

## SHELL-SHOCKED DIFFUSION MODEL FOR THE LIGHT CURVE OF SN 2006gy

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### ABSTRACT

We explore a simple model for the high luminosity of SN 2006gy involving photon diffusion of shock-deposited thermal energy. The distinguishing property of the model is that the large “stellar” radius of  $\sim 160$  AU required to prevent adiabatic losses is not the true stellar radius, but rather, it is the radius of an opaque, unbound circumstellar envelope, created when  $\sim 10 M_{\odot}$  was ejected in the decade before the supernova in an eruption analogous to that of  $\eta$  Carinae. The supernova light is produced primarily by diffusion of thermal energy following the passage of the blast wave through this shell. This model differs from traditional models of supernova debris interacting with an external circumstellar medium (CSM) in that here the shell is optically thick and the escape of radiation is delayed. We show that any model attempting to account for SN 2006gy’s huge luminosity with radiation emitted by ongoing CSM interaction fails for the following basic reason: the CSM density required to achieve the observed luminosity makes the same circumstellar envelope opaque ( $\tau \gtrsim 300$ ), forcing a thermal diffusion solution. In our model, the weaker CSM interaction giving rise to SN 2006gy’s characteristic Type II<sub>n</sub> spectrum and soft X-rays is not linked to the power source of the visual continuum; instead, it arises *after* the blast wave breaks free from the opaque shell into the surrounding wind. While a simple diffusion model can explain the gross properties of the early light curve of SN 2006gy, it predicts that the light curve must plummet rapidly at late times, unless an additional power source is present.

*Subject headings:* circumstellar matter — stars: evolution — supernovae: individual (SN 2006gy)

### 1. INTRODUCTION

The recent extremely luminous supernova (SN) 2006gy has challenged our understanding of the deaths of massive stars and may represent a new class of explosions. It was discovered by Quimby (2006) and was subsequently studied in detail by Ofek et al. (2007) and Smith et al. (2007). It is a Type II<sub>n</sub> event, with strong narrow lines of H in its spectrum, although the details of its light curve and spectrum are unlike most other members of this class (e.g., Filippenko 1997). Its enormous total radiated energy of  $>10^{51}$  ergs, the late ( $\sim 70$  days) peak of the light curve, and the observed constant expansion speed of  $v_{\text{exp}} \approx 4000$  km s<sup>-1</sup> (Smith et al. 2007) place important constraints on the model. SN 2006gy exploded in the host galaxy NGC 1260, which is a peculiar S0/Sa galaxy with ongoing star formation (see Smith et al. 2007 and Ofek et al. 2007).

The optical displays of all Type Ia SNe and most Type II SNe are believed to be dominated by the radioactive decay sequence  $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ . If that is also the case for SN 2006gy, then a mass  $M(^{56}\text{Ni}) \approx 10 M_{\odot}$  is required to produce the observed luminosity (Smith et al. 2007).

Not surprisingly, SN 2006gy has prompted varying suggestions to account for its extreme energy budget. Ofek et al. (2007) proposed a SN Ia exploding in a dense H-rich circumstellar medium (CSM), where continual interaction with an external CSM was the power source for the luminosity. They suggested that the dense CSM was probably the result of binary star common envelope ejection, and that the extreme energy budget may need to draw on a super-Chandrasekhar Type Ia explosion or perhaps a massive star explosion. Smith et al. (2007) argued that many different spectral properties of SN 2006gy and its CSM were incompatible with a Type Ia explosion but were entirely consistent with the known properties of some very massive stars. To account for the luminosity with

CSM interaction, Smith et al. (2007) proposed that the star suffered a tremendous explosive but nonterminal mass-loss event in the decade preceding the SN, analogous to the 19th century eruption of  $\eta$  Carinae. Woosley et al. (2007) proposed a similar model, in which the  $\eta$  Car–like explosion in the decade preceding the SN could have been triggered by the pulsational pair instability (which is different from a genuine pair-instability SN) in a star with an initial mass of  $110 M_{\odot}$ .

