Coronal emission from the shocked circumstellar ring of SN 1987A

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Received 30 March 2006 / Accepted 9 June 2006

ABSTRACT

High resolution spectra with UVES/VLT of SN 1987A from December 2000 until November 2005 show a number of high ionization lines from gas with velocities of \( \pm 350 \text{ km s}^{-1} \), emerging from the shocked gas formed by the ejecta–ring collision. These include coronal lines from [Fe X], [Fe XI] and [Fe XIV] which have increased by a factor of \( \sim 20 \) during the observed period. The evolution of the lines is similar to that of the soft X-rays, indicating that they arise in the same component. The line ratios are consistent with those expected from radiative shocks with velocity \( 310–390 \text{ km s}^{-1} \), corresponding to a shock temperature of \( (1.6–2.5) \times 10^6 \text{ K} \). A fraction of the coronal emission may, however, originate in higher velocity adiabatic shocks.

Key words. supernovae: individual: SN 1987A – circumstellar matter – shock waves

1. Introduction

The collision of the ejecta of SN 1987A with the circumstellar ring has been observed in many wavelength ranges (e.g., McCray 2005 for a review). In the UV/optical range this has been monitored with HST showing an increasing number of hot spots around the ring (Michael et al. 2000, 2002; Pun et al. 2002). Most likely, these hot spots are caused by the impact of the blast wave on protrusions from the inner circumstellar ring. As time progresses an increasing number of these are expected to appear, and finally the whole ring will be immersed in the collision.

The spectroscopic HST observations have identified three different velocity components (Pun et al. 2002). One narrow, nearly Gaussian, with \( FWHM \sim 10 \text{ km s}^{-1} \), coming from the unshocked ring gas. Secondly, there is an intermediate velocity component arising from shocked cooling gas, with a clearly non-Gaussian form, extending to \( \pm 300 \text{ km s}^{-1} \). Finally there is a very broad component extending to \( \sim 15 \text{000 km s}^{-1} \), probably coming from the reverse shock, resulting from the interaction with the surrounding medium (Michael et al. 1998; Smith et al. 2005). We will refer to these as the narrow, intermediate and high velocity components, respectively.

The collision is also seen in the radio as a rising non-thermal synchrotron flux (Gaensler et al. 1997; Manchester et al. 2002, 2005). The light curves in this range show a roughly linear increase with time. Further, Bouchet et al. (2006) find from ground based and Spitzer mid-IR observations evidence for hot dust as well as highly ionized line emission.

* Based on observations performed at the European Southern Observatory, Paranal, Chile.

In X-rays ROSAT and Chandra have observed SN 1987A at several epochs, and also in this energy range a steadily rising flux is seen (Park et al. 2004, 2005a). While the hard X-rays correlate well with the radio flux, the rise time in the soft X-rays is considerably shorter. Of special interest are the high resolution spectral observations (Zhekov et al. 2005, 2006), which show a number of lines from H and He like ions of N, O, Ne, Si, Mg and S, as well as Fe XVII. Zhekov et al. (2005) argue that these lines arise in the radiative shocks propagating into the protrusions, as well as the reflected shock propagating back from these. In this paper we discuss optical observations complementary to these X-ray observations of highly ionized gas.

In Gröningsson et al. (2006) we report on spectral shapes and fluxes of optical lines created by the ejecta/ring interaction. As we use high-resolution echelle spectroscopy, we can easily disentangle the different velocity components from each other. Here we concentrate on the evolution of intermediate velocity high-ionization lines, such as [Fe XI] \( \lambda6374.5 \), [Fe XI] \( \lambda7891.8 \) and [Fe XIV] \( \lambda5302.9 \), as they are efficient probes of the shocked gas.

In our analysis we use a recession velocity of \( 281 \text{ km s}^{-1} \) (the bulk motion of the northern side of the inner circumstellar ring (Gröningsson et al. 2006)) and a reddening of \( E_{B-V} = 0.16 \) (Fitzpatrick & Walborn 1990) with \( E_{B-V} = 0.06 \) from the Milky way (e.g., Staveley-Smith et al. 2003) and \( E_{B-V} = 0.10 \) from the LMC. The reddening law was taken from Cardelli et al. (1989) using \( R_V = 3.1 \). The differences between the LMC extinction law and the Galactic law are negligible in the optical at low color excess (Fitzpatrick 1999) and have therefore been ignored. In Sects. 2 and 3 we describe the observations and observational results, respectively. In Sect. 4 we discuss modeling...
of the lines, followed by a general discussion in Sect. 5 and conclusions in Sect. 6.

