_{\nu_{\Delta}}^{\nu_{\Delta}} - \frac{2}{\gamma_c^2} L_{\nu_{\mathcal{C}}}^{\nu_{\mathcal{C}}} A_{\mathcal{C}}^{\nu_{\mathcal{C}}} \left( \gamma_{\mathcal{C}}^2 + 3 \right) t_{\mathcal{C}}^{\nu_{\mathcal{C}}} \frac{1}{\nu_{\mathcal{C}}} \beta_{\mathcal{C}}^{-2} \nu_{\mathcal{C}}^{\nu_{\mathcal{C}}} .
\]

(11)

Irrespective of the fast cooling (\( \gamma_{\mathcal{C}} < \gamma_{\Delta} \)) or slow cooling (\( \gamma_{\mathcal{C}} < \gamma_{\Delta} \)) regime, the synchrotron flux at \( \nu > \max(\nu_{\Delta}, \nu_{\mathcal{C}}) \) can be given by

\[
F_{\nu,\mathcal{S}} = \begin{cases} 
F_m \nu^{-1/2} \nu_{\mathcal{C}}^{1/2} \nu_{\Delta}^{-2}, & \nu < \nu_{\Delta} \\
F_m \nu^{-1/2} \nu_{\mathcal{C}}^{1/2} \nu_{\mathcal{C}}^{-1/2}, & \nu \geq \nu_{\mathcal{C}} 
\end{cases}
\]

(12)

where \( \nu_{\mathcal{C}} \) and \( \nu_{\mathcal{C}} \) are the characteristic frequencies emitted by electrons with LFs of \( \gamma_{\mathcal{C}} \) and \( \gamma_{\mathcal{C}} \), respectively, and

\[
F_m = f_{\mathcal{C}} \gamma_{\mathcal{C}}^2 B/4\pi d_l^2,
\]

with \( B = \sqrt{3} e^3 B/m_e c^2 \) being the synchrotron specific power of a single electron at its characteristic frequency \( \nu = 3\gamma_{\mathcal{C}}^2 B/4\pi m_e c^2 \). Thus we can derive

\[
F_m = 2.87 \times 10^5 \nu^{-1/2} A_{\mathcal{C}}^{1/2} B^{-1} d_l^{-2} \beta_{\mathcal{C}}^{-2} \beta_{\mathcal{C}}^{-2}.
\]

(13)

If the CSM is dense and ionized or partially ionized, free-free absorption could be important for radio emission. The optical depth of the wind from radius \( R \) toward the observer, due to free-free absorption, is given by

\[
\tau_{\mathcal{F}} = 1.6 \times 10^4 \nu_{\mathcal{F}}^{-1.5} A_{\mathcal{F}}^{1.5} B^{-1} d_l^{-2} \beta_{\mathcal{F}}^{-2} \beta_{\mathcal{F}}^{-2},
\]

(14)

where \( T_{\mathcal{F}} \) is the temperature of the electrons in the CSM (Lang 1999). We take \( T_{\mathcal{F}} = 2.0 \times 10^4 \text{ K} \). Below the observed synchrotron flux after correction for free-free absorption should be \( F_{\nu} = F_{\nu,\mathcal{S}} \exp(-\tau_{\mathcal{F}}(\nu)) \).

4. Parameter Constraints

We use the model described above to fit the X-ray and radio data of ASASSN-15lh. The X-ray data can be interpreted as IC radiation due to upscattering of the intense UV radiation. In order to calculate the IC radiation we need the UV light curve as input, thus we first fit the UV light curve with two connecting third-order polynomials, \( L_{UV} = a_3 t^3 + a_2 t^2 + a_1 t + a_0 \), with \( (a_3, a_2, a_1, a_0) = (3.95 \times 10^{-6}, -7.77 \times 10^{-4}, 3.44 \times 10^{-2}, 11.5) \) for \( t < 100 \text{ days} \) (rest-frame time since explosion), and \( (2.77 \times 10^{-8}, -2.83 \times 10^{-5}, 6.30 \times 10^{-3}, 10.7) \) for \( t \geq 100 \text{ days} \). Here \( L_{UV} \) is in units of L_0, and \( t \) in days. This fitting function is shown in Figure 1 as a red solid curve, in comparison with the UV data from Godoy-Rivera et al. (2017). With these seed photons, the calculated IC flux is also shown in Figure 1. We have integrated the IC flux over the energy range 0.3–10 keV to match the observed X-ray energy range. The IC luminosity is constant with time, well fitting the detected persistent X-ray flux (Table 1).

