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SELF-SHIELDING OF SOFT X-RAYS IN TYPE Ia SUPERNOVA PROGENITORS

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ABSTRACT

There are insufficient super-soft (∼0.1 keV) X-ray sources in either spiral or elliptical galaxies to account for the rate of explosion of Type Ia supernovae (SNe Ia) in either the single-degenerate or the double-degenerate scenarios. We quantify the amount of circumstellar matter that would be required to suppress the soft X-ray flux by yielding a column density in excess of 10^{23} cm^{-2}. We summarize evidence that appropriate quantities of matter are extant in SNe Ia and in recurrent novae that may be supernova precursors. The obscuring matter is likely to have a large, but not complete, covering factor and to be substantially non-spherically symmetric. Assuming that much of the absorbed X-ray flux is re-radiated as blackbody radiation in the UV, we estimate that $\lesssim$100 sources might be detectable in the *Galaxy Evolution Explorer* All-sky Survey.

Key words: binaries: general – dust, extinction – novae, cataclysmic variables – supernovae: general – white dwarfs – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

The first suggestion that Type Ia supernovae (SNe Ia) may arise through mass transfer from a non-degenerate star onto a white dwarf may have been by Wheeler & Hansen (1971). This suggestion of a single-degenerate (SD) model was quantified by Whelan & Iben (1973) and has been pursued by many since. An alternative model is the merger of two degenerate stars, the double-degenerate (DD) model (Iben & Tutukov 1984; Webbink 1984). Both of these models are constrained by the paucity of bright, soft, X-ray sources (Di Stefano 2010a, 2010b). In the SD model, an associated constraint is the strong expectation that the mass transfer rate must be sufficiently large that accretion leads to non-degenerate shell burning on the surface of the white dwarf in order to avoid classical nova explosions that eject the accreted matter and, probably, some of the white dwarf material as well (see, e.g., Nomoto 1982; Iben 1982; Fujimoto 1982; Shen & Bildsten 2008, and references therein). This constraint requires the progenitor to be bright and hot, qualities exhibited by the super-soft X-ray sources (SSS; van den Heuvel et al. 1992; Kahabka & van den Heuvel 1997). The problem is that there are not enough SSS seen in either spiral or elliptical galaxies to account for the rate of production of SNe Ia by about a factor of the order of 100 (Di Stefano 2010a). Similar constraints arise for the DD model. Binary synthesis models require that the progenitor systems go through a phase of rapid accretion onto the primary white dwarf prior to the common envelope phase that reveals the second white dwarf. One way to avoid these constraints is to shroud the progenitor systems in sufficient material that soft X-rays may be produced, but absorbed and transmuted into other wavelengths rather than radiated directly. One possibility is the production of winds from the surface of the accreting white dwarf (Hachisu et al. 1996, 2010; Kato & Hachisu 1999). A constraint on this particular suggestion is the lack of evidence for such a wind in the remnant of SN Ia 1572 (Badenes et al. 2007).

Here we explore the general constraints on circumstellar matter (CSM) that might produce sufficient absorption to suppress super-soft (∼0.1 keV) X-rays, describe two lines of evidence that such circumstellar absorption exists, and discuss the bands in which such absorbed soft flux might be re-emitted and the likelihood that such systems could be observed. The bulk of this paper was written in 2012 January, independent of the recent posting by Nielsen et al. (2012), who make some of the same points from a different perspective.

2. SOFT X-RAY COLUMN DENSITIES

Observations of SSS and models of rapidly accreting, shell-burning white dwarfs suggest that the flux emerges from the surface of the accreting white dwarf with thermal spectra at energies of about 0.1 keV (Kahabka & van den Heuvel 1997). Very little matter is required to absorb this flux. Figure 1 shows the emergent spectrum of a thermal blackbody with an effective temperature of 0.1 keV subject to absorption by a range of column depths of neutral material of solar metallicity. This figure shows that for such a characteristic thermal emission, a column depth of solar abundance matter of 10^{23} cm^{-2} would reduce the flux density at about 1 keV by a factor of about 100. Detection in X-rays is based on the integrated flux over a standard bandpass. Figure 2 shows the effects of absorption on this integrated flux. The integrated flux is down by a factor of 100 around a column of 10^{22} cm^{-2}. For a column density of 10^{23} cm^{-2}, the integrated flux is reduced by a factor of roughly 10^6. Such column depths would, in principle, solve the problem of the paucity of SSS. Any higher column depth effectively would totally block such soft flux.

