THE EFFECT OF RELATIVISTIC PARTICLE BEAMS
ON THE EVOLUTION OF SUPERNOVA ENVELOPES:
SELF-CONSISTENT SOLUTIONS

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ABSTRACT. We consider the effect of a relativistic particle beam
produced as part of the collapse process of a supernova core into a
neutron star or black hole on the evolution of the expanding envelope.
Relativistic bremsstrahlung is the dominant energy loss mechanism until
the material through which the beam propagates becomes ionized. After
an ionized channel is formed, plasma processes and inverse Compton losses
become the dominant loss mechanisms. The energy loss processes
associated with the beam impart significant momentum to the irradiated
segments of the shell. This suggests a natural explanation for the
asymmetric expansion of some supernovae, including SN1987a, and may
account for the early mixing seen in that object. It also implies that
some fraction of the X-ray light from very early in a supernova explosion
originates in an inverse Compton emission process wherein relativistic
electrons from the beam collide with optical photons from the expanding
envelope. In this paper we present self-consistent solutions to the rate
equations for the energy loss due to collective processes and calculate the
momentum transferred to the envelope by the beam. We then comment
on the expected X-ray emission from SN1987a using such a model (Beall
1979), and make estimates of the associated γ-ray flux.

1. Introduction

The detection of X-rays from supernova explosions is of considerable
astrophysical interest. In combination with the radio fluxes detected from
supernovae, X-ray emission suggests the presence of relativistic particles.
The acceleration mechanisms which produce relativistic particles in
supernovae appear to operate on a number of time scales. For example,
radio and X-ray emission from supernova remnants arises on time scales of
decades after maximum light. The detection of such emission clearly
represents the presence of relativistic particles accelerated by the Fermi
mechanism, and seems to occur after the expanding shell of material
begins to slow appreciably due to its interaction with the interstellar
medium. Prompt radio and X-ray emission (within a few days or weeks of maximum light) is also of interest, since it illuminates the nature of the interaction between the ejecta thrown out from the explosion and the ambient medium near the precursor star.

Between these two extremes (on time scales of months to years), as the overburden of expanding material becomes optically thin, it is generally assumed to be possible to detect the presence of the collapsed object left as the remnant of the star's core. Such emission would at first be highly absorbed at X-ray frequencies.

The occurrence of a comfortably nearby supernova during the current era has provided a wealth of data on the early evolution of such objects. The detection of X-ray emission from SN1987a (see e.g. Sunyaev et al. 1987, Dotani et al. 1987) provides an interesting addition to the generally expected picture of X-ray emission from supernovae. A number of models have been developed to explain the observed X-ray spectrum, which seems to have arisen earlier than expected. Itoh et al. (1987) have modeled the optical light curve as being powered with $^{56}$Co mixed uniformly up to the outer edge of the helium layer. They note that such mixing is essential to fit the observed optical light. Sunyaev et al (1987) have modeled the X-rays from the source by a pulsar embedded in the expanding, optically thick ejecta. Their calculations show that the emission detected in August 1987 was brighter than that expected by roughly a factor of five. Sutherland et al. (1987) have also calculated a plausible model in which the X-ray radiation is produced by degradation of $\gamma$-rays via Compton scattering to produce the observed X-ray spectrum. In their calculation, they also assume that extensive mixing has occurred between the processed material in the remnant's core and the overburden.

The high-energy X-ray spectrum of the source has been measured by a number of experiments (see, e.g. Dotani et al., Sunyaev et al., and Ubertini et al. 1989), which show a relatively constant flux at 50 keV from August 1987 through April 1988 (Fishman et al. 1989) after the initial upper limits early in 1987 (Sood et al. 1988 and Ubertini et al. 1989). Important corroborations of the presence of processed material come from various reports of nuclear line fluxes at 847 and 1238 keV by Matz et al. (1987), Leising (1988), Leising and Share (1989), Teegarden et al. (1989), and Tueller et al. (1990). The common theme of these calculations is a requirement for extensive mixing between the core material and the hydrogen envelope (see Bussard, Burrows, and The 1989, Pinto and Woosley 1988, and Grebenev and Sunyaev 1989 for discussions). Arnett, Fryxell, and Muller (1989) calculate the growth of Rayleigh-Taylor instabilities during shock propagation through a realistic presupernova structure, and show that significant Rayleigh-Taylor mixing (see e.g., Chevalier and Klein 1978) can occur on time scales of order $10^4$ seconds.

Added to these arguments is the controversial nature of the low-energy spectrum for the prompt X-ray flux, which was detected by Ginga (see, e.g. Makino 1988), but was not detected by KVANT-MIR instrument (see, e.g. Staubert 1988, Aschenbach et al. 1987). Bandiera, Pacini, and Salvati