2. Observations

SN 1987A was observed in service mode with the Ultraviolet and Visual Echelle Spectrograph (UVES) at ESO/VLT at Paranal, Chile. UVES is a cross-dispersed echelle spectrograph covering (with two different dichroic settings) the spectral range $\sim 3100$–$10000$ Å (Dekker et al. 2000). The light beam is split up in two separate arms. The arm covering the blue part of the spectrum ($\sim 3100$–$4900$ Å) has a single CCD detector with a spatial resolution of 0′/246/pix. The other arm covering the red part ($\sim 4800$–$10000$ Å) is equipped with two CCDs having the somewhat higher spatial resolution of 0′/182/pix. The slit width used resulted in a resolving power of $\sim 50000$ corresponding to a spectral resolution of $\sim 6$ km s$^{-1}$.

Spectra of the ring and ejecta of SN 1987A were obtained on October 16, 1999, December 9–14, 2000, October 4–7, 2002, March 21–April 12, 2005 and October 20–November 12, 2005, in the following referred to as epochs 1–5, respectively. In all cases, except for epoch 1, the position angle was PA = 30°. For epoch 1 it was PA = 20°. The log of the observations is given in Table 1. The observations and data reduction are discussed in detail in Gröningsson et al. (2006). As can be seen from Table 1, the exposure of the first epoch was very short and the S/N low. This made it impossible to obtain meaningful fluxes for the coronal lines for this epoch, and therefore we do not discuss it further in this paper.

Because the spatial resolution of these ground-based observations is limited compared to the dimensions of the ring, we cannot distinguish between different hot spots located on the same side of the ring. To identify how many hot spots were covered by the slit we retrieved and studied HST images taken with the WFPC2 and ACS instruments at roughly the same epochs. These show that only Spot 1 is responsible for the emission from the shocked ring at epoch 1. At epoch 2 Spot 1 still dominates the shocked gas emission on the north side of the ring, but also two spots on the opposite side of the ring are now prominent. At epoch 3, three to four different hot spots contribute to the emission on the northern side and by the time of the last epochs the entire ring is lit up by the ejecta-ring collision. Because of the difference in velocity and to isolate a limited part of the ring we will in the following only discuss the spectrum from the north side of the ring, i.e., where Spot 1 first appeared. A comparison of the the kinematics and flux of the two sides will be given in Gröningsson et al. (2006).

To estimate the accuracy of the absolute flux level of the spectra we compared the individual sensitivity functions created from the reduced standard star spectra and their corresponding physical fluxes. The sensitivity curves differed typically by $\leq 10\%$ from each other. These exposures of the standard stars used a wide slit (10″) and hence no slit losses are likely to occur. Our science data exposures, on the other hand, used a relatively narrow slit and since SN 1987A is an extended source the slit losses could be considerable and depend on atmospheric conditions such as the seeing. To estimate how much the atmospheric conditions could influence our results we have compared line fluxes of the individual science spectra for the epochs which have more than one exposure. This comparison reveals that the line fluxes differ by $\leq 10\%$ from one exposure to another. Finally, to estimate the total systematic error, we have compared our fluxes with HST spectra and photometry (see Gröningsson et al. 2006), and find that the accuracy of the VLT fluxes should in general be better than $\sim 30\%$.

3. Results

In Gröningsson et al. (2006) we give a full list of the different lines present, both from the unshocked and the shocked ring. The former are dominated by thermal broadening with a $FWHM$ of $\sim 10$ km s$^{-1}$. The lines from the shocked gas are on the other hand dominated by the macroscopic velocity and are highly asymmetrical, extending to $\sim 250$–$400$ km s$^{-1}$ (HWZI). The two components can therefore easily be well separated, and
a subtraction of the broader from the narrower component by interpolation of the intermediate components by regression splines is fairly straightforward. More problematic is the blending of different lines from the shocked component. In particular, the large number of Fe II lines from this component causes a considerable number of blenders.

The full spectrum between 3100–10 000 Å contains ~170 intermediate velocity lines. About one third of these are Fe II lines, but there are also strong lines from more highly ionized ions, like [O III] λ5007, 5006.8, [Ne III] λ4631, 4680, 4686, [Ne V] λ3426, 3485, 3487, 5109, and [Ar III] λ6967. The most interesting result is, however, that we find a number of highly ionized coronal lines, which can only be seen thanks to the high S/N and high spectral resolution of our UVES observations.

In Figs. 1–4 we show a compilation of the most important of these lines for the December 2000, October 2002, March/April 2005 and November 2005 epochs. These include [Ne V] λ3425.9, [Ar V] λ7005.7, [Fe VII] λ6087.0, [Fe X] λ6374.5, [Fe XII] λ7891.8, and [Fe XIV] λ5302.9, which are all likely to originate from the cooling post-shock gas. In addition, we include for comparison the [O III] λ5006.8, [Ne III] λ3868.8, [Fe II] λ5195.2, [Fe III] λ4658.0 lines, which are, however, likely to come from considerably cooler, photoionized gas (Sect. 4). Because these are very useful as diagnostics of the shocked ring gas we concentrate in this paper on these lines, and refer to Grüningsson et al. (2006) for a more detailed analysis of the full spectrum.