Any CSM must be rather sparse and diluted in order not to perturb the early light curve of SNe Ia on the rise to maximum (Kasen 2010; Hayden et al. 2010). If there is CSM in an SD configuration, then there is some a priori expectation that it resides at a distance representative of the size of the orbit, for instance, in an accretion disk or in the base of a wind from either the white dwarf or the secondary star. In a typical mass-transferring situation, that would be an orbital period of hours to days or a radius of order 10^{11}–10^{12} cm. To have a column depth of $\sigma = 10^{23}$ cm^{-2} at this radius requires a particle density of $n \sim 10^{11} \sigma_{23} R_{12}^{-1}$ cm^{-3} or a mass density of $\rho \sim 1.6 \times 10^{-13} \sigma_{23} R_{12}^{-1}$ g cm^{-3}, where σ_{23} is the column

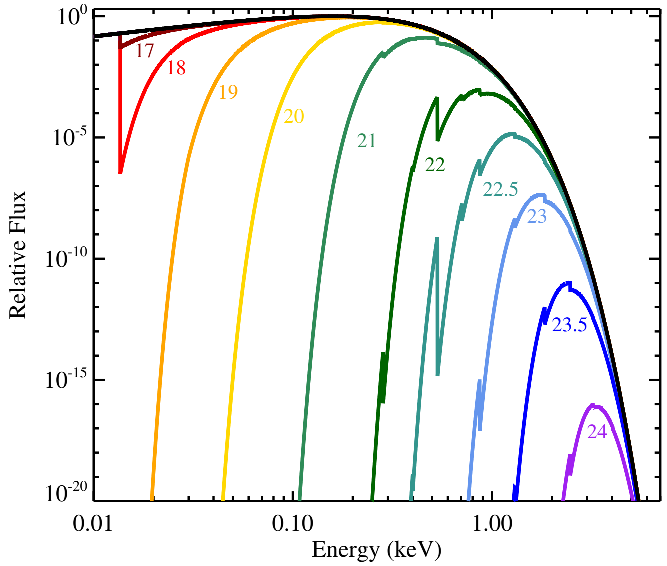

Figure 1. Spectra of a thermal blackbody of temperature 0.1 keV corresponding to a super-soft X-ray source subject to absorption by varying column depths of neutral matter with solar abundance.

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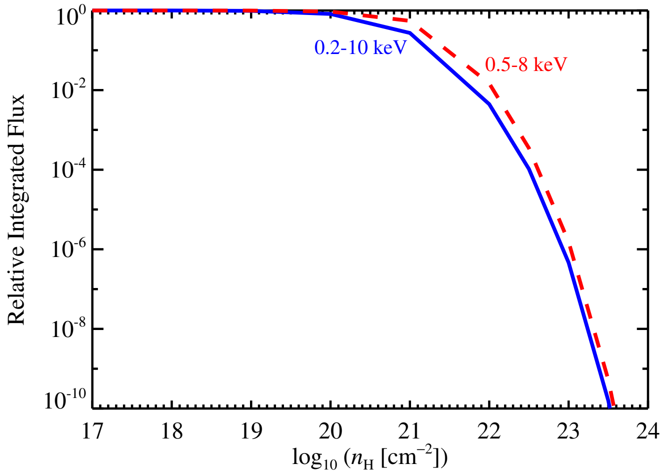

Figure 2. Absorbed integrated flux of $kT = 0.1$ keV blackbody relative to the unabsorbed flux as a function of column density. The blue curve shows the 0.2–10 keV band, commonly used for *XMM* observations, and the red curve shows the 0.5–8 keV band, commonly used for *Chandra* observations.

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depth in units of 10^{23} cm^{-2} and R_n here and following is the characteristic radius of a distribution of absorbing matter in units of 10^n cm. A density of this order in a volume of this radius implies a mass of

$$m_{\rm csm} \sim 3 \times 10^{-10} \sigma_{23}\, R_{12}^2\, M_\odot. \qquad (1)$$

Minor amounts of matter could easily obscure an SSS. Both mass transfer and possible shell burning on the surfaces of white dwarfs are likely to be messy events. We next explore the degree to which this "mess" is likely to produce a CSM that obscures any soft X-rays. The possibility that CSM matter is distributed more broadly by recurrent nova outbursts is discussed in Section 4.

