Supernova progenitor constraints from circumstellar interaction: Type Ia

By PETER LUNDQVIST
AND ROBERT J. CUMMING

Stockholm Observatory, S-133 36 Saltsjöbaden, Sweden
(e-mail peter@astro.su.se, robert@astro.su.se)

Searching for the presence of a circumstellar medium (CSM) is a direct observational way to discriminate between different types of progenitor systems for Type Ia supernovae (SNe Ia). We have modeled whether such gas may give rise to detectable emission, especially in Hα, and compare the models with observations of SN 1994D. We obtain $\dot{M} \lesssim 2.5 \times 10^{-5}$ $M_\odot$ yr^{-1} for a wind speed of 10 km s^{-1}. We find that X-ray observations in the range $5 - 10$ keV, e.g., with *AXAF*, provide the most useful limits on the mass loss, while high-resolution optical spectroscopy offers the only direct way of identifying circumstellar hydrogen.

1. Introduction

SNe Ia are thought to be exploding white dwarfs in binary systems. The most likely type of progenitor system (Branch et al. 1995; see also Iben & Tutukov 1984) is a C-O white dwarf accreting H/He-rich gas from a companion, either from its wind or through Roche lobe overflow. Coalescing pairs of C-O white dwarfs are also possible, while accreting sub-Chandrasekhar-mass white dwarfs are less likely (Branch et al. 1995). In the non-coalescing scenarios, circumstellar gas will be present. The composition and geometry of this depend on the type of progenitor system. If the CSM emits detectable radiation, or absorbs radiation from the supernova, this can be used to distinguish between types of progenitor system. For example, any circumstellar lines of hydrogen would have to come from gas lost by the companion, and the luminosity of these lines are therefore particularly sensitive to the type of system.

The interaction of the ejecta with the putative CSM can generate radio (Boffi & Branch 1995) and X-ray emission (Schlegel & Petre 1993). If dusty and asymmetric, the CSM may also result in polarization of the supernova light (Wang et al. 1996). None of these studies have resulted in a detection. A different approach was taken by us in Cumming et al. (1996; henceforth CLSPK96). We used a high-resolution optical spectrum of SN 1994D around Hα taken only 6.5 days after the explosion to search for circumstellar hydrogen. The observations were compared with detailed photoionization calculations to establish a limit on the mass loss from the progenitor system. In addition, we discussed the effect of asymmetry of the CSM, and compared the sensitivity of optical studies to those at other wavelengths. Here we expand this discussion. In particular, we check the sensitivity of our results to the adopted maximum velocity of the ejecta, and demonstrate that absorption of soft ($\lesssim 1-2$ keV) X-rays by the CSM must be taken into account in interpreting X-ray limits. Following from this we reassess the X-ray limit from SN 1992A reported by Schlegel & Petre (1993).

2. Circumstellar excitation and expected circumstellar emission

There are four sources of radiation which could excite the CSM of SN Ia (CLSPK96): the radiation accompanying the supernova shock breakout, γ-rays from the decay of

