NON-EQUILIBRIUM MODELLING OF THE STRUCTURE AND SPECTRA OF SHOCK WAVES

Michael A. Dopita and Luc Binette
Mount Stromlo and Siding Spring Observatories
Research School of Physical Sciences
Australian National University, Canberra.

1. INTRODUCTION

Our understanding of the structure of radiative shocks of modest ($v_s \lesssim 200$ km s^{-1}) velocity has improved greatly since the pioneering work of Cox (1972). This advance has been accomplished primarily by a more complete development of the physics of the shock front, its ionisation precursor and of the cool recombination zone. (Dopita 1976, 1977; Raymond 1979; Shull and McKee 1979; Shull, Seab and McKee, this conference; D'Odorico and Dopita, this conference). However, all models used for spectrum synthesis have so far involved one dimensional steady-flow hydrodynamics and most have covered only a very limited range in parameter space. This has meant that whilst they can be used to estimate shock velocities and metallicities of the (assumed) fully radiative shocks found in nearby SNRs, they are of limited applicability in more exotic types of objects.

In this paper, we discuss new models for three classes of more unusual object; the oxygen-rich Cass A type of filament, very high velocity shocks and/or thermal instabilities and shocks which are not yet fully radiative. These models have been generated using the general purpose modelling code MAPPINGS, (Binette 1982; Binette, Dopita and Tuohy 1983).

2. THE OXYGEN-RICH SNR

The fast-moving knots of Cass A have been intensively studied (Chevalier and Kirshner 1979), since the strong oxygen and neon emission lines and the absence of hydrogen and helium recombination lines suggest that here we are actually seeing the material thrown out from the core of a massive star at the time of the supernova event. If the spectra of such regions could be interpreted, we would therefore expect to derive a wealth of information on nucleosynthesis in massive stars and the role of these objects in the chemical evolution of galaxies.

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Recent SNR searches in our Galaxy, (Goss et al. 1979) the Magellanic Clouds (Danziger and Dennefeld 1976, Mathewson et al. 1980, Dopita, Tuohy and Mathewson 1981) and in NGC 4449 (Kirshner and Blair 1980) have revealed several other objects of this type, and these show subtle but important spectral differences between them.

It has generally been assumed that the optical emission of this fast-moving material is the result of shock-heating (Peimbert and van den Bergh 1971, Lasker 1978, Chevalier and Kirshner 1978, 79; Goss et al. 1979; Murdin and Clark 1979, Kirshner and Blair 1980). However, interpretation of spectra has been hampered by a lack of theoretical modelling.

The work of Itoh (1981a,b) represents a major advance in this regard, and he was the first to describe the curious structure of a shock propagating through a pure oxygen plasma. We have recently applied our modelling code MAPPINGS to this problem, and the results are the subject of this section.

As far as the general shock structure is concerned the characteristics of our models (Fig. 1a,b) agree with the Itoh work. In the initial cooling zone, the electron temperature is much lower than the ion temperature (T_i), and T_e reaches a quasi-equilibrium level at which the rate