Interaction with an external CSM can, in principle, generate high luminosity as seen in other Type II<sub>n</sub> SNe (e.g., Chugai et al. 2004). However, Smith et al. (2007) argued that this mechanism is difficult to reconcile with the relatively low progenitor mass-loss rate inferred from the weak X-rays detected by *Chandra* and the narrow H $\alpha$  emission in SN 2006gy’s spectrum. In other words, signs of CSM interaction are seen in SN 2006gy, but that interaction appears far too weak to power the visual continuum. Even more troubling, the CSM interaction hypothesis cannot account for why the blast wave apparently did not decelerate while it was drained of more than  $10^{51}$  ergs (Smith et al. 2007). These inconsistencies, combined with the slow rise, low expansion speed, and high luminosity of SN 2006gy, led Smith et al. (2007) to appeal to the alternative of a pair-instability SN (Barkat et al. 1967; Rakavy & Shaviv 1967; Bond et al. 1984; Heger & Woosley 2002) where the core of the star is obliterated and the light is powered by radioactive decay of  $\sim 10 M_{\odot}$  of  $^{56}\text{Ni}$ . As we discuss below, however, it may be possible to account for the luminosity of SN 2006gy without placing such extreme demands on SN nucleosynthesis.

The most pressing question about SN 2006gy boils down to this: Do we *need* a pair-instability SN to provide a consistent explanation for its extremely high luminosity and its spectral properties? The pair-instability hypothesis requires the introduction of an exotic phenomenon; while the idea has been around for decades, it has never been observed and is only expected to have occurred in the early universe (e.g., Heger & Woosley 2002). Published models of the light curves from pair-

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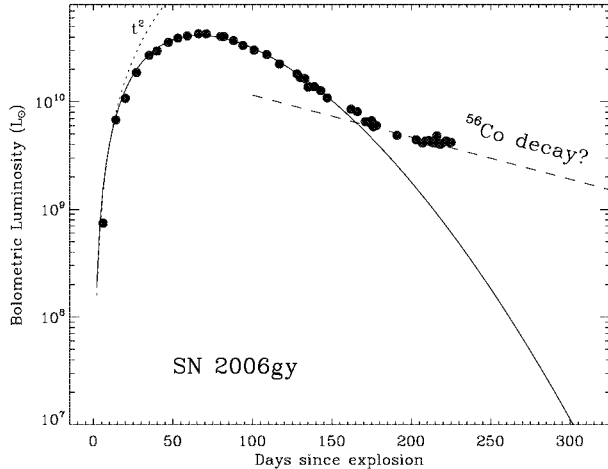


FIG. 1.—Light curve of SN 2006gy from Smith et al. (2007) converted to solar luminosities from  $M_R$ , assuming a zero bolometric correction. The solid curve shows a simple light curve, for a model of thermal diffusion from an extended stellar envelope (see text). The dashed line shows the hypothetical  $^{56}\text{Co}$  decay luminosity expected for  $8 M_\odot$  of nickel.

instability SNe do indeed predict high luminosities, slow rise times, long durations, and slow expansion speeds (e.g., Scannapieco et al. 2005) qualitatively similar to SN 2006gy. The light curve shape depends on the assumed mass of the envelope, and, so far, most studies have been conducted for zero-metallicity stars with no mass loss. Further work is in progress, with various assumptions about the mass of the envelope (Nomoto et al. 2007; Kasen 2007; Young 2007). The progenitor of SN 2006gy is likely to have been a very massive star (Smith et al. 2007), but whether or not it was massive enough to suffer the pair instability remains an open question.