3. ABSORPTION IN SNe Ia

While there are indications of variable NaD circumstellar absorption in some normal SNe Ia (Patat et al. 2007; Simon et al. 2009; Blondin et al. 2009; Dilday et al. 2012) this behavior is rare. Some SN Ia-like events show obvious evidence for substantial circumstellar hydrogen (SN 2001ic; Hamuy et al. 2003), but again these are rare, peculiar events. Tycho's supernova remnant (SNR) shows no evidence of a progenitor wind (Badenes et al. 2007), but Kepler's may (Chiotellis et al. 2012). A hint that CSM may be common is given by the ubiquity of blueshifted NaD in many SNe Ia (Sternberg et al. 2011). Another more common hint of CSM may be revealed in the high-velocity Ca features routinely seen in early spectra of SNe Ia (Wang et al. 2003; Mazzali et al. 2005). These features are not seen in every SN Ia, but may appear in order of 80% (G. H. Marion, private communication). There is no direct evidence that these high-velocity features are associated with CSM, but a plausible model has been presented by Gerardy et al. (2004) in which CSM is impacted by the ejecta of a delayed-detonation model of an SN Ia. The collision leads to the formation of a shell at the contact discontinuity. The resulting shell is dense enough to reveal strong absorption in the lines of a solar abundance of calcium in the form of the Ca II IR triplet where the high-velocity feature is most often observed. The models suggest that it would still be very difficult to directly detect the hydrogen (or helium) substrate. To leave the dense shell at the observed velocity, it must have a mass of about 0.02 $M_\odot$. Gerardy et al. point out that this CSM must be at a radius $\ll 10^{15}$ cm, the typical radius for the photosphere of a supernova at maximum light, so that the energy of the collision is radiated quickly and does not adversely affect the early rise of the light curve.

If we take this model at face value, we can estimate the implied column depth to soft X-rays. Taking the mass to be $10^{31}\, M_{31}$ g at a radius of less than $10^{14}\, R_{14}$ cm will yield a mass density of about $2.4 \times 10^{-12}\, M_{31}\, R_{14}^{-3}$ g cm^{-3} or a number density of about $1.4 \times 10^{12}\, M_{31}\, R_{14}^{-3}$ cm^{-3}. At this radius, the column density would be

$$\sigma \sim 1.4 \times 10^{26}\, M_{31}\, R_{14}^{-2}\ {\rm cm}^{-2}, \qquad (2)$$

a huge column depth. If the putative dense shell were at smaller radius, the column density would be even larger. Such a shell of absorbing material would be ample to absorb the soft X-rays and render an underlying source unobservable to either *Chandra* or *XMM*.

The high-velocity feature is strongly polarized (Wang et al. 2003; Wang & Wheeler 2008; Patat et al. 2009) and hence asymmetric. Whatever this feature is, it shows a different perspective from different aspect angles. The fact that a strong majority of SNe Ia reveal this feature means that its covering factor is large. Since some SNe Ia do not show this feature, the covering factor is likely not to be 100%. Perhaps 10%–20% of the sky is free of sufficient material to yield the appropriate absorption. This large percentage would be too large for the observed suppression of SSS sources, but as we have illustrated, very little mass is required for the latter. X-ray absorbing mass may "fill the hole" that is implied by the lack of complete coverage of the polarized high-velocity feature without yielding substantial Ca IR triplet absorption on that particular line of sight.

4. RECURRENT NOVAE

Recurrent novae have long been discussed as possible precursor systems for SNe Ia (Schaefer 2010 and references therein).