As an important example we show in Fig. 5 the region of the [Fe XIV] λ5302.9 line. It is here seen that the blue wing of the [Fe XIV] λ5302.9 line is blended with the intermediate velocity [Fe II] λ5296.8 line. To remove this we use the [Fe II] λ5527.6 line as a template. The reason why we have chosen this line instead of the stronger [Fe II] λ7115.2 line is the similar excitation potential to the [Fe II] λ5296.8 line. The result of this subtraction can be seen in the lower panel of Fig. 5. In addition, we also see a narrow component of [Ca V] λ3439.1 at 350 km s⁻¹.

The [Fe X] λ6374.5 line is close to the red wing of the very strong [O I] λ6363.8 line. In addition, there is a narrow Si II λ6371.4 line close to its peak. The [O I] λ6300.3 line was used as a template to deblend [O I] λ6363.8 from the [Fe X] λ6374.5 line. The extension of the blue wing is therefore for this line uncertain.

In Fig. 6 we show the most important high ionization lines from the October 2002 observations after deblending. The other epochs have been deblended in the same manner.
We have also searched the spectra for [S XII] $\lambda_{7611}$, [Ar XIV] $\lambda_{4412.2}$ and [Ca XV] $\lambda_{5694.4, 5694.4}$. The [S XII] line unfortunately falls on top of some very strong atmospheric bands. While in the data there is some evidence that a line may be present at the wavelength of the [S XII] line we cautiously attribute this to the effects of the atmosphere. We have also searched HST spectra in this spectral region. Because of the low dispersion, 4.92 Å pixel$^{-1}$ or 194 km s$^{-1}$ pixel$^{-1}$, and fairly low S/N, only a weak upper limit of $\sim 10^{-15}$ erg s$^{-1}$ for the flux around our epoch 3 can be set.

In the region of the [Ar XIV] $\lambda_{4412.2}$ line there is a line redshifted from this wavelength by $\sim 200-300$ km s$^{-1}$ in our VLT spectra. This is, however, likely to be a blend of [Fe III] $\lambda_{4413.8, 4416.3}$, which matches well with the velocity of the observed feature. Subtracting these lines, using [Fe II] $\lambda_{7155.2}$ as a template in the best S/N spectrum of this region at epoch 5, we estimate an upper limit of $\sim 15\%$ of the [Fe XIV] flux at this epoch, i.e. $\leq 2.2 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$.

We have also looked for the [Ca XV] $\lambda_{5694.4}$ line, but do not detect this to a flux limit of $\sim 15\%$ of [Fe XIV] $\lambda_{5302.9}$ at epoch 4.

In Table 2 we give the fluxes of the intermediate velocity component for the highly ionized lines in the spectrum at the four well observed epochs. These fluxes are corrected for blending, as described above, but not for reddening. The estimated...
extinction correction factors are listed in Table 2. In addition, we detect the [Fe VI] \(\lambda 5335.2\) line at epoch 4 with a flux of \((1.3 \pm 0.2) \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}\).

As we see from Table 2 and Figs. 1–4, there is an increase in the fluxes of all lines between epochs 2 and 5. Over this period the [Fe X], [Fe XI], and [Fe XIV] lines have increased by a factor \(\approx 24−30\). At epoch 2 some of the weaker lines are, however, close to the noise level, and only the fluxes at epoch 3 are reliable. In Fig. 7 we show the evolution of the fluxes at the observed epochs. To compare with the X-ray and radio flux evolution, the fluxes in the figure have been normalized to the October 2002 level, i.e., epoch 3. From this figure it is seen that the [Fe X], [Fe XI] and [Fe XIV] lines evolve very similar to the flux evolution of the soft X-rays, and considerably faster than the hard X-rays or the radio. The [Ne V], [Ar V], and [Fe VII] lines, however, increase considerably more slowly. We return to this result in Sect. 5.

Although there seem to be considerable differences between the line profiles of the different ions, it is important to realize that both the deblending procedure and the low S/N for the faintest lines may introduce considerable uncertainties. Only for lines of high S/N is it meaningful to compare the line profiles directly. The velocities of the different lines will be discussed in detail in Gröningsson et al. (2006). Here we only make some brief remarks about the most relevant issues. If we compare the red extension of [Fe XIV] \(\lambda 5302.9\) with the [Fe II] \(\lambda 7155.2\) line we find evidence for an extension to \(~350 \text{ km s}^{-1}\) for [Fe XIV], while the [Fe II] line extends to \(~250 \text{ km s}^{-1}\). There are, however, important systematics due to uncertainties in background subtraction both in the spatial and dispersion directions. In addition, deblending of line profiles gives rise to uncertainties especially when the deblended line is strong compared to the line in consideration. This makes e.g., the extent of the blue wing of the [Fe XIV] \(\lambda 5302.9\) line more uncertain than the red. With the systematic uncertainties included we estimate that the values for maximum velocities should be accurate to within 50 km s\(^{-1}\).