Here we describe how a simple photon diffusion model can account for the high luminosity and long duration of SN 2006gy. Because the explosions of core-collapse SNe typically deposit  $E_0 \approx 10^{51}$  ergs of energy in the SN envelope, an exceptional mass of  $^{56}\text{Ni}$  is not necessarily required for SN 2006gy if an efficient mechanism could convert the energy of the initial SN blast into emergent light. In SNe from compact progenitors, the light from the blast wave itself normally falls short by orders of magnitude. The trapped internal radiation will cool by virtue of adiabatic expansion, and its energy will consequently be transferred to the kinetic energy of the expanding debris. The fraction of the blast energy emerging as radiation will be roughly  $R_0/R_{\text{max}}$ , where  $R_0$  is the initial radius of the progenitor and  $R_{\text{max}}$  is the radius of the SN photosphere at peak light.  $R_0$  ranges from  $\sim 10^{-2}$  AU for the Wolf-Rayet progenitors of SNe Ib/c to  $\sim 1$  AU for the red supergiant progenitors of SNe II, whereas, typically,  $R_{\text{max}} \approx 100$  AU.

Falk & Arnett (1973, 1977) showed that a SN from a progenitor having a very extended envelope could produce a light curve with a long timescale and high luminosity, with very efficient conversion of blast wave energy into radiation. Below we consider this idea as a possible explanation for the light curve of SN2006gy. Although we argue that this mechanism may provide a plausible explanation for the early light curve, we caution that it *does not negate* the possibility that SN 2006gy is powered by some other mechanism at late times, such as  $^{56}\text{Co}$  decay or continued CSM interaction.

## 2. SHELL-SHOCKED MODEL

We have in mind a model in which the SN progenitor (having mass  $M_{\text{SN}}$  and radius  $\lesssim 1$  AU) is enshrouded by an opaque shell having mass  $M_{\text{shell}}$  and characteristic radius  $R_0 \approx 160$  AU. The SN blast imparts  $E_0 = 10^{51} E_{51}$  ergs of kinetic energy. When the SN debris strike the shell, roughly  $E_0 M_{\text{shell}} / 2(M_{\text{SN}} + M_{\text{shell}})$  of the total SN energy will be converted into radiation by the resulting forward and reverse shocks. This radiation will be produced initially as X-rays but will quickly thermalize to an approximate Planck spectrum with substantially lower temperature, determined by the postshock thermal energy density. The radiation will escape with little adiabatic loss if the characteristic diffusion timescale,  $\tau_{\text{diff}}$ , is comparable to, or less than, the expansion timescale,  $\tau_{\text{exp}}$ , of the ejecta. If the opacity is dominated by electron scattering, then the characteristic time for photon diffusion is  $\tau_{\text{diff}} \approx (n\sigma_T R^2)/c$ , where  $n$  is the electron density,  $\sigma_T = 6.65 \times 10^{-25}$  cm<sup>2</sup> is the Thomson scattering cross section,  $R$  is the initial radius, and  $c$  is the speed of light. For a uniform density spherical envelope with solar composition, this simplifies to roughly  $\tau_{\text{diff}} \approx 23$  days  $(M/R_{15})$ , where  $M$  is the mass of the stellar envelope in  $M_\odot$  and  $R_{15}$  is its radius in units of  $10^{15}$  cm. The expansion timescale is just  $\tau_{\text{exp}} \approx (\Delta R/v_{\text{exp}})$  for constant expansion speed.

In a thermal diffusion model for SN 2006gy, we take the light-curve peak at 70 days (Smith et al. 2007) as representative of both  $\tau_{\text{diff}}$  and  $\tau_{\text{exp}}$ . From the observed constant expansion speed of  $v_{\text{exp}} \approx 4000$  km s<sup>-1</sup> (Smith et al. 2007), we have  $\Delta R \approx v_{\text{exp}} \tau_{\text{exp}} = 2.4 \times 10^{15}$  cm or about 160 AU. Thus, for  $\tau_{\text{diff}} = \tau_{\text{exp}}$ , the mass of ejecta through which the radiation must travel is  $\sim 10 M_\odot$ .

