RADIO EMISSION FROM YOUNG SUPERNOVA REMNANTS: EFFECTS OF AN INHOMOGENEOUS CIRCUMSTELLAR MEDIUM

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Abstract: The evolution of young supernova remnants has been modeled using a 1-dimensional hydrodynamic code. Turbulent dynamo amplification of magnetic fields and both turbulent and shock acceleration of relativistic electrons have been included macroscopically to produce synchotron radiation. The observed radio morphology cannot be reproduced by expansion into a homogeneous medium; it appears that many small cloudlets must be present in the circumstellar material.

Introduction: The evolution of a supernova remnant (SNR) as it expands into the local surroundings is a fundamentally straightforward hydrodynamic process (cf. Chevalier 1982). The ejected stellar material initially accelerates down an external density gradient and then decelerates when it reaches a constant-density circumstellar medium. This creates a double shock structure: an inner shock where the ejectum decelerates, a region of hot shocked ejectum, a contact surface, a region of shocked circumstellar material, and finally, an outer shock. This structure forms within the first few days of the remnant's life. When it has swept up about eight times the ejected mass, the remnant enters the blast wave phase modeled by Sedov (1959).

The radio luminosity, however, does not arise directly from the hydrodynamics. The luminosity traces processes which are essentially side effects: the amplification of magnetic fields in turbulent regions and the acceleration of relativistic electrons at shocks and in the turbulent regions. A shock will compress any tangential magnetic field and further accelerate any already relativistic electrons. The interface between the ejectum and the circumstellar medium is Rayleigh-Taylor unstable and will develop turbulence which will amplify the magnetic field and further accelerate the relativistic electrons.

To investigate the conditions in the SNR and the resultant radio emission we have used a hydrodynamic code to follow physical variables

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and have modeled macroscopically both shock and turbulent energization of fields and particles.

Model: We start with the 1-dimensional explicit Lagrangian hydrodynamic code developed by Jones and colleagues (Jones, Smith, and Straka 1981). An artificial viscosity term is used to handle shock discontinuities. The code follows the development of turbulence in the remnant by evaluating the Rayleigh-Taylor stability conditions everywhere and by using a 1-dimensional method to trace the dynamical evolution of the resultant "fingers" in unstable regions. Because the fingers rarely move more than a few times their own diameter during the length of the pre-Sedov phase, we need not consider the complication of fully developed turbulence. We need only describe the growth of the fingers at their source and their subsequent propagation through the Lagrangian mesh used to calculate the mean flow. In particular, at each boundary we describe the moving fingers by inward- and outward-directed eddy velocities and corresponding eddy masses.

Relativistic electrons can be accelerated by MHD turbulence which should occur in the unstable regions even in the early stages of development described herein. The very small fraction of the turbulent energy transferred to relativistic electrons is kept track of macroscopically by noting that the rate of transfer is proportional to the rate of energy turnover in the turbulence (e.g. Eilek and Henriksen 1984). This depends upon the eddy size which is taken to be the local density scale height. Already relativistic electrons can also be accelerated at shocks in a first order Fermi process (e.g. Axford et al. 1982). This is handled numerically by converting at each shock a small fraction of the upstream kinetic energy to relativistic electrons. The particle spectrum is not followed in the calculations but we note that shocks can apparently form power law spectra whereas turbulent acceleration will require longer time scales to develop a feedback mechanism to form a power law.

The turbulent motion will also amplify any existing magnetic field in the flow as the local averaged Lorentz force acts to drive currents and generate new magnetic field energy (e.g. Moffatt 1979). Again only a small fraction of the energy is transferred to fields but this effect is most important in producing the radio morphology of the SNR because the synchrotron radiation depends upon a power of the magnetic field strength.

As the remnant expands, flux freezing in the highly conductive medium will redirect the field. Although most of it remains disordered on a small scale, a stretching of a small part of the field along the radial direction of eddy motion at the unstable interface can create the net (radial) orientation of the magnetic fields and small fractional polarization observed in young SNRs (e.g. Matsui et al. 1984).