| Ion   | Rest wavel. \(\lambda\) \(\text{Å}\) | Epoch | Flux \(\times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}\) | Extinction correction |
|-------|---------------------------------|-------|---------------------------------|----------------------|
| [Ne V] | 3425.86                         | 2     | 5.25 \pm 0.61                   | 2.36                 |
|       |                                 | 3     |                                 |                      |
|       |                                 | 4     | 8.58 \pm 1.26                   |                      |
|       |                                 | 5     | 9.69 \pm 1.83                   |                      |
| [Ar V] | 7005.67                         | 2     | –                               | 1.41                 |
|       |                                 | 3     | 0.34 \pm 0.07                   |                      |
|       |                                 | 4     | 0.31 \pm 0.09                   |                      |
|       |                                 | 5     | 0.35 \pm 0.08                   |                      |
| [Fe VII] | 6087.0                         | 2     | 0.80 \pm 0.11                   | 1.50                 |
|       |                                 | 3     |                                 |                      |
|       |                                 | 4     | 1.23 \pm 0.15                   |                      |
|       |                                 | 5     | 1.50 \pm 0.26                   |                      |
| [Fe X]  | 6374.51                         | 2     | 0.51 \pm 0.11                   | 1.47                 |
|       |                                 | 3     | 3.11 \pm 0.24                   |                      |
|       |                                 | 4     | 6.54 \pm 0.37                   |                      |
|       |                                 | 5     | 9.27 \pm 0.69                   |                      |
| [Fe XI] | 7891.94                         | 2     | 0.91 \pm 0.17                   | 1.32                 |
|       |                                 | 3     | 2.98 \pm 0.25                   |                      |
|       |                                 | 4     | 9.10 \pm 0.40                   |                      |
|       |                                 | 5     | 9.65 \pm 0.34                   |                      |
| [Fe XIV] | 5302.86                         | 2     | 0.67 \pm 0.12                   | 1.61                 |
|       |                                 | 3     | 3.89 \pm 0.31                   |                      |
|       |                                 | 4     | 11.00 \pm 0.39                  |                      |
|       |                                 | 5     | 14.89 \pm 0.69                  |                      |

Fig. 6. Deblended line profiles from October 2002 of the high ionization lines in Fig. 2.

Fig. 7. Evolution of fluxes of the high ionization lines compared to that of the X-ray flux from Park et al. (2005a).
4. Origin of the coronal emission

The intermediate component of both the [O III] $\lambda$5006.8 and the [Ne V] $\lambda$3425.9, as well as several strong UV lines, like N V $\lambda$1238.8, 1242.8, Si IV $\lambda$1393.8, 1403.8, C IV $\lambda$1548.2, 1550.8, C II $\lambda$2325 and Mg II $\lambda$2795.5, 2802.7, were seen in the HST spectra of Pun et al. (2002). However, no coronal lines were seen probably due to the lower spectral resolution, as well as the lower S/N. The [Fe X] $\lambda$6374.5 and [Fe XIV] $\lambda$5302.9 coronal lines have, however, been observed in several supernova remnants, like the Cygnus loop (Woodgate et al. 1974), Pup A, RCW86 (Lücke et al. 1979) and IC433 (Woodgate et al. 1979).

Pun et al. (2002) propose that the intermediate component arises when the blast wave hits dense protrusions from the ring. The velocity of the shocked gas behind the transmitted shock is given by $\sim (\rho_{\text{HII}}/\rho_{\text{blast}})^{1/2} V_{\text{blast}}$. Here $\rho_{\text{HII}}$ is the density of the H II region of the progenitor star. Estimates give $\rho_{\text{HII}} \sim 10^2$ cm$^{-3}$ (Chevalier & Dwarkadas 1995), while the density of the hot spot should be close to that of the main ring material $\sim 10^4$ cm$^{-3}$. For a blast wave velocity of $\sim 3800$ km s$^{-1}$ (Park et al. 2005b) the velocity of the transmitted shock should be $\sim 1.1 V_{\text{blast}} \approx 300$–500 km s$^{-1}$. This is close to that observed from the intermediate component.

The origin of the X-ray emission is, however, not so clear. Part of the X-rays may arise from the blast wave propagating with a velocity of $\sim 3500$ km s$^{-1}$ into the H II region of the progenitor, interior to the equatorial ring. Zhekov et al. (2005), however, find a velocity from the line profiles much smaller than that inferred from the expansion from the size of the X-ray image (Park et al. 2004) and the radio source (Manchester et al. 2002, 2005), which implies an expansion rate of $\sim 3000$ km s$^{-1}$.