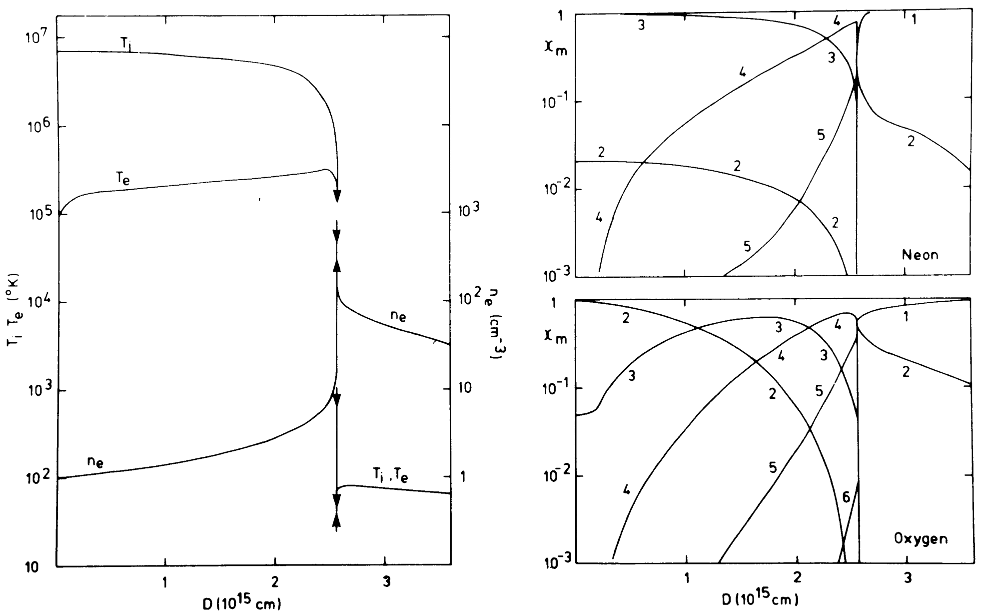

Figure 1a,b The temperature (a) and ionisation (b) structure of the oxygen-rich shock model described in the text. Note how the ionisation state continually increases up to the region of temperature 'collapse' of energy loss by collisional excitation of the ions matches the gain by collisional transfer of energy from the ions (Spitzer 1967). This temperature varies little through much of the cooling zone. If collective heating of the electrons by plasma instabilities is important (McKee and Hollenbach 1980), this result may be invalid, and then a model which sets $T_e = T_i$ would be more applicable. This can be done with MAPPINGS, but has not yet been investigated.

As T_e and T_i draw together, the approximately isobaric compression of the gas causes a rapid increase in volume emissivity of the plasma and a collapse in temperature. Because the heavy elements are such important coolants, the cooling time remains shorter than the recombination time until infrared cooling in fine structure lines is quenched, which occurs below 100°K. Thus, a high ionisation state is 'frozen' in at very low temperatures.

The initial recombination of the plasma is very rapid because of the high rates and densities prevailing at such low temperatures, but when the plasma has recombined sufficiently to see the UV radiation it produced while hot, photionisation heating becomes important in a very extended final recombination zone.

The major discrepancy between the models (Table 1) occurs in this recombination zone. At no point do we see the bounce-back to over 1000°K in temperature which characterised the pure-oxygen Itoh models. Similarly, in the radiative precursor (Itoh 1981b) temperatures remain low. This is most likely due to the very important [CII] $\lambda 156\mu$ and

Table 1: Comparison of oxygen-rich shock models.

Parameter		Itoh	Dopita & Binette
Composition		Oxygen	Mixed[1]
Shock conditions			
Velocity	V	141.4 km s^{-1}	137.8 km s^{-1}
Pre-shock density	n_1	1.0 cm^{-3}	0.25 cm^{-3}
Post-shock ion temp.	T_i	7.2×10^6 °K	7.2×10^6 °K
Post-shock elect. temp.	T_e	10^4 °K	10^4 °K
Cooling length to $T_e < 10^4$ °K		$10^{15}\left(\frac{n_1}{cm^{-3}}\right)^{-1}$ cm	$6.5\times10^{14}\left(\frac{n_1}{cm^{-3}}\right)^{-1}$ cm
Max T_e		105000°K	186000°K
Max T_e, T_i (recombination zone)		∿ 2000°K	86°K

[1] Inner 10 $M_\odot$ or 25 $M_\odot$ model; Woosley and Weaver (1980). A mixture of C, O, Ne, Mg, Si, Ca, S and Ar.

[SiII] λ35μ lines, which dominate the cooling in these zones by very large factors. This has the unfortunate consequence that shocks of a more realistic composition give less good agreement with observations, as in our models there is negligible flux in the [OI] λ6300, 63 Å lines either in the shock structure or its photoionisation precursor, and the [OIII] λ4363/λ4959+5007 Å ratio, predicted at 0.086, indicates a higher temperature than observed. (Lasker 1978; Chevalier and Kirshner 1979; Kirshner and Blair 1980).

More generally, we are not optimistic about the prospects for this type of model to ever describe the observations in a satisfactory manner. For example, the excitation as measured by the [OII] λ3727,9/[OIII] λ5007 ratio is an exceedingly sensitive function of temperature. For the model of Table 1 it is 0.86, about the middle of the observational range. However, a variation of shock velocity of only about 50 percent in either direction is sufficient to drive the theoretical value away from the observed range. It seems to us most improbable that objects with a velocity dispersion of several thousand km s^{-1}, sometimes showing shears of order a thousand km s^{-1} within an individual knot are excited by shocks with such a narrow range of velocities. If the knots are excited by the propagation of a radiative reverse shock into a cloudy ejecta, then equating the ram pressures implies a cloud/intercloud density ratio of order 100:1, which seems unreasonably high. In any case, such a scenario would not predict velocity shear within a cloudlet, nor why the fast-moving knots are only visible over comparatively short timescales (Kamper and van den Bergh 1976).