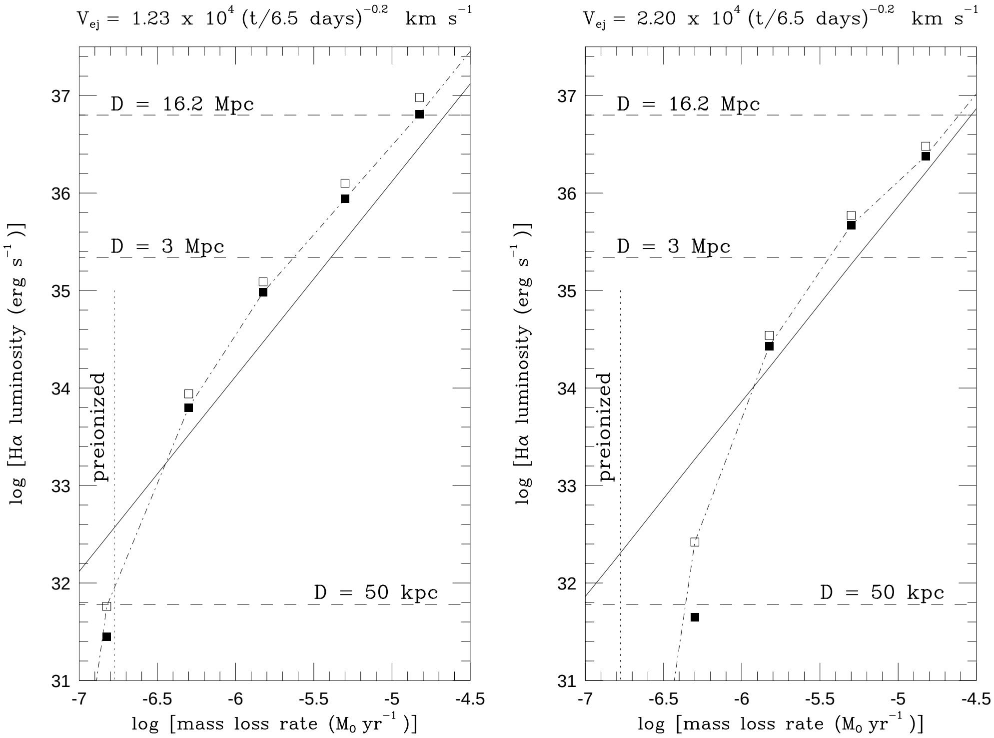


Figure 1. Luminosity of circumstellar Hα from a Type Ia supernova at 6.5 days after explosion, as a function of mass loss from the progenitor system, assuming a wind velocity of 10km s^{-1}. Squares show model calculations where the wind is ionized by the radiation from the region of circumstellar interaction. The solid lines show the corresponding luminosities for a fully ionized wind at 2×10^4 K. The maximum velocity of the ejecta is given at the top of each panel. Preionization by the progenitor white dwarf is only important for $\dot{M}/u_{10} \lesssim 2 \times 10^{-7}$ $M_\odot$ yr^{-1}. See text for details.

^{56}Ni, the radiation emitted by the progenitor prior to explosion (which can 'preionize' the CSM), and radiation from the interaction of the ejecta with the CSM itself. Of these, the first two are not important at all, while preionization is only observationally important for SN Ia in the Magellanic Clouds, or closer (CLSPK96). For more distant supernovae, the only important excitation mechanism is the radiation from the circumstellar interaction. In Figure 1, we present the calculated circumstellar Hα luminosity at 6.5 days as a function of mass loss from the progenitor system. We show results both for $V_{\rm ej} \approx 1.23 \times 10^9$ km s^{-1} and $V_{\rm ej} \approx 2.20 \times 10^9$ km s^{-1} at 6.5 days, where $V_{\rm ej}$ is the maximum velocity of the ejecta. For a wind with density falling off as $\rho \propto r^{-2}$, the interaction model of Chevalier (1982) predicts that the ejecta are slowed down at a rate $\propto t^{-1/(n-2)}$. Here n is the power law index for the density of the unshocked ejecta, $\rho_{\rm ej} \propto r^{-n}$. We use $n = 7$, which is a reasonable approximation to the commonly used W7 model of Nomoto, Yoki, & Thielemann (1984), resulting in $V_{\rm ej} \propto t^{-0.2}$. For the CSM we assume solar abundances.