Zhekov et al. therefore propose a scenario where the blast wave propagates with this comparatively high velocity inside the ring in a medium which is dominated by a density characteristic of the H II region, $\sim 10^2$ cm$^{-3}$. In this scenario most of the X-ray line emission arises where the blast wave hits the dense protrusions from the ring, forming transmitted shocks into the dense gas. In addition to this, Borkowski et al. (1997) find that there will be reflected shocks going back from the hot spot into the shocked gas behind the blast wave. The velocity of the shocked gas behind the reflected shock is $\sim (\rho_{\text{HII}}/\rho_{\text{blast}})^{1/2} V_{\text{blast}} \approx 0.5 V_{\text{blast}} \approx 1000$–1500 km s$^{-1}$. This, and the even lower velocity from the transmitted shocks, explains the low velocity compared to the blast wave inferred from the X-ray line emitting gas. The higher density behind reflected shocks, as well as the transmitted, causes these to dominate the X-ray emission over the blast wave. It also suggests that most of the X-ray emission should be correlated with the optical emission from the hot spots. Because of the lower density and higher temperature behind the reflected shocks, these are likely to be adiabatic. The cooling gas seen in the coronal lines, as well as in the optical/UV emission from lower ionization stages, is therefore likely to arise in the radiative shocks in the hot spots. We will therefore investigate this possibility more quantitatively below.

For a gas with $x = n(\text{He})/n(\text{H}) = 0.25$ (Lundqvist & Fransson 1996) the temperature behind the shock going into the hot spot is

$$T_s = 2.27 \times 10^8 \left( \frac{1 + 4x}{2 + 3x} \right)^2 \left( \frac{V_s}{300 \text{ km s}^{-1}} \right)^2 {\text{K}}.$$  

Michael et al. (2002) find that for a shock with velocity 500 km s$^{-1}$ equipartition between electrons and ions takes place on a time scale of $\sim 60$ (n$_e/10^4$ cm$^{-3}$)$^{-1}$ days. Shocks with lower velocity will equilibrate faster. In the following we therefore assume that $T_s = T_{\text{ion}} = T_e$.

For $100 \leq V_s \leq 600$ km s$^{-1}$ the cooling function for the CNO-enriched composition found for the ring in Lundqvist & Fransson (1996) is $\Lambda(T_e) \approx 4.0 \times 10^{-337} (T_e/10^5 \text{K})^{-0.7}$ erg s$^{-1}$ cm$^3$, using the code by Nymark et al. (2005). The cooling time of the shock may therefore be approximated by

$$t_{\text{cool}} \approx 8.3 \left( \frac{\rho_{\text{spot}}}{10^4 \text{ cm}^{-3}} \right)^{-1} \left( \frac{V_s}{300 \text{ km s}^{-1}} \right)^{3.4} \text{years}, \tag{2}$$

where $\rho_{\text{spot}}$ is the pre-shock density. Therefore, depending on the density and the shock velocity, the shock may be either adiabatic or radiative. While coronal emission lines may arise in any hot gas with a temperature of $\sim 10^6$ K, the wide range of ionization stages with similar line profiles seen in the intermediate velocity component, from Fe II to Fe XIV, strongly indicates that at least some of the emission is originating in radiative shocks.

The structure of the radiative shocks was discussed in Pun et al. (2002). Pun et al., however, mainly focused on low and intermediate ionization lines. To calculate the flux of the optical/UV/IR coronal lines, as well as some of the other high ionization lines, we compute the spectrum of the shock, using the shock code of Nymark et al. (2005). Although originally used for the reverse shock in supernovae, this, is of course, applicable for any radiative shock, independent of shock direction. This determines the temperature and ionization structure of the shocked gas by solving the time dependent ionization and hydrodynamic equations, assuming that the structure is stationary and one-dimensional. The latter should be sufficient as long as the shock is radiative. Collisional ionization rates, as well as recombination rates, are from the most recent data, and references are given in Nymark et al. (2005). In addition, we include charge transfer, which becomes important at these comparatively low temperatures. The uncertainties of the ionization and recombination data especially for iron have been discussed by Masai (1997) and Gianetti et al. (2000). The emissivity is calculated using full multi-level atoms. Pre-ionization of the un-shocked gas by X-rays from the shock is calculated using an updated version of the code in Chevalier & Fransson (1994). The abundances used are the ones used by Pun et al. (2002), which are the CNO enriched abundances for He, C, N and O, taken from Lundqvist & Fransson (1996), and LMC abundances from Russell & Dopita (1992) for the other elements, with exception to Si which is from Welty et al. (1999).