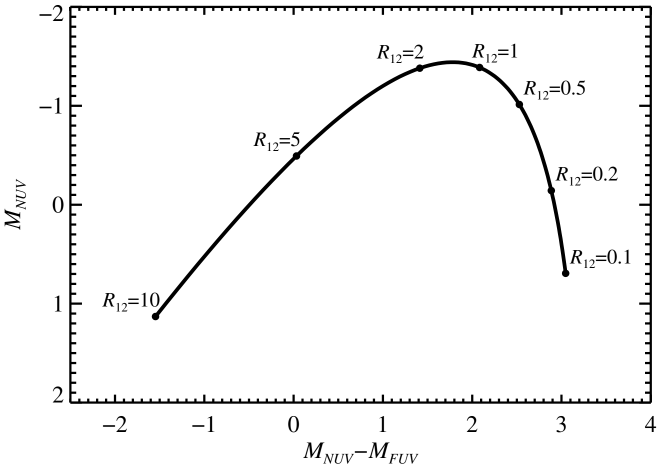

Figure 3. Color–magnitude diagram for FUV and NUV flux is given for blackbodies of specified radius and luminosity.

Their shell burning is sporadic and the masses of the white dwarf are generally thought to be large and growing. The recurrent nova eruption is sure to eject some matter into the circumstellar environment. Patat et al. (2011; see also Patat 2011; Dilday et al. 2012) have obtained high-resolution spectroscopy of the recurrent nova RS Oph before, during, and after its 2006 outburst. They deduce that the eruptions create complex structures within the material lost by the donor star. There are signs of the interaction of matter ejected in the most recent outburst with matter ejected in the previous outburst in 1986. Kinematics put that interaction at a radius less than 4×10^{14} cm, within the volume of the photosphere of a supernova at maximum light. The evidence suggests that recurrent novae outbursts do not destroy the slow-moving shells produced in previous outbursts and that recurrent novae are able to produce long-lasting structures in their circumstellar environments. Patat et al. emphasize the similarity of the Na D absorption structure in RS Oph compared to a sample of SNe Ia. The mass involved in this CSM is not well constrained, but Patat et al. estimate masses of the order of $10^{-5}\,M_{\odot}$, presumed to arise in a wind from a red-giant companion. With this mass, we can estimate a column density of

$$\sigma \sim 3 \times 10^{23}\, R_{14}^{-2}\, \mathrm{cm}^{-2}. \qquad (3)$$

Even with large uncertainties, this is still a substantial column depth with the promise of severely obscuring any soft X-ray emission.

5. EMERGENT FLUX

If the soft X-ray flux generated by SN Ia progenitors is absorbed, it will appear at other wavelengths. One estimate of this process is to assume that the X-ray flux is thermalized and radiated as a blackbody at another appropriate temperature. The SSS have characteristic luminosities around the Eddington limit for a solar mass, $\sim 10^{38}$ erg s^{-1}. Let us assume for the sake of argument, that the soft X-rays are absorbed and re-emitted at a characteristic radius of $10^{12}\, R_{12}$ cm. The characteristic temperature of the re-emitted radiation is then about

$$T_{\rm eff} \sim 1.9 \times 10^{4} L_{38}^{1/4}\, R_{12}^{-1/2}\, \mathrm{K}. \qquad (4)$$

For this choice of parameters, the frequency at the peak of the blackbody distribution would be, by Wien's law, about

$$\lambda \sim 250\, L_{38}^{-1/4}\, R_{12}^{1/2}\, \mathrm{nm}. \qquad (5)$$

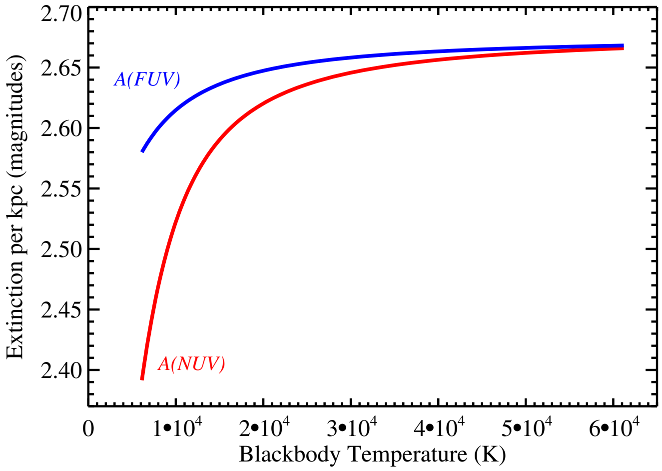

Figure 4. NUV and FUV extinction per kpc based on a blackbody spectral model as a function of the temperature of the blackbody.

(A color version of this figure is available in the online journal.)