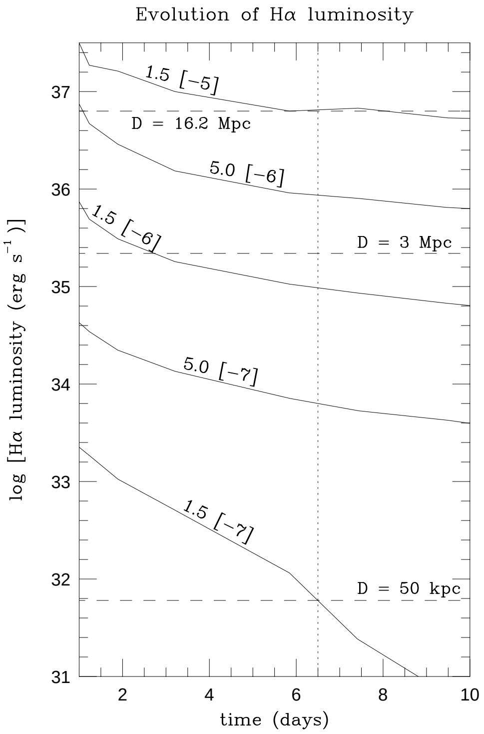
The ionizing radiation in the interaction model comes from the C/O-rich ejecta shocked by the reverse shock propagating (in mass coordinate) into the supernova. The temperature of this gas, $T_{\rm rev}$, at 6.5 days increases with the velocity of the ejecta, and is $\sim 1 \times 10^8$ K and $\sim 4 \times 10^8$ K for the two velocities shown in Figure 1. The spectrum of the ionizing radiation is therefore a free-free spectrum with $kT_{\rm rev} \sim 10$ keV and

$kT_{\rm rev} \sim 40$ keV, respectively. However, for low values of $\dot{M}$, electrons and ions in the shocked ejecta are not in energy equipartition, which affects the level and cutoff energy of the ionizing flux. Figure 1 shows the resulting Hα emission from the photoionized wind for two cases: full equipartition between electrons and ions, and an electron temperature which is a factor of 2 below the equipartition value. The dashed-dotted lines join the most likely models. A general feature of these models is that the circumstellar shock is preceded by an ionization precursor. The thickness of this photoionized region increases with $\dot{M}/u$ (CLSPK96), but decreases with $V_{\rm ej}$. The reason for the latter is mainly that the ratio of the dynamical time scale of the shock to the ionization time scale of the CSM decreases with increasing $V_{\rm ej}$. Using the Hα limit for SN 1994D (distance '16.2 Mpc' in Figure 1), and the fact that $V_{\rm ej}$ of the supernova at 6.5 days may have been as fast (Patat et al. 1996) as in the fastest model in Figure 1, we obtain $\dot{M}/u_{10} \lesssim 2.5 \times 10^{-5}~M_\odot~{\rm yr}^{-1}$. Here u_{10} is the wind speed in 10km s^{-1}. This limit is a factor ~ 1.7 higher than in CLSPK96, where we assumed somewhat slower ejecta, and close to the upper limit observed for mass loss rates in symbiotic systems. Observing SNe Ia in the Local Group (limit marked '3 Mpc' in Figure 1) for 10 000 s as early as 3 days after explosion, should take us down to a detection limit of $\dot{M}/u_{10} \sim 10^{-6}~M_\odot~{\rm yr}^{-1}$. Figure 2 demonstrates that the limit is rather sensitive to how soon after explosion the supernova is observed. Earlier than 3 days is probably observationally unrealistic.

3. Comparison with radio and X-ray limits

Radio limits have been presented for SN 1981B (Boffi & Branch 1995) and SN 1986G (Eck et al. 1995), using scaling arguments. In particular, for the close (~ 4 Mpc) SN 1986G, the range $10^{-7} - 3 \times 10^{-6}~M_\odot~{\rm yr}^{-1}$ was excluded. This limit is at the same sensitivity level as we can expect from early high-resolution optical observations (cf. §2). However, as we noted in CLSPK96, radio limits are subject to large systematic errors, because we do not know how efficiently the synchrotron radiation is generated. X-ray limits are potentially firmer and more sensitive than both radio and optical limits. Schlegel & Petre (1993) estimated $\dot{M} \lesssim (2-3)\times 10^{-6}~M_\odot~{\rm yr}^{-1}$ from *ROSAT* observations of SN 1992A (distance $\sim$17 Mpc) at $\sim$16 days after explosion. This is about an order of magnitude more sensitive than we can expect from Hα using the estimate in §2. However, Schlegel & Petre did not consider X-ray absorption in the CSM. In Figure 3 we show the photon energy below which the optical depth through the CSM is greater than unity (the cutoff energy, $\epsilon_{\rm cut}$) for the faster model in Figure 1. For the mass loss rates claimed to be excluded for SN 1992A, X-ray absorption below ~ 1 keV is severe. Schlegel & Petre (1993) observed in the range 0.2−2.4 keV, with a sensitivity peak around ~ 1 keV, so their limit on the mass loss rate was probably too optimistic. Furthermore, for $\dot{M}$ above $10^{-5}~M_\odot~{\rm yr}^{-1}$, the collapsed shocked ejecta probably block out all the flux in the *ROSAT* range (cf. SN 1993J at early times; Fransson, Lundqvist, & Chevalier 1996), unless the CSM is aspherical and the interaction region is viewed through the less dense part of the CSM. More reliable X-ray limits can be expected for photon energies in the range 5−10 keV.

