X-rays from circumstellar interaction

Tanja K. Nymark

Stockholm Observatory, S-106 91 Stockholm, Sweden
tanja@astro.su.se

Summary. We present a model for the emission from the cooling region behind the reverse shock created by the interaction between the supernova ejecta and the circumstellar medium. Applications to X-ray emission from the interaction region between supernova ejecta and pre-supernova wind are discussed.

1 Circumstellar interaction

For supernovae with sufficiently dense circumstellar medium the interaction between the ejecta and the circumstellar gas creates a strongly emitting region of shocked gas. The interaction region consists of two distinct shells which are separated by a contact discontinuity. The outer shell consists of shocked circumstellar gas with temperatures of the order of 10^9 K, which emits mainly hard X-rays from free-free interactions. The inner shell is created by the reverse shock which moves backward into the ejecta, and consists of shocked ejecta with temperatures up to 10^7 K. This region emits soft X-rays and due to the lower temperature line emission is strong. The energy loss caused by the strong line emission causes the region to collapse, forming a dense, cool shell close to the contact discontinuity. At early stages the cool gas absorbs the line emission and soft X-rays, but as the shell expands the optical depth drops and more of the reverse shock emission emerges. Eventually it comes to dominate the X-ray spectrum from the supernova.

2 Shock structure

For the radiative reverse shock, where the cooling time is short compared with the expansion time, we may assume that the post-shock region is thin compared to the size of the ejecta. We describe the region behind the shock as a steady state flow, for which the input parameters are given by a self-similar solution. The post-shock region is divided into a fine grid with a constant density step between the zones, and the steady state equations are solved in each zone. In this way we determine the density structure of the shocked ejecta as well as the temperature and velocity at each grid point. From figure 1 we see that the size of the region is of the order of 10^{12} cm. Since a typical size of the supernova is 10^{15} cm, the assumption of a thin shell clearly holds.

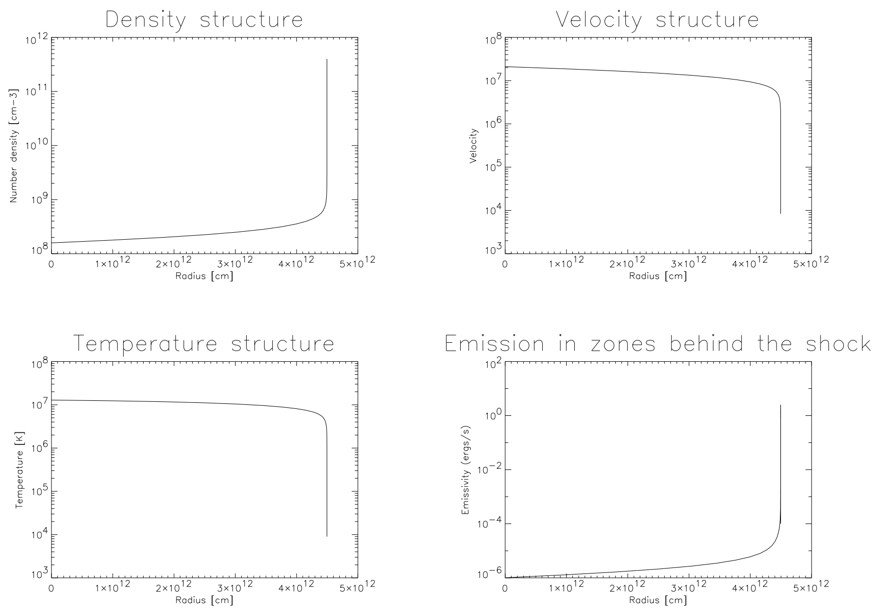

Fig. 1. The structure of the shocked ejecta behind the reverse shock. The lower right plot shows the emission behind the shock, most of which comes from the thin, cool shell close to the contact discontinuity, which also absorbs a significant amount of the emitted radiation.