Because the focus in this paper is on the coronal lines we do not attempt to calculate the structure of the photoionization heated gas behind the cooling, shocked gas. This region dominates the flux for medium and low ionization lines, like [O III], [Ne III] and lower ionization stages. The structure of this region, as well as the pre-ionized emission lines, will be discussed in a separate paper. Here we only note that the low and intermediate ionization lines, like [O III], [Ne V], [Ar V], and [Fe VII], all have narrow components at zero velocity. The higher ionization lines, [Fe X], [Fe XII], and [Fe XIV], however, lack such a component. This indicates that pre-ionization of the un-shocked gas does not reach more than the former stages. Models similar to those in Lundqvist & Fransson (1996) show that gas ionized by the initial UV/soft X-ray flash at shock break out with densities $\lesssim 10^4$ cm$^{-3}$ is at these epochs mainly found in Fe I-II, with $\lesssim 10^{-3}$ in Fe III. Only in gas with densities $\lesssim 10^5$ cm$^{-3}$ can ions like Fe VII be found.
The collision strengths of the important coronal lines are mainly from the Chianti data base (Dere et al. 1997; Landi et al. 2006), but in some cases supplemented with more recent calculations. The critical densities for collisional de-excitation of the [Fe X-XIV] lines are in the range $10^3-10^6$ cm$^{-3}$, and collisional destruction is therefore not important for these. Consequently, the relative line ratios are not sensitive to the exact value of the density. Here we take a value of $n_{\text{spot}} = 10^2$ cm$^{-3}$ for the pre-shock density.

In Fig. 8 we show the strengths of the most important optical, high ionization lines as a function of the shock velocity relative to the kinetic flux through the shock, $\rho V^3_{\text{shock}}/2$. From this we see that at shock velocities $<400$ km s$^{-1}$ the line ratios vary strongly with velocity, while above this velocity they are, with the exceptions of [S XII] 7.611.0 and [Ar XIV] 4.412.2, nearly constant. This is explained by the fact that above $>400$ km s$^{-1}$ the most abundant ions in the immediate post-shock gas are ions more highly ionized than Ne V and Fe XIV. For a radiative shock with velocity higher than $\sim 400$ km s$^{-1}$ the fraction of the cooling region above $\sim 2 \times 10^{6}$ K, which corresponds to ionization stages higher than these ions, is largely irrelevant to the flux of the coronal lines, and the line ratios will therefore be insensitive to the shock velocity.

In Fig. 9 we show the ionization and temperature structure of iron. For the pre-shock density of $10^4$ cm$^{-3}$, the ions adjust from their pre-ionization values to their equilibrium abundances. Behind this region Fe IX-XIV all have high abundances in most of the shocked gas. As the gas cools the temperature and ionization decreases. When the temperature has fallen below $\sim 10^{6}$ K cooling increases catastrophically and drops to $(1-3) \times 10^{4}$ K. This region is too thin to be resolved in the plot, but is very important for the observed emission lines (see below). The different lines are therefore direct probes of the temperature interval where they have their maximum abundance.

To more clearly illustrate the sensitivity of the different lines to the temperature we show in Fig. 10 the contribution to the luminosity per logarithmic temperature interval to different lines behind a shock with velocity $350$ km s$^{-1}$. At $(1-2) \times 10^6$ K, while the [Ne V], [Ar V] and [Fe VII] lines arise at $\sim 3 \times 10^5$ K in a geometrically narrow, but important, region, where the temperature falls from $10^6$ K to $10^4$ K. Because the whole post-shock region is in near pressure equilibrium, the density is $n_e (T_e) \approx 4n_{\text{spot}}T_e/T$. The [Ne V] and [Fe VII] lines, e.g., arise at $T_e \sim 3 \times 10^5$ K, corresponding to $\sim 2n_{\text{spot}} \approx 2.4 \times 10^5$ cm$^{-3}$, for a pre-shock density of $n_{\text{spot}} = 10^2$ cm$^{-3}$. The critical densities for these lines are $\lesssim 10^7$ cm$^{-3}$, and collisional de-excitation is therefore clearly not important for these.

For completeness Fig. 10 also shows the [N II], [O III] and [Ne III] lines. In the collisionally ionized part of the shock they each trace different temperature intervals from $\sim 10^4$ K to $\sim 4 \times 10^5$ K. They all have, however, more important contributions from the photoionized, cooling gas, not included in these models.

To compare the models with our observations we relate all line fluxes to that of [Fe XIV] 15302.9 at the different epochs. These ratios are given for the different epochs in Table 3. In the same Table we also give the shock velocity corresponding to the different line ratios, taken from Fig. 8. As can be seen, the range of shock velocities is for all line ratios surprisingly small, $310-390$ km s$^{-1}$. The corresponding temperature behind the shock is $(1-2.5) \times 10^6$ K. This comparison assumes that the emitting area in each line is the same. If there are shocks with a range of velocities this assumption may be questionable. Because of the rapid variation of the line ratios with velocity, this

Fig. 8. Fluxes of the most important optical lines from radiative shocks as function of the shock velocity. The fluxes are given relative to the energy flux, $F_{\text{shock}} = \rho V^3_{\text{shock}}/2$, through the shock.