Searches for circumstellar matter are beginning to provide interesting observational limits on the progenitor systems of SNe Ia. The most informative limits will come from X-ray telescopes like *AXAF*. High-resolution optical spectroscopy is less sensitive, but has the potential to provide information about velocities and abundances of the CSM. Radio observations are difficult to interpret. At all wavebands, observation as soon as possible after the explosion is highly desirable.



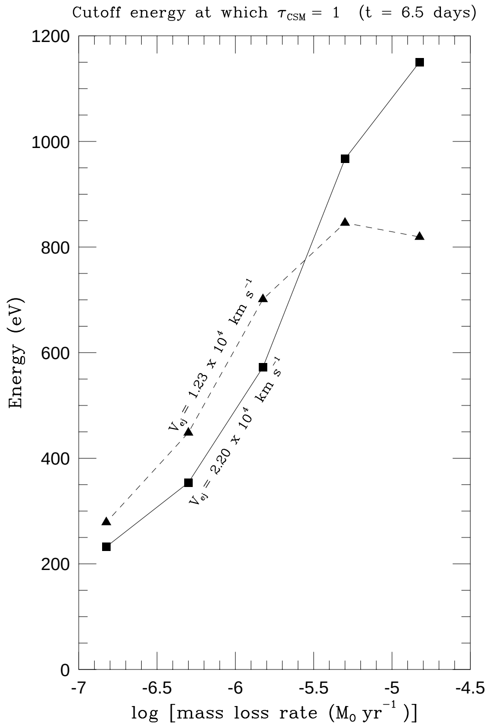


Figure 2. (left) Evolution of Hα luminosity for the models in Figure 1. Models are labeled with their $\dot{M}/u_{10}$. The vertical dotted line marks 6.5 days after explosion. The horizontal dashed lines mark the sensitivity of the SN 1994D observation of CLSPK96 at different distances. Figure 3. (right) Cutoff energy, $\epsilon_{\rm cut}$, at which the optical depth through the CSM is unity for the models in Figure 1. Below $\epsilon_{\rm cut}$ the CSM is opaque to X-ray emission from the supernova.

Acknowledgements: We thank David King, Linda Smith and Max Pettini for enlightening collaboration, and the Swedish Natural Science Research Council for support.

REFERENCES

Boffi F., Branch D. 1995, PASP, 107, 347

Branch D., Livio M., Yungelson L. R., Boffi F. R., Baron E. 1995, PASP, 107, 1019

Chevalier R. A. 1982, ApJ, 259, 302

Cumming R. J., Lundqvist, P., Smith, L. J., Pettini, M., King, D. L. 1996, MNRAS, in press (CLSPK96)

Eck C., Cowan J., Branch D., Boffi F. 1995, ApJ, 451, L53

Fransson, C., Lundqvist P., Chevalier, R. A. 1996, ApJ, 461, 993

Iben, I., Jr., Tutukov, A. V. 1984, ApJS, 54, 335

Nomoto K., Thielemann F.-K., Yokoi K. 1984, ApJ, 286, 644

Patat, F., Benetti, S., Cappellaro, E., Danziger, I. J., Della Valle, M., Mazzali, P. A., Turatto, M. 1996, MNRAS, 278, 111

Schlegel E. M., Petre R. 1993, ApJ, 418, L53

Wang L., Wheeler J. C., Li Z., Clocchiatti A. 1996, ApJ, 467, 435