The visual light curve of SN 2006gy is unlike any other SN II<sub>n</sub> observed to date. It is very broad, rounded, and smooth (Fig. 1; Smith et al. 2007). It looks like the light curve of SN 1987A multiplied by a factor of  $\sim 250$ . Can this shape be explained by the photon diffusion model?

In generating a simple analytic light curve, we borrow directly from the early work of Falk & Arnett (1973, 1977), who studied this physical situation. In general, the peak due to photon diffusion becomes more luminous, more stretched-out in time, and smoother with progressively larger initial radii. Following the scaling arguments above, we assume a constant density envelope of  $10 M_\odot$  and initial radius  $R = 160$  AU, with  $\tau_{\text{diff}} = \tau_{\text{exp}} = 70$  days.

The SN will appear suddenly at  $t = t_0$ , when the blast wave reaches the surface of the shell, delayed by a few weeks after the actual explosion occurs because during that time the blast wave was expanding through the opaque shell. The initial rise is basically that of a constant-velocity-expanding blackbody, so that  $L \propto t^2$  at early times (Fig. 1). It levels off near maximum as the photosphere recedes through the cooling ejecta, where we have adopted expressions from equations (40) and (44) of Arnett (1982). For a reasonable emitting photosphere temperature of  $T_{\text{eff}} = 10^4$  K, the radius required at the light-curve peak on day 70 to account for the luminosity of  $L = 50 \times 10^9 L_\odot$  is  $R_{\text{max}} = 320$  AU. Working backward with a constant expansion speed of  $4000$  km s<sup>-1</sup> gives an initial radius of 160 AU at  $t_0$ . This agrees with our derived value for  $R_0$  above.

The decline in luminosity following the peak at day 70 is determined by thermal diffusion. The shape of the light curve depends on the adopted values of  $\tau_{\text{diff}}$  and  $\tau_{\text{exp}}$ . Arnett (1996) provides a highly simplified model in which the SN light is due to diffusion of internal radiation through a homogeneous

expanding sphere. In this case, the light-curve decline is expressed as

$$L = L_{\max} e^{-((\tau_{\text{exp}} t + t^2/2)/\tau_{\text{exp}} \tau_{\text{diff}})}, \quad (1)$$

where  $t$  is the time in days after  $t_0$ . Adopting  $\tau_{\text{diff}} = \tau_{\text{exp}} = 70$  days gives the decline rate shown in Figure 1, providing a satisfactory fit to light curve of SN 2006gy until about day 160. With a faster expansion speed and lower envelope mass, and hence smaller values for both  $\tau_{\text{exp}}$  and  $\tau_{\text{diff}}$ , the light curve would evolve more rapidly. Recently, Quimby et al. (2007) advocated just such a model for SN 2005ap, which had an extremely high peak luminosity exceeding that of SN 2006gy, but faded much faster.

The agreement of the early light curve of SN 2006gy with our simple analytic light curve in Figure 1 is surely an oversimplification of the actual situation. The density profile resulting from the impact of the SN debris with an opaque shell will not be a homogeneous sphere, and the internal impact may continue over a timescale comparable to or greater than  $\tau_{\text{diff}}$ .

The total radiated energy of the thermal diffusion model in Figure 1 is  $E_{\text{rad}} = 1.4 \times 10^{51}$  ergs, and the kinetic energy for  $\sim 10 M_{\odot}$  expanding at  $4000 \text{ km s}^{-1}$  is  $E_{\text{kin}} = 1.6 \times 10^{51}$  ergs. It is mildly comforting to find that these two are nearly equal, because that is about the highest efficiency that we can expect. It is also roughly the efficiency we expect from  $R_0/R_{\max}$ , as noted earlier. However, this is likely an underestimate of the kinetic energy of the SN, because it is the mass of the accelerated pre-SN envelope (see below) and does not include the mass of the stellar ejecta themselves, which may be comparable. Thus, the *minimum* total energy involved in SN 2006gy may be  $\geq 3 \times 10^{51}$  ergs, which, in any case, requires a highly energetic explosion.