Fig. 9. Ionization structure for iron and temperature behind a radiative shock with velocity $350$ km s$^{-1}$ and pre-shock density $10^4$ cm$^{-3}$.

Fig. 10. Contribution to the luminosity per logarithmic temperature interval to different lines behind a shock with velocity $350$ km s$^{-1}$. At $(1-2) \times 10^6$ K, while the [Ne V], [Ar V] and [Fe VII] lines arise at $\sim 3 \times 10^5$ K in a geometrically narrow, but important, region, where the temperature falls from $10^6$ K to $10^4$ K. Because the whole post-shock region is in near pressure equilibrium, the density is $n_e (T_e) \approx 4n_{\text{spot}}T_e/T$. The [Ne V] and [Fe VII] lines, e.g., arise at $T_e \sim 3 \times 10^5$ K, corresponding to $\sim 2n_{\text{spot}} \approx 2.4 \times 10^5$ cm$^{-3}$, for a pre-shock density of $n_{\text{spot}} = 10^2$ cm$^{-3}$. The critical densities for these lines are $\lesssim 10^7$ cm$^{-3}$, and collisional de-excitation is therefore clearly not important for these.

For completeness Fig. 10 also shows the [N II], [O III] and [Ne III] lines. In the collisionally ionized part of the shock they each trace different temperature intervals from $\sim 10^4$ K to $\sim 4 \times 10^5$ K. They all have, however, more important contributions from the photoionized, cooling gas, not included in these models.

To compare the models with our observations we relate all line fluxes to that of [Fe XIV] 15302.9 at the different epochs. These ratios are given for the different epochs in Table 3. In the same Table we also give the shock velocity corresponding to the different line ratios, taken from Fig. 8. As can be seen, the range of shock velocities is for all line ratios surprisingly small, $310-390$ km s$^{-1}$. The corresponding temperature behind the shock is $(1-2.5) \times 10^6$ K. This comparison assumes that the emitting area in each line is the same. If there are shocks with a range of velocities this assumption may be questionable. Because of the rapid variation of the line ratios with velocity, this

Fig. 8. Fluxes of the most important optical lines from radiative shocks as function of the shock velocity. The fluxes are given relative to the energy flux, $F_{\text{shock}} = \rho V^3_{\text{shock}}/2$, through the shock.

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Table 3. Reddening corrected fluxes relative to \([\text{Fe XIV} \lambda 5303]\) and corresponding shock velocities (km s\(^{-1}\)).

| Line       | Epoch 2 | Epoch 3 | Epoch 4 | Epoch 5 |
|------------|---------|---------|---------|---------|
| [Fe VII] \(\lambda 6087.0\) | –       | 0.19    | 0.10    | 0.094   |
| [Fe X] \(\lambda 6374.5\)     | 0.65    | 0.68    | 0.54    | 0.57    |
| [Fe XI] \(\lambda 7892.0\)    | 369     | 369     | 391     | 381     |
| [Ne V] \(\lambda 3425.9\)     | 1.05    | 0.63    | 0.68    | 0.53    |
| [Ar V] \(\lambda 7005.7\)     | 326     | 340     | 338     | 348     |
| [Ar V] \(\lambda 7537.5\)     | 0.076   | 0.025   | 0.021   |         |

is, however, not likely to affect the derived velocities by a large factor.

There is some tendency for lines from ions with lower ionization potential, e.g., Ne V, Ar V and Fe VII, to give a somewhat lower velocity than the lines from high ionization ions like Fe X and Fe XI. The fact that we do not see [Ar XIV] \(\lambda 4412.2\), at a flux level of \(\sim 15\%\) of the [Fe XIV] line is consistent with a shock velocity \(\lesssim 500\) km s\(^{-1}\). The [Ca XV] \(\lambda 5694.4\) line gives a similar upper limit of \(\sim 500\) km s\(^{-1}\) (Fig. 8).

Finally, we note that although only barely covered by these observations, one also expects the [Fe XIII] \(\lambda 3388.5\) and \(\lambda 10746.8-10797.9\) lines to be detectable in the UV and near-IR, respectively. In particular, the IR lines are expected to have a strength comparable to that of [Fe X] \(\lambda 6374.5\) (see Fig. 8). The \(\lambda 3388.5\) line is within our observed range, but the spectrum is here noisy due to the decreasing sensitivity of the instrument and the influence of the atmosphere. We estimate a maximum strength comparable to that of [Fe XIV] \(\lambda 5302.9\). Because the expected flux is \(\sim 10\%\) of this line, this limit is not very useful. The IR lines are outside the range.