We explain why the IC flux is constant here. The X-ray-emitting electrons are cooling fast due to upscattering the intense UV photons, so the X-ray range lies in a regime of \( \nu \gg \max(\nu_{\mathcal{F},\mathcal{C}}, \nu_{\mathcal{S},\mathcal{C}}) \). In this regime, irrespective of whether the bulk electrons are fast or slow cooling (i.e., \( \gamma_{\mathcal{C}} < \gamma_{\mathcal{F}} \) or \( \gamma_{\mathcal{C}} < \gamma_{\mathcal{S}} \)), the IC flux is given by \( F_{\nu,\mathcal{IC}} = F_{\nu,\mathcal{IC}}(\nu_{\mathcal{F},\mathcal{C}}^{1/2} + \nu_{\mathcal{S},\mathcal{C}}^{1/2})^{\nu_{\mathcal{F},\mathcal{C}}^{1/2} + \nu_{\mathcal{S},\mathcal{C}}^{1/2}} \); see Equations (9) and (10). During the evolution stage concerned, the CSM material swept up by the SN shock is not enough to decelerate the shock, and the shock keeps a constant velocity \( \beta \approx \beta_{\mathcal{C}} \); hence the postshock electrons’ characteristic LF is also a constant, since \( \gamma_{\mathcal{C}} \approx \beta^2 \) or \( \gamma_{\mathcal{C}} = 2 \). Thus \( \nu_{\mathcal{C}} \approx \nu_{\mathcal{C}}^2 \) is a constant. Next, the total number of swept-up CSM electrons \( N_{\mathcal{C}} \) is \( \propto R \times t \), within which the fraction of relativistic electrons is also constant, \( f_{\text{rel}} = 1 \) or \( \propto \beta^2 \), and the peak specific IC power is \( P_{\text{m,IC}} \propto U_{\text{ph}} \), then the peak IC flux scales as \( F_{\text{m,IC}} \propto f_{\text{rel}} N_{\text{m,IC}} \propto U_{\text{ph}} \). Finally, the electron cooling LF \( \gamma_{\mathcal{C}} \propto U_{\text{ph}} \), thus \( \nu_{\mathcal{C}} \propto \gamma_{\mathcal{C}}^{1/2} \propto U_{\text{ph}}^{1/2} \). Putting all these together, we have \( F_{\nu,\mathcal{IC}} \propto t^0 \) being constant. In short, for a medium with density \( n \propto R^{-2} \) and IC radiation in the fast cooling regime, the IC flux is
Figure 2. Parameter constraints in the 2D space ($\beta_0$, $A$) with observations. The red oblique-line region shows the X-ray flux constraint. The blue grid (pink shaded) region shows the constraint from the upper limit of 9 GHz, without (with) free–free absorption taken into account. The parameters used are $e_b = 0.1$, $e_c = 0.1$, $p = 3$, and $T_e = 2.0 \times 10^4$ K.

a constant. Actually, for $\nu > \max(\nu_{a,m}, \nu_{a,c})$ we can derive

$$F_{\nu,IC} = 1.0 \times 10^{-6} \mu Jy A_{38} \beta_0^{-2} d_{1.28}^{-2} \nu^{-1} \nu_0^{-7/2} f_{rel},$$

independent of time.

The phase of constant IC flux may end when the break $\nu_{a,c}$ crosses the observation band. Letting $\nu_{a,c} \approx 10^{18}$ Hz, we obtain that the crossing occurs at time

$$t_{cross} = 2.7 \times 10^5 \text{days} L_{UV, ASASSN-15lh}^{-1/2} \beta_0^{1/2}.$$ (16)

After $t_{cross}$ the X-ray band enters the regime of $\nu_{a,c} > \nu > \nu_{a,m}$, where the IC-produced flux at $\approx 10^{18}$ Hz is $F_{\nu,IC} \propto F_{\nu,IC} \propto U_{ph,t} \propto L_{UV} t^{-1}$, decreasing with time.