### 3. CAN THE RADIUS BE THAT BIG?

The requirements of the shell-shocked model as an explanation for the early light curve of SN 2006gy are roughly the following: (1) the initial radius of the “star” at shock breakout must have been roughly 160 AU; (2) the radius of the photosphere at peak  $\sim 70$  days after that must have been about twice as large, or  $\sim 320$  AU; (3) the mass of the extended envelope needs to have been about  $10 M_{\odot}$ .

Of course, it is nonsense to invoke a progenitor star with an actual radius of 160 AU, because even the most extreme, tenuously bound red supergiants have radii 20 times less (e.g., VY CMa; Smith et al. 2001). So the essential question then is *how could the progenitor star have had such a huge initial radius?*

The most likely answer is that it was not the star’s true hydrostatic radius but rather, the photospheric radius of an opaque circumstellar envelope. Smith et al. (2007) suggested that the progenitor of SN 2006gy may have suffered an explosive mass-loss event in the decade before the SN. This would have been analogous to events observed in very massive progenitor stars like  $\eta$  Carinae, which ejected  $10\text{--}15 M_{\odot}$  in about a decade (Smith & Owocki 2006; Smith et al. 2003). A shell of that mass is sufficient to convert  $10^{51}$  ergs into light. High-resolution spectra of SN 2006gy suggest that the expansion speed for pre-SN mass loss was of order  $200 \text{ km s}^{-1}$  (Smith et al. 2007). A mass of  $10 M_{\odot}$  ejected at those speeds would require  $\sim 4 \times 10^{48}$  ergs, a substantial energy release but still much less than that of a SN.

In our shell-shocked model, the luminosity in the main emission peak of SN 2006gy comes from thermal diffusion of shock

energy deposited into an optically thick  $\sim 10 M_{\odot}$  extended circumstellar envelope. Thus, the mass inferred from the diffusion timescale is the envelope mass, not the stellar mass.

This brings up a critical distinction between our shell-shocked diffusion model and previous CSM-interaction models for Type II<sub>n</sub> SNe. In an optically thin interaction model (see Chevalier & Fransson 1994), such as that invoked to explain SN 1994W by Chugai et al. (2004), a shock plows into a dense but optically thin CSM. Radiation emitted directly from the swept-up shell of post-shock gas accounts for the continuum luminosity of the SN, which can be considerably greater than that of normal SNe II. For SN 2006gy, Ofek et al. (2007) suggested a model where a Type Ia explosion expands into a dense H-rich CSM, and the continuous conversion of kinetic energy into radiation powers the visual luminosity; this model is similar to those proposed for SN 2002ic and 2005gj by Hamuy et al. (2003) and Aldering et al. (2006), respectively.

This type of CSM-interaction model cannot account for SN 2006gy because *the extremely high CSM density required to power the radiated luminosity will also cause that same circumstellar envelope to be very opaque*. It is clear that a circumstellar mass of order  $10 M_{\odot}$  is required to reprocess  $10^{51}$  ergs of kinetic energy into light (Smith et al. 2007; Ofek et al. 2007). If this much mass is distributed inside a sphere with a radius corresponding to the characteristic expansion radius of the SN ( $R = 160$  AU), then the particle density is roughly  $n = 2 \times 10^{11} \text{ cm}^{-3}$  and the optical depth  $\tau = n\sigma R$  is greater than 300. This automatically forces the situation back into the thermal diffusion approximation described in this Letter, because the radiation generated by the CSM interaction cannot escape freely. For such a large optical depth, even relatively hard ( $\sim 10$  keV) X-rays will be thermalized. The only way to avert this situation would be if the preshock CSM is fully recombined so that the opacity is lower than for Thomson scattering, allowing the massive envelope to be optically thin at visual wavelengths. Given the high radiative luminosity involved, this is unlikely, especially since high-resolution spectra of the H $\alpha$  line (Smith et al. 2007) show that the pre-shock CSM is in fact ionized.