An idea which seems promising to us is that the knots are not radiative, but are in fact collisionless shocks. If we immerse a cloud of sufficiently small dimension into a lower density intercloud medium with large relative velocity, the intercloud medium will pass through the cloud more or less freely as a suprathermal gas. Since the stopping timescale varies as the cube of the relative velocities (Spitzer 1967), this effect is favoured at high velocity. The optical emission will then result from the ionisation and heating by these suprathermal particles, which will occur throughout the cloudlet. By analogy with X-ray ionised regions, which are predominantly heated and ionised by suprathermal Auger electrons, we expect a spectrum showing a mixture of ionisation states at fairly modest equilibrium temperature. Such a physical state seems, from the observational material, to be exactly what is required. We have therefore undertaken to model this situation.

2. HIGH VELOCITY SHOCKS AND THERMAI INSTABILITIES.[1]

For none of the published steady-flow radiative shock models does the velocity exceed 200 km s^{-1}. In part, the reason for this is that the physics is computationally complex, but the major reason must be that cooling timescales in the plasma become much longer than the timescales relevant to SNR evolution. At galactic scales, however, it is possible for a low density, high velocity shock to become radiative or for low

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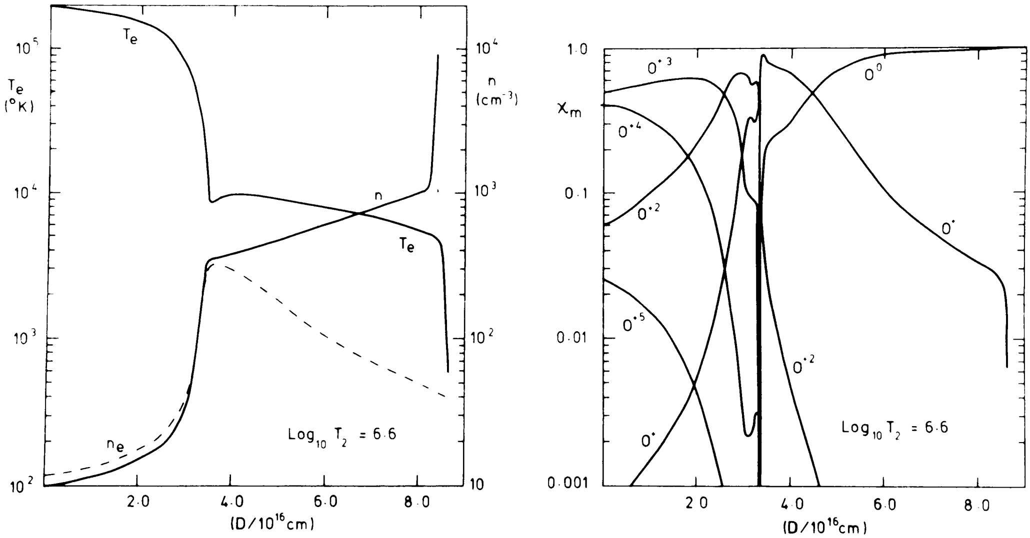

Fig. 2a,b The temperature (a) and ionisation structure in oxygen (b) for a high velocity shock of initial Temperature log T_e = 6.6 °K. Note how the cooling zone is followed by an extended region ionised by X-rays.

density hot plasma to cool by thermal instability in the condensation mode (Field 1965; Mathews 1978). Such models may therefore be applicable to optical nebulosity associated with galactic jets, such as in Cen A (Blanco et al. 1975; Osmer 1978; Graham and Price 1981) or to filaments in the vicinity of giant elliptical galaxies such as NGC 1275 (Kent and Sargent 1979) or M87 (Ford and Butcher 1979).

To simplify the computation with MAPPINGS, we have divided the cooling zone in which photoionisation is unimportant into an X-ray emission zone with $T_e > 2 \times 10^5$ and a cooler UV-optical emission zone. Since the first zone determines the radiation field for photoionisation but is too highly ionised to treat with our code, we have assumed that the plasma cools isobarically and at collisional ionisation equilibrium, and computed the resulting radiation field between 7.64 and 5000 eV using the Raymond-Smith code. (Raymond and Smith 1977; Raymond, Cox and Smith 1976). For the cooler region and the subsequent zones, we solve the full time dependent hydrodynamic flow.