Results: The expansion of such a model SNR into a homogeneous circumstellar medium can produce an apparent shell with some central bright-

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ness, the appropriate polarization characteristics, and comfortably low efficiencies. For a 1.4 solar mass star and a circumstellar density of 1 particle cm^{-3}, the efficiencies for conversion of turbulent and shock energies to relativistic electrons are less than 1%; less than 5% of the turbulent energy goes into field amplification and 3% of the field is stretched radially.

Two important parameters are not reproduced by this model, however. These are brightness fluctuations of 20-30% between clumps within the shell and also the observed thickness of the shell which is typically 1/4 of the radius; the homogeneous model gives only about 0.1 to 0.15. To overcome these deficiencies, models with a clumpy circumstellar medium were constructed. By trial and error it was found that clumps with a peak density of about 2 cm^{-3}, halfwidths of about 10^{17} cm, and random spacings with a mean value of 5 x 10^{17} cm could reproduce the observations. Sample results are shown in the

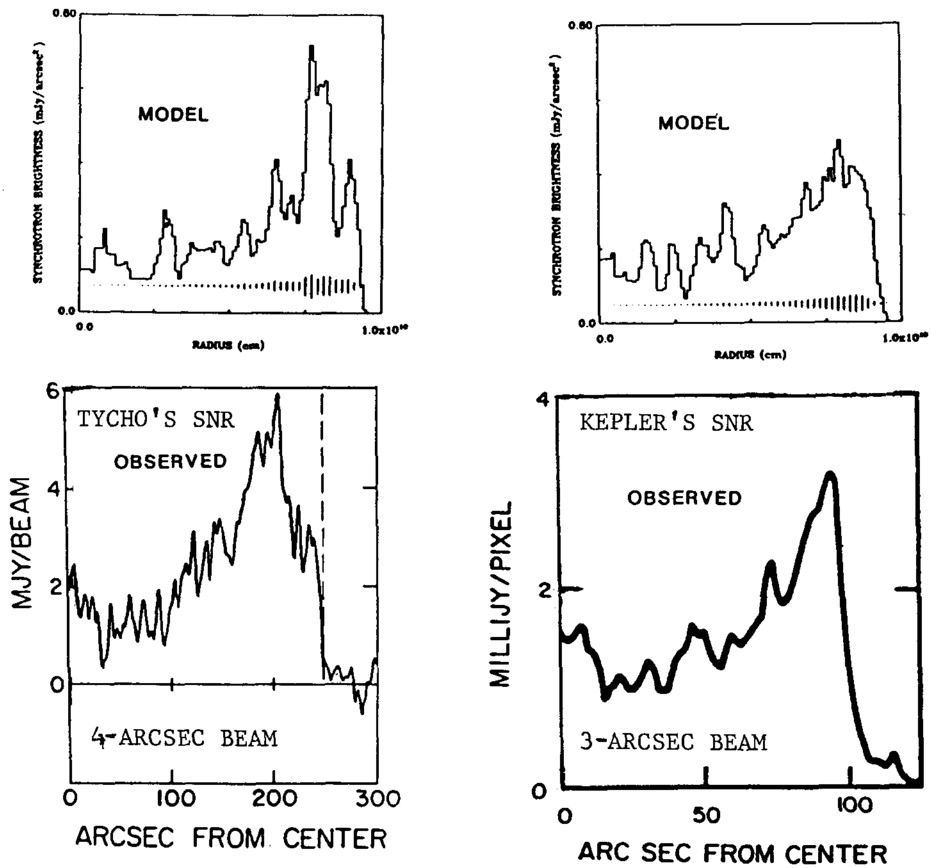

Figure: Observed and predicted radio synchrotron emission at a time of 400 years after explosion. The vertical vectors near the bottom represent the polarized power in a direction corresponding to a radial magnetic field.

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figure. Because the model is only 1-dimensional but the observed slices represent an integral along the line of sight, we have made 4 model runs with different random spacings of the clumps. These were treated as wedges and randomly placed inside a semicircle. Summation through the semi-circle produced an effective slice through the remnant for comparison with the observations. Two different random summations are shown.

The good match between the model calculations and the data has shown that the expansion of the ejected material into a clumpy circumstellar medium with the resultant unstable interfaces can produce the observed structure of young SNRs. The turbulent amplification of magnetic fields plus the turbulent and shock acceleration of relativistic particles necessary to produce the synchrotron radiation require only a small fraction of the energy present and are dynamically unimportant.

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