In principle, then, the circumstellar matter ejected by the star before the SN event is so dense and opaque that it mimics a gigantic red supergiant envelope with a radius of more than 100 AU, although it is not bound to the star and is probably expanding at  $200 \text{ km s}^{-1}$  (Smith et al. 2007). Thermal energy from the shock is deposited throughout this very large envelope, so that it can escape without suffering great adiabatic losses. This fact accounts for the exceptional luminosity of the SN when the shock breaks through the circumstellar envelope.

Of course, after the shock escapes the pseudo-photosphere of the opaque shell, it will propagate into the lower-density wind that must surely reside outside that photosphere. It is this interaction that likely gives rise to the characteristic Type II<sub>n</sub> spectrum of SN 2006gy, whereas the optical continuum is generated by the thermal radiation escaping from the shocked opaque envelope. This model may have the potential to explain many observed aspects of SN 2006gy that have been grounds to favor the pair-instability SN hypothesis over CSM interaction (Smith et al. 2007), such as the faint X-ray emission, the weak pre-shock H $\alpha$  emission, the lack of any deceleration in the shock, and the properties of the unusual broad P Cygni absorption feature in H $\alpha$ .

### 4. SUMMARY AND A PREDICTION

The diffusion model for SN 2006gy that we present here does not require any new physical processes beyond those that

account for core-collapse SNe. The only new ingredient is the hypothesis that the SN progenitor must have ejected an opaque shell having  $\sim 10 M_{\odot}$  extending to  $\sim 160$  AU shortly before it exploded. According to our model, the light curve of SN 2006gy observed up to about day 170 comes entirely from energy deposited by the initial blast and does not require any source of radioactive energy or ongoing CSM interaction.

However, this internal energy source cannot last. As the shocked shell continues to expand, the radiative diffusion time becomes shorter than the time since explosion, after which the light curve will faithfully track the energy deposition rate. Most of the kinetic energy of the SN must reside in debris having velocity  $\geq 4000$  km s $^{-1}$ , and thermal energy deposition from the impact of this debris with the expanding shell must terminate in  $\leq 1$  yr. After that, there are only two other obvious sources of energy deposition to account for the light curve.

The first source is the decay of  $^{56}\text{Co}$ , which would produce an exponential tail to the light curve with luminosity  $L \approx 1.4 \times 10^{43} M(^{56}\text{Ni}) \exp(t/113.6d)$  ergs s $^{-1}$ , where  $M(^{56}\text{Ni})$  is the mass of newly synthesized  $^{56}\text{Ni}$  produced by the SN. If this is the explanation for the excess luminosity above the diffusion model after day 170, then about  $8 M_{\odot}$  of  $^{56}\text{Ni}$  would be required, indicated by the dashed line in Figure 1. On the other hand, failure to detect a continued exponential tail in the visual

light curve at late times does not necessarily give an upper limit to the  $M(^{56}\text{Ni})$  produced in SN 2006gy. The bolometric flux may shift to near-infrared wavelengths as ejecta cool, and it is quite possible that dust will form in the shocked shell, reprocessing the luminosity into far-infrared radiation. This cooling may also cause changes in the bolometric correction as the SN evolves with time, and may play a role in the tail after day  $\sim 160$  seen in Figure 1.

A second source could be continued shock interaction with the transparent CSM external to the opaque shell. We see clear signs of that interaction in emission lines observed in the optical spectrum and in the faint X-ray emission (Smith et al. 2007). CSM interaction could produce a lower-luminosity tail to the light curve of SN 2006gy as long as the CSM density remains high.

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