The general characteristics of this are as follows (see Fig. 2a,b). When the initial temperature exceeds 10^6 °K, photoionisation effects become important in the region normally associated with the recombination of hydrogen. A narrow 'supercooled' zone appears where the ionisation state is still fairly high so that photoionisation heating is not sufficient to maintain the temperature. This is followed by a bounce-back in temperature as the plasma adjusts to photoionisation equilibrium. For high initial temperature of the plasma, there exists an X-ray absorbing photoionised region which comes to dominate the total emission for initial temperatures, T_i, in excess of 2×10^6 °K. As Figure 2 shows, this region has low ionisation state and modest temperature, and the equilibrium is dominated by Auger electrons and the secondary ionisation and heating they produce.

The emission from plasma cooling from $T_i > 2 \times 10^6$ °K is therefore rather similar to that computed for regions ionised by a power law non-thermal spectrum. Indeed, the ionising radiation field computed can be fairly well approximated by a power law of the form:

$$F_\nu = F_{\nu_c} (\nu_c/\nu)^{0.5} \qquad \nu \lesssim \nu_c$$

$$= F_{\nu_c} (\nu_c/\nu)^{2.5} \qquad \nu > \nu_c$$

Where ν_c is a critical frequency determined by the initial temperature and the geometry of the hot plasma with respect to the cool. This result demonstrates that the ability to model a emission-line region in a galaxy or a QSO by a power law ionising spectrum does not necessarily imply a non-thermal source for the ionisation.

4. SHOCKS OF FINITE AGE

Consider the timescale for cooling of a shocked plasma. For a final temperature of 10^4, this timescale (t_c) for 'cosmic' abundance is given in our models by:

$$t_c = 870\ V_{100}^2 / n_1 \quad \text{yr}$$

where V_{100} is the shock velocity measured in units of 100 km s^{-1} and n_1 is the pre-shock density in units of cm^{-3}. Thus, even for a typical shock velocity of 150 km s^{-1} with an ambient density of 5 cm^{-3}, this cooling timescale of 400 yr is uncomfortably long compared with typical ages of SNR. When one considers that the timescale for full recombination is about ten times longer, and that magnetic pressure support extends both of these timescales, it is clear that the steady flow approximation is of dubious validity.

Shocks in SNR can then be characterised by an 'age parameter' which can be defined as the ratio of shock age and cooling timescale. Consider two clouds of different density shocked at the same epoch. If the inter-cloud pressure is the same, then it follows from the above expression for t_c that the ratio of the age parameters is in the ratio of the square of the pre-shock densities of the two clouds. Thus in a cloudy medium, the densest cloudlets will become radiative first, and different filaments will be characterised by different age parameters.

It has been shown elsewhere (Dopita, Binette, D'Odorico and Benvenuti 1982 and D'Odorico and Dopita this conference) that neither the pre-ionisation condition nor the shock velocity has much effect on the visible spectra of SNR, provided that the shock velocity exceeds 100 km s^{-1}. Also, global spectrophotometry of SNR in external galaxies shows that SNR shock spectra are primarily dependent on chemical abundances. Thus, assuming that all filaments in an SNR have a given chemical abundance suggests that all the spectrophotometric data within a given SNR should be capable of being modelled simply by changing the age parameter.

Figure 3 suggests that something of the sort is happening. In RCW 103, the filaments are dense, and there is little evidence for scatter in line ratios between filaments (the solid lines show the approximate limits defined by global spectrophotometry of SNR in external galaxies). However, both RCW 86 and IC 443 show evidence for systematic spectral variations between filaments, and the measurements scatter along a line at roughly 45^{o}, showing that strong [NII] is correlated with strong [SII]. Ruiz (1981) suggests that this is an abundance effect, but this conclusion is not consistent with our abundance grids, which are characterised by a 'saturation' in the relative intensity of the [SII] lines at these abundances.

We have attempted to model this effect by radiative shocks of finite age, generated by the simple expedient of 'sawing off' the recombination zone when the required shock age is reached. Figure 4 shows the result for RCW 86. The abundance set used in the MAPPINGS model was adjusted to fit filament B1 of Ruiz (1981) which shows the weakest [SII] and [NII] lines with respect to hydrogen, and is therefore assumed to be the most envolved. The model was a fully self-consistent (Shull and McKee 1979)