With the approximation that $\lambda L_{\lambda} \sim L$ and using Equation (5) for the characteristic wavelength, we can write the unextincted flux density as

$$f_{\lambda} \sim \frac{L}{4\pi \lambda D^2}. \qquad (6)$$

With $D_{\rm pc}$ the distance to the source in parsecs, the flux density can be written as

$$f_{\lambda} \sim 3 \times 10^{-4}\, L_{38}^{5/4}\, R_{12}^{-1/2}\, D_{\rm pc}^{-2}\, \mathrm{erg\, s^{-1}\, \AA^{-1}\, cm^{-2}}. \qquad (7)$$

For typical radii $\sim 10^{12}$ cm, the re-radiated flux would be emitted in the UV and would itself be subject to extinction in the circumbinary material and the interstellar medium. As a simple illustration of one possibility, we assumed a fiducial luminosity of 10^{38} erg s^{-1} and that this luminosity was re-radiated from a perfect blackbody of various radii. These blackbody spectra were then passed through the *Galaxy Evolution Explorer* (*GALEX*) near-UV (NUV) and far-UV (FUV) responses. The emergent fluxes were converted to magnitudes according to the *GALEX* prescriptions.[3] A distance of 10 pc was assumed in order to compute absolute magnitudes. The results are shown in Figure 3. As one moves to large radii, the blackbody temperature drops, and most of the flux is well outside either *GALEX* bandpass where analogous limits to those we derive here would apply.

The re-radiated flux will be subject to circumbinary and interstellar absorption. Here, we ignore the former in order to estimate a lower limit to the UV extinction and hence an upper limit to the number of sources that might be detected in the UV. To compute these effects, the FUV and NUV magnitudes were calculated without any extinction and with the extinction law given by Cardelli et al. (1989). The absorption effects depend both on the shape of the spectrum in each band (i.e., the temperature of the re-radiated blackbody) and the amount of interstellar material that the light passes through (i.e., the distance to the source). We took the extinction in the optical to be 1 mag kpc^{-1}, and we calculated the absorption of all the models. The extinction does depend on temperature, as shown in Figure 4. We take as representative values $A(\mathrm{NUV}) = A(\mathrm{FUV}) = 2.65\, D_{\rm kpc}$, where $D_{\rm kpc}$ is the distance in kiloparsecs. We note that Rey et al. (2007) addressed the extinction at a single wavelength corresponding to the characteristic wavelength of

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[3] http://galexgi.gsfc.nasa.gov/docs/galex/FAQ/counts_background.html

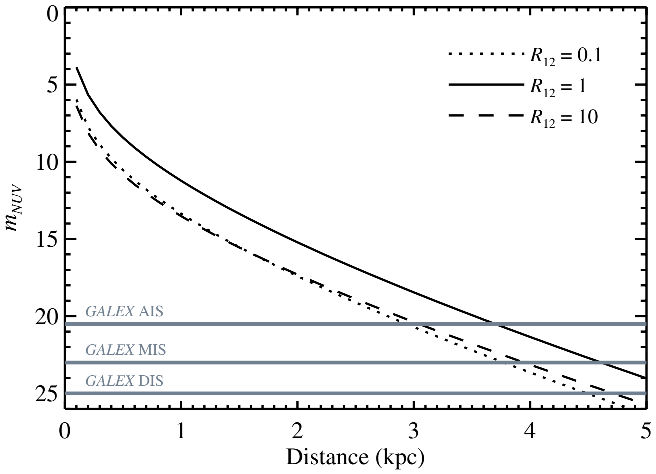

Figure 5. Apparent NUV magnitude ($m_{\rm NUV}$) is shown as a function of distance, taking extinction into account, for each fiducial luminosity and three values of R_{12}. Also shown are the limiting magnitudes for three large-area *GALEX* surveys: the All-sky Survey (AIS) covered an area of 40,000 deg^2; the Medium Imaging Survey (MIS) covered 1000 deg^2; and the Deep Imaging Survey (DIS) covered only 80 deg^2.

the NUV passband. Our procedure of integrating over the passband is somewhat more accurate and somewhat more conservative, yielding a slightly smaller extinction. The absolute magnitudes shown in Figure 3 can be readily translated to a particular distance using these A(NUV) and A(FUV) relations and a distance modulus.