3 Spectral code

Once the temperature and density of each zone is known, the ionization structure can be computed. Assuming steady state also here, we obtain the ionization state of each element in each zone. We then solve the full multi-level equations for most ions, yielding the populations of a number of levels [1]. From the level populations we obtain the emission in each line, which is given by $P_{ij} = n_i E_{ij} A_{ij}$, where n_i is the population of level i, E_{ij} is the energy difference between levels i and j ($i > j$) and A_{ij} is the probability that this transition will take place. The continuum emission is computed by the method of Mewe et al [4].

4 One temperature versus many

The reverse shock is often modeled with a single temperature. While this is a good approximation for an adiabatic shock, it is not sufficient for reproducing the emission from a radiative shock. The total emission will be overestimated, and many lines from low-temperature regions will not be present in the synthetic spectrum. By combining hydrodynamic calculations with an emission code, our model traces the cooling region better (figure 2).

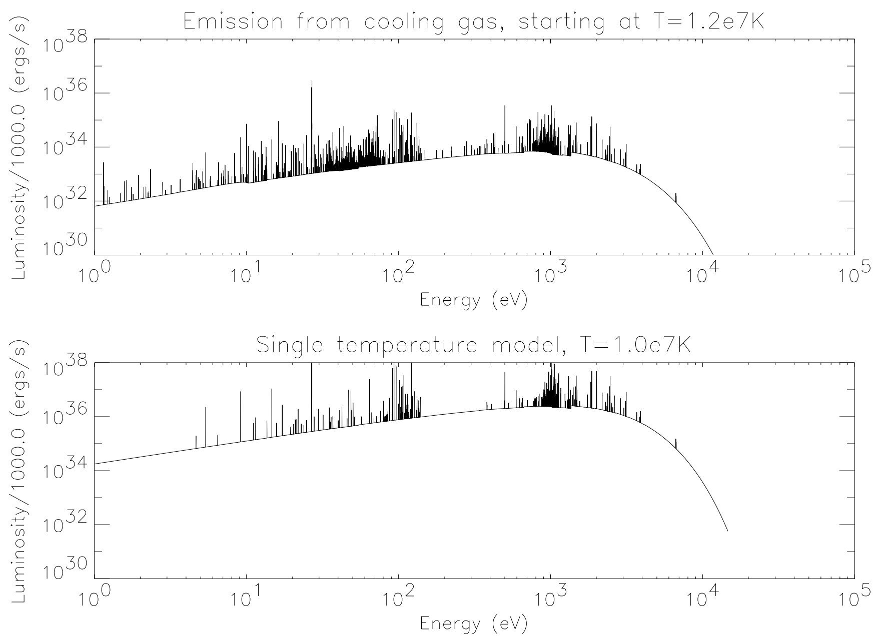

Fig. 2. Spectrum created by our model (upper) and by a single temperature model of T= 10^7 K (lower).

5 Composition effects

Since the gas behind the reverse shock consists of shocked ejecta, the composition of this gas is determined by the composition of the ejecta at the position of the shock. This in turn reflects the composition of the outer layers of the progenitor star as well as the explosion physics. As the reverse shock moves backward into the ejecta it passes through regions abundant in elements which are rare in the circumstellar medium, resulting in quite distinct spectra, which change over time as the shock moves on (figure 3).