In order to constrain the parameters, we apply the least-squares fitting method to fit the persistent X-ray emission. We define $\chi^2 = \sum_{i=1}^{N}(F_{\nu,i} - F_{\nu,i})^2$, where $F_{\nu,i}$ is the theoretical value calculated from the IC radiation in Equations (9) and (10), $F_{\nu,i}$ is the observed X-ray flux as presented in Table 1, and $N$ is the total number of data. We look for the minimum $\chi^2$ value, $\chi^2_{min}$, in the 2D space ($A$, $\beta_0$), then constrain the parameters $\beta_0$ and $A$ in the 2D space by requiring $\chi^2 < 2.0\chi^2_{min}$. The resulting parameter region is shown in red in Figure 2. We see that there is a correlation between the constrained $A$ and $\beta_0$ values. Actually by equating the IC flux at $\nu > \max(\nu_{a,m}, \nu_{a,c})$ (Equation (15)) and the observed X-ray flux we can derive the $A - \beta_0$ relation, $A_{38} \approx 0.018\beta_0^{-1} f_{rel}^{-1}$. Moreover, the upper limit on $\beta_0$ can be obtained by requiring $t_{cross} > \beta_0 \approx 0.06$.

The radio upper limits can further help to constrain parameters. Figure 3 shows the synchrotron spectrum at 197 days in comparison with radio limits from observations. By requiring the synchrotron flux (Equation (12)) to satisfy the upper limit $F_{\nu, syn} < 21 \mu Jy$ at 9 GHz at 197 days, we constrain the allowed region in the space ($A$, $\beta_0$) (Figure 2). Furthermore, by requiring the observed flux $F_{\nu} = F_{\nu, syn} \exp(-\tau_{UV}(\nu))$, with free–free absorption taken into account, to satisfy the observed limit, the allowed parameter region is larger, as shown in Figure 2. It is seen that there is no overlap between the region constrained by X-rays and the region constrained by synchrotron self-absorption alone in Figure 2. So it is important to note that strong free–free absorption of the wind is required to account for the radio upper limit in ASASSN-15lh.

Combining the constraints from X-ray and radio observations, the allowed parameter ranges are $A \gtrsim 10^{38}$ cm$^{-1}$ and $\beta_0 \lesssim 0.02$, shown in Figure 2 as the overlapping region between the region constrained by X-rays (red-oblique-lined) and the region constrained by radio (pink-shaded).

5. Conclusion and Discussion

We have investigated the persistent X-ray emission from the location of ASASSN-15lh, and found that it can be produced by the SN shock propagating in a dense wind ($\rho \propto R^{-2}$), where the shock-accelerated electrons emit the X-rays by upscattering the incoming UV photons from the SN photosphere. We also found that the non-detection in radio requires that the wind is dense enough so that free–free absorption of the wind is important. With observation data we can constrain that the wind density parameter is $A \gtrsim 10^{38}$ cm$^{-1}$ and that the SN shock’s initial velocity is $V_{sh} < 0.02c$. This $A$ value corresponds to a mass-loss rate from the stellar wind of $M \gtrsim 3 \times 10^{-5} M_\odot$ yr$^{-1}$, assuming a wind velocity of $v_w = 10^8$ cm s$^{-1}$. The constrained SN shock velocity is somewhat lower than the average among radio SNe, $V_{sh} \sim 0.07$ (e.g., Kamble et al. 2016, and references therein).

The upper limit to the shock velocity $V_{sh} \lesssim 0.02c$ leads to a constraint on the ejecta mass of $M_{ej} \sim 2 E_{56}/v_{sh}^2 \gtrsim 56(E_{56}/2 \times 10^{52}$ erg)$M_\odot$. This extremely large ejecta mass implies a massive progenitor star of ASASSN-15lh, consistent with a pair-instability SN (e.g., Woosley 2017; Woosley et al. 2007).

With the constraints $A_{38} \beta_0^{-2} \lesssim 0.018$ and $\beta_0 \lesssim 0.02$, we can calculate the shock energy (Equation (2)) at $t \sim 500$ days, $E \lesssim 2 \times 10^{49}$ erg, which is much smaller than the total radiation energy of ASASSN-15lh, $\sim 10^{52}$ erg, and the typical kinetic energy of normal SNe, $\sim 10^{51}$ erg. The shock radius at $t \sim 500$ days is $R = \beta_0 c t \lesssim 8 \times 10^{-3}$ pc, within which the CSM mass is about $M = 4\pi A_{56} \beta_0 c t \simeq 0.027 M_\odot$. This mass should be ejected by the wind of ASASSN-15lh’s progenitor within a time of $R/v_w \lesssim 8$ yr before the SN explosion. Note that this CSM mass is about three orders of magnitude lower.
than that derived by using the interaction model to interpret the UV emission (Chatzopoulos et al. 2016).