We have taken both distance and A(NUV) into account in Figure 5, which shows the apparent NUV magnitude ($m_{\rm NUV}$) as a function of distance for the fiducial luminosity and three values of R_{12}. Also shown are the limiting magnitudes for three large-area *GALEX* surveys. The All-sky Survey (AIS) covered an area of 40,000 deg^2 and reached a limiting magnitude of 20.5. The Medium Imaging Survey (MIS) covered 1000 deg^2 and reached a limiting magnitude of 23. The Deep Imaging Survey (DIS) covered only 80 deg^2 and reached a limit of 25 mag.

For all but the lowest temperature blackbodies (those re-radiated at large radii), the re-radiated emission is brighter than the detection limits of the *GALEX* AIS. Such blackbody re-radiating sources should be detectable out to ∼3.7 kpc for $R_{12} = 1$ and to ∼3.0 kpc for $R_{12} = 0.1$ or 10. An area around the Sun of this radius represents about 10% of the area of the optical disk of the Galaxy ($\sim 10^9$ pc^2). Di Stefano (2010a) estimates that if the SD scenario provides the bulk of SNe Ia, the Galaxy should contain ∼1000 nuclear shell-burning white dwarfs that will explode within 10^5 years. If the soft X-ray flux from those sources is absorbed and re-emitted in the UV as we have assumed here, then there should be ∼100 bright UV sources within the limits of the *GALEX* AIS. The DIS goes much fainter and could, in principle, detect a source to 5 kpc, but examined a much smaller portion of the sky, so one would expect at most a single source to be detected. Searches for such bright UV sources would be of interest. If there remains circumbinary matter that can absorb UV, then the absorbed X-ray luminosity would come out in yet another bandpass. We leave to others to do a proper estimation of the re-radiated flux in more general and realistic situations (see, e.g., Ferland & Truran 1981).

6. CONCLUSIONS

Small amounts of CSM matter local to the progenitor binary system of SNe Ia could easily suppress X-ray emission from nuclear burning on the surface of an accreting white dwarf. This suggests that the paucity of SSS to account for the required rate of explosion of SNe Ia in either the SD or DD models is not beyond understanding in terms of local extinction.

Gaining some perspective on the role of SSS in the production of SNe Ia does not address all the issues associated with understanding the progenitors of SNe Ia. In the SD model, the mass transfer rate is required to be sufficiently high to avoid degenerate, unstable shell ignition, and explosion on the surface of the white dwarf. Published models that satisfy this constraint and also provide a reasonable number of progenitor systems, locally extincted or not, require the mass-transferring secondary star to be a moderately massive main-sequence star ($>1.16\ M_\odot$; Schaefer & Pagnotta 2012), a sub-giant or giant star. The recent advent of SN 2011fe, an apparently normal "plain vanilla" SN Ia, has provided new constraints on the progenitor systems. Nugent et al. (2011) argue that lack of light-curve contamination implies that the secondary star was not a red giant, and more likely to be a main-sequence star. Li et al. (2011) use archival images to put limits on the companion and rule out luminous red giants and almost all helium star models. Bloom et al. (2012) show that the exploding star was a white dwarf, as expected, and that the secondary star was likely to have had a radius less than 0.1 that of the Sun, excluding companion red-giant and main-sequence stars that fill their Roche lobes.

SNR 0509−67.5 in the LMC was established by scattered, time-delayed spectra to be an SN Ia of the SN 1991T spectral subclass that exploded about 400 years ago (Rest et al. 2008). Schaefer & Pagnotta examined deep *Hubble Space Telescope* images of this remnant to put even tighter limits on the progenitor of this explosion. They found that any secondary star must be dimmer than $M_V \sim 8.4$ mag, ruling out basically all published SD models, including those with companion main-sequence stars of greater than about 1 $M_\odot$, sub-giants, giants, and those involving the stripped cores of evolved stars. While one might adopt the dodge that this was a single event responsible for a somewhat peculiar and ill-understood sub-class of SNe Ia, and hence not typical of "plain vanilla" SNe Ia, these limits remain a very tight constraint on SD models. Either SD models must be rejected for this system, or some means must be found to impeach the current set of SD models, virtually all of which are based on one-dimensional, spherically symmetric, non-rotating, non-magnetic accretion that is undoubtedly incorrect, at least in detail. An attempt in this direction is presented by Wheeler (2012).

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