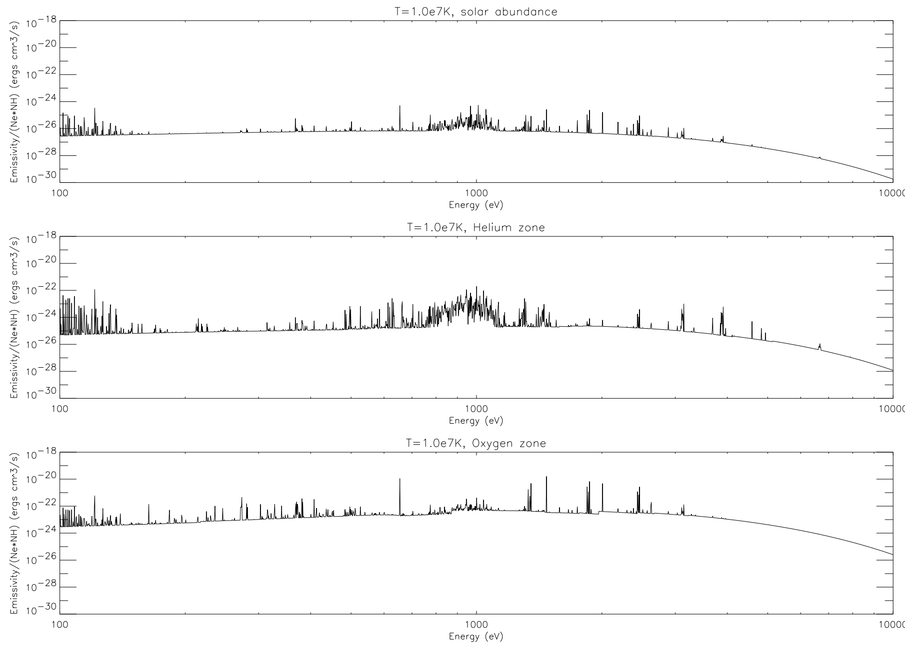

Fig. 3. Effects of varying composition in the reverse shock. The upper panel shows the emitted spectrum from a single-temperature model if the composition of the shock is solar, while the middle and lower panels show the spectrum from the reverse shock when the shock is in the helium zone and oxygen zone respectively.

6 Absorption in the cool shell

At early times most of the energy emitted by the cooling gas is absorbed in the cool shell close to the contact discontinuity. At first only the most energetic emission passes through, while lower energies are completely absorbed. As the emitting region expands, the optical depth in the cool shell drops. The absorption decreases, first at high energies, later at lower energies. As time passes, more of the low-energy emission emerges, so that even though the total emission decreases, the emerging emission from the reverse shock increases.

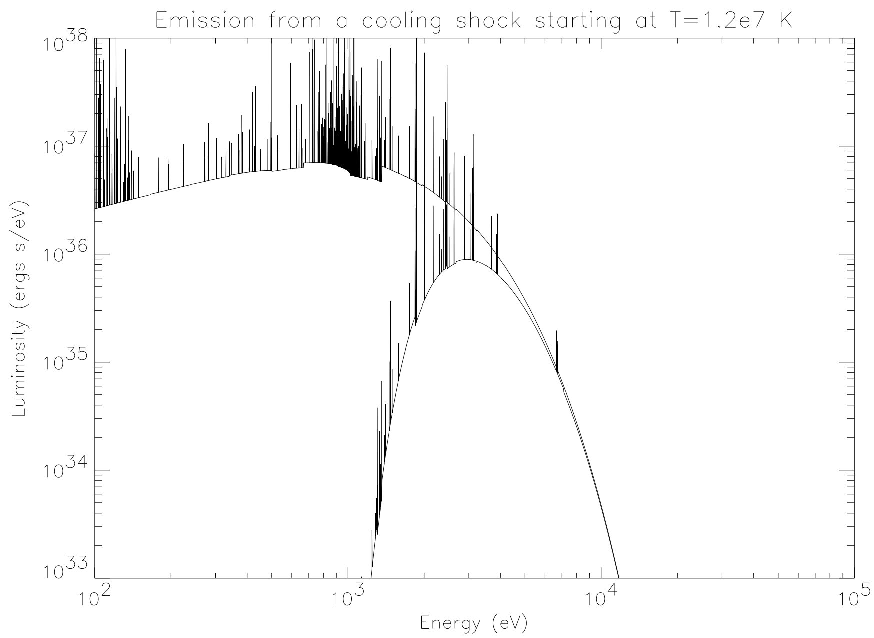

Fig. 4. The upper line shows the energy emitted by the whole cooling region, while the lower line is the emerging luminosity after absorption. In this case all the emission below 1 kEv is absorbed.

7 Discussion

A model has been developed for the emission from the reverse shock created by the interaction between supernova ejecta and the dense circumstellar gas. By combining multi-level calculations of the most abundant ions with a hydrodynamic model our model gives a better description of the interaction than earlier models. When applied to observations our model can be used to trace the density structure and composition of the ejecta, and can thus give valuable information on the progenitor star and the explosion physics.

References

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