Recent observations of SN spectra within days of explosion have led to the discovery of narrow emission lines in the early spectra of various kinds of SNe, indicating a dense CSM immediately surrounding the progenitor stars. Gal-Yam et al. (2014) first reported the detection of strong emission lines in an SN Ib’s early spectrum, indicating a strong Wolf-Rayet-like wind with \( M \sim 10^{-2} \text{M}_\odot \text{yr}^{-1} \). More recently, Yaron et al. (2017) observed narrow emission lines from a regular type II SN within 10 hr after explosion, implying a dense wind of \( M \sim 3 \times 10^{-3} \text{M}_\odot \text{yr}^{-1} \) ejected years before explosion. The spectra obtained rapidly within five days of SN II explosion have lead to the detection of narrow emission lines in a significant fraction, 18%, of early spectra of SNe II (Khazov et al. 2016). These observations imply that dense winds may be common in core-collapse SNe. Our interpretation of X-ray emission from ASASSN-15lh may indicate that type I SLSNe are also surrounded immediately by a dense wind, ejected \sim 10 \text{yr} before the SLSN explosion.

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Appendix

Synchrotron Self-absorption Frequency

The radio band that is of interest here is in the frequency regime of \( \nu \gg \text{max}(\nu_e, \nu_m) \). The electrons responsible for the radio emission are, due to fast cooling, distributed as \( dn_e/d\gamma_e = C\gamma_e^{-(p+1)} \) at \( \gamma_e(\nu) \gg \text{max}(\gamma_e, \gamma_m) \), where \( p \) is the index of injected electrons. Using \( \int_{\gamma_m(\gamma_m)}^{\infty} (dn_e/d\gamma_e)d\gamma_e = 4n_{\text{rad}} \), we derive \( C \approx 4n_{\text{rad}} \gamma_m^{p+1}n \). The absorption coefficient at \( \nu \) is given by (Rybicki & Lightman 1979)

\[
\alpha_\nu = \frac{P + 3}{8\pi m_e \nu^2} \int_{\gamma_{\text{obs}}} \frac{P(\gamma_e, \nu)C\gamma_e^{p-2}}{d\gamma_e},
\]

where \( P(\gamma_e, \nu) = P_m(\nu/\nu_m(\gamma_e))^{1/3} \) is the specific synchrotron power for an electron with \( \gamma_e, \nu_m = 3\gamma_e^2eB/(4\pi m_e c) \), and

\[
\gamma_{\text{obs}} = \left(4\pi m_e c \nu/3eB\right)^{1/2}.
\]

Thus we further derive

\[
\alpha_\nu = \frac{\sqrt{5} e^3}{8\pi m_e c^2} \left(\frac{3e}{4\pi m_e c}\right)^{-1/3} \frac{\nu + 3}{\nu + \frac{3}{5}} \frac{C B^2}{2 Y_{\nu}^{-5/3}} \gamma_{\text{obs}}^{-5/3}, \quad (A2)
\]

\[
= 5.32 \times 10^{33} \text{cm}^{-1} f_{\text{rad}} t_d \left(\frac{\nu + 3}{\nu + \frac{3}{5}}\right) \varepsilon_{B, -1}^2 \varepsilon_{\nu, -1}^{-5/3}, \quad (A3)
\]

where in the second equation we have plugged in the expressions for \( C, B \), and \( \gamma_{\text{obs}} \). The coefficient is calculated for \( p = 3 \). By setting the optical depth \( \tau \approx \alpha_\nu R/10 = 1 \), we obtain the absorption frequency

\[
\nu_d \approx 343 \text{ GHz} t_d \left(\frac{\nu + 3}{\nu + \frac{3}{5}}\right) \varepsilon_{B, -1}^2 \varepsilon_{\nu, -1}^{-5/3}. \quad (A4)
\]

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