5. Discussion

Although we get good agreement for a rather narrow range of shock velocities, it is clear that the dynamics is more complex. This can be seen in the hydrodynamic simulations of the collision performed by several groups (Luo et al. 1994; Masai & Nomoto 1994; Borkowski et al. 1997). In particular, Borkowski et al. (1997) have modeled the structure and X-ray emission from the impact with 2D hydro simulations. The interplay of the shock propagating into the dense ring gas and reflected shocks from the ejecta–CSM gives a time dependence, as well as spatial de-

In Sect. 3 we found that the [Fe XIV] \(\lambda 5302.9\) line extends to \(\sim 350\) km s\(^{-1}\), while the lower ionization lines only extend to \(\sim 250\) km s\(^{-1}\). This may indicate that the low ionization lines have a dominant contribution from tangential shocks with lower velocity, while the high ionization lines also come from shocks perpendicular to the blast wave, having a high velocity.

Michael et al. (2002) find that the relative fluxes of the lines observed with the grating spectrometer on Chandra in October 1999 are best fitted with a shock temperature of \(kT_e \sim 2.9 \pm 0.4\) keV. The lower dispersion CCD spectra observed in December 2000 indicated a marginally lower temperature, \(kT_e \sim 2.7 \pm 0.2\) keV. In addition, they find that they get a slightly better fit to the spectrum with an additional softer component with \(kT_e \sim 0.4 \pm 0.1\) keV. The flux contribution from this was \(\sim 7\%\). It is worth noting that even the high temperature component has an electron temperature that is considerably lower than the shock temperature, corresponding to equipartition, \(\sim 17\) keV. This is in common with several other SNRs.

Due to the increase in the X-ray flux Zhekov et al. (2005, 2006) were able to repeat this study with considerably higher S/N. Zhekov et al. find that they get a good fit to the X-ray line ratios, as well as the widths, for a model with a range of temperature, 0.15–4 keV, corresponding to \(V_\parallel = 340–1700\) km s\(^{-1}\). The lower part of this range is similar to that observed in the optical lines, and it is very likely that they arise from the same region. As Zhekov et al. (2005) remark, the upper range of velocities is, however, likely to come from adiabatic shocks, probably reflected from the impact on the protrusions. If they are adiabatic and with velocity \(\gtrsim 400\) km s\(^{-1}\), corresponding to a temperature of \(\gtrsim 3 \times 10^6\) K, they will not produce optical emission.

We propose that the regions that produce the soft X-ray flux also account for most of the emission in the [Fe X], [Fe XI] and [Fe XIV] lines. This is supported by the similar evolution of the flux between these two components (Fig. 7), and, as mentioned above, the comparable shock velocities required to produce them, \(\sim 350\) km s\(^{-1}\) (see also Table 3). However, in order to explain the slower evolution of the intermediate ionization lines such as [Ne V], [Ar V] and [Fe VII], we do require that some fraction of the [Fe X–XIV] fluxes arise from adiabatic shocks which would not be contributing to the intermediate and low ionization lines. The sensitivity of the cooling time scales to the shock velocities and the density of the hot spots (Eq. (2)) makes this a plausible scenario. The somewhat narrower line widths that the intermediate ionization lines exhibit also support this argumentation.

6. Conclusions and summary

The most important result of this paper is the discovery of a number of high ionization lines coming from gas of temperatures up to \(\sim 2 \times 10^6\) K. The rapidly increasing flux of these is well correlated to the flux in the soft X-rays, and offer a complimentary view of the interaction of the ejecta and the ring material. The large range in ionization stage with similar line profiles shows that most of the emission is coming from radiative shocks with velocity \(310–390\) km s\(^{-1}\), although a fraction of the coronal line emission may originate in adiabatic shocks. The shock velocity we find from our spectral modeling is consistent with the width of the lines. We hope in the future to do a more detailed modeling of the spectra, including both the lower ionization lines from the photoionized, cooling gas, as well as the X-ray lines. Also a more detailed modeling of the hydrodynamics of the explosion along the lines of Borkowski et al. (1997) with these extra constraints from the line strengths, as well as the line profiles would be highly interesting. Continued monitoring of the ring collision is of obvious high importance. The increasing flux, as well as new instruments using adaptive optics, will enable us to study this unique collision in even more detail.
Acknowledgements. We are grateful to the referee for several useful comments. This work was supported in part by the Swedish Research Council and the Swedish National Space Board. Part of this research was performed while CF and RAC were visiting the Kavli Institute of Theoretical Physics, supported in part by the National Science Foundation under Grant No. PHY99-07949. PL is a Research Fellow at the Royal Swedish Academy supported by a grant from the Wallenberg Foundation.

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