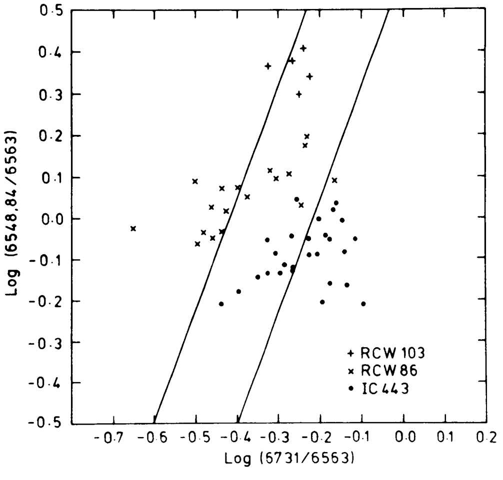

Fig. 3 Spectrophotometry of individual filaments in three galactic SNR, showing evidence for variable age parameter (see text). The data are drawn from D'Odorico 1974; Dopita, D'Odorico and Benvenuti 1980; Ruiz 1981 Leibowitz and Danziger 1982 and Fesen and Kirshner 1980.

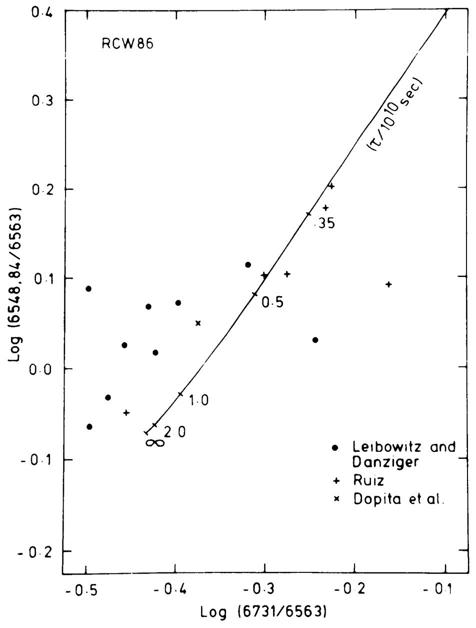

Fig. 4 Spectrophotometry of the individual filaments of RCW 86 fitted by models of varying age parameter. The pre-shock density, magnetic field and post-shock temperature were respectively 22 cm^{-3}, 2.2 μG and 180000 ^{o}K. A time of 10^{10} sec corresponds to an age parameter (see text) of 6.7.

plane-parallel radiative shock wave of finite age. As can be seen, all observed points lie within 0.15 dex of the computed age trajectory, which is well within modelling and observational errors. We thus conclude that RCW 86 shows evidence for varying age parameter in its filaments.

Curiously enough, the spectrophotometric results of Fesen, Blair and Kirshner (1982) on seventeen filaments in the Cygnus Loop cannot be as simply explained. They found a tight correlation between the intensity ratios of the [OII] and [OIII] lines with respect to Hβ, and a similar correlation between the [NeIII] λ3869 Å/H ratio and the [OIII]/Hβ ratio. Such a correlation is expected in shocks of varying age parameter, but we find that the slope of the expected correlation is wrong in the sense that the [OIII]/Hβ ratio increases more slowly from the [OII]/Hβ ratio. This remains true even if we suppose that the spectrophotometry refers to a 'time slice' of a shock only, as may be the case in shocks which have propagated through very thin sheets of denser gas.

We have only two possible explanations for these observations. It is possible that a few filaments may have unusual abundances. However enhancements of the oxygen abundance by a factor of about twenty are needed in some filaments, which would be very surprising in such an old remnant. An alternative explanation, which we have not yet investigated, is that the lower density filaments are photoionised by the UV radiation field produced by the denser ones. If this maintained a higher degree of ionisation in the cooling zone, the observations might be explicable.

[1]This section is the subject of a paper with I.R. Tuohy which has been submitted to Astrophysical Journal.

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DISCUSSION

PREITE-MARTINEZ: I do not understand how you can get a strong recombination zone behind a shock with V = 141 km/s and n = 0.25. According to fully HD computations the remnant should be in the transition phase between adiabatic and radiative phases, with no recombination region at all. Even more puzzling is the cool almost neutral region behind a shock with $V_s \sim 10^3$ km/s. A remnant with such a shock velocity is certainly in the adiabatic phase.

DOPITA: If you are referring to the oxygen-rich shocks in the first part of your question, the answer is that oxygen is a very efficient coolant. The model described in the text took only 35.8 years to cool to 10^4 °K. With regard to the high velocity shocks, these models do not apply to SNRs but to galactic jets and cooling pools of hot gas.

FALLE: With reference to the spread of shock velocity necessary to explain the observations, we have some evidence that a steady radiative shock with a velocity greater than 100 km s^{-1} cannot exist. Would this effect your results?

DOPITA: Probably.