FINE STRUCTURE IN THE INTERSTELLAR MEDIUM

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We discuss some peculiar structures in the interstellar medium of the Milky Way and other galaxies which have not been explained. Two are associated with supernova remnants and a third concerns the temperature and density structure of cold interstellar gas.
Several supernova remnants have breakouts or apparent jets emanating from spots in their shells. It remains unclear if the shapes of these features are controlled by ejected material or structures inherent in the surroundings.
The filaments in individual supernova remnants show a great variety of shapes – some appear as if they can be represented by sheets seen from various angles while others appear more like sections of small bubbles centered near the periphery of the shell. In these dense filaments the magnetic field may be compressed enough to control the motion of the material in the plasma and observed structures.
Observations at low radio frequencies of high Rydberg state recombination lines of carbon in both emission and absorption can provide valuable information on the temperature and density of cold gas in the interstellar medium but current data are limited by poor resolution which does not allow separation of several components within the beam along a given line of sight. Newly proposed radio telescopes will improve the resolution and give a better picture of this gas distribution.

INTRODUCTION

The interstellar medium has a great variety of structures on many size scales. These range from large loops many hundreds of pc in size seen in the 21-cm line [13] and radio continuum [3] down to clumps a small fraction of a pc across which cause scintillation of radio sources. In this short presentation, we cannot describe all the types of observed features in the interstellar medium but will discuss some interesting structures, the properties and origins of which have not been fully explained. In all cases new telescopes being planned will have both increased sensitivity and resolution to help us determine the detailed properties of the observed features. Rpid advances in computer power are allowing the calculation of new 3-dimensional hydrodynamic models using the observed properties which will help us to understand the physics behind the formation and evolution of such phenomena.

JETS AND BREAKOUTS ASSOCIATED WITH SUPERNOVA REMNANTS

In general, supernova remnants (SNRs) have reasonably circular outlines although they do show irregularities around the shell. These can be explained by clumps in the interstellar medium which impede the expanding flow in some directions while leaving it unhindered in others. Indeed, the regions which are expanding more slowly are often bounded by molecular clouds or other enhancements in density. Good examples of molecular clouds slowing the expansion occur on the east sides of both W 44 in the Milky Way [4, 30] and N 49 in the Large Magellanic Cloud [5, 2].

In a few other cases, however, there appear to be highly collimated "jets" of emission breaking out of an SNR. The diameter of the opening angle can be less than 10°. A most spectacular example of such a structure is the SNR Kes 32 which has a diameter of about 25 pc, with a 16 pc long jet of width 3 pc extending out of the northeast side at an angle of about 20° to the tangent point in the shell [22]. Beyond the jet, the emission spreads out into a broad plume which rises to over 35 pc above the edge of the shell of the SNR.

A quite different example is N11 L [28] which shows a thick shell of radio emission with an apparent breakout emerging from one spot and then curving around to fill a volume about half that of the SNR along one side. In x-rays, the emergence from the shell is similar but the emission extends further from the remnant and does not spread out as much in angle. In optical emission lines we see the shell and a structure that looks like a hollow tube surrounding the radio and x-ray jet but no emission associated with the more diffuse area seen in the other wavelengths. In both these examples, the emission outside the SNR appears to have a flatter radio spectrum than that from within the shell and polarimetry of the jet from Kes 32 show no detectable polarization (Roger *et al.*, 1985).

All other known jets in astrophysics are double, such as that seen in the binary system SS 433 in the center of the SNR W 50, *e.g.*, [15], or in many star-forming regions (*e.g.*, Shulga, this conference). We see no evidence for counter jets in either Kes 32 or N11 L, however. The remnant CTB 80, on the other hand, appears to have three non-symmetrical jets [26] in addition to an extended plateau of emission associated with a small shell SNR containing an offset pulsar [25].

The lack of symmetry plus the indication that the radio emission from the extended structures may be thermal rather than synchrotron, suggest that, for these SNRs, we may be seeing emission related to some existing structure rather than jets from a central object. Perhaps low density tunnels of neutral gas between denser molecular clouds could be ionized by the progenitor star and remain heated by x-rays from the interior of the SNR. Alternatively, the structures might just represent a break in the shell where the expanding material may be moving outward through a low density hole. A different radio spectral index could be caused by different shock acceleration conditions in the tunnel through which the shock and ejected material is moving. How the initial tube structures formed in the interstellar medium remains a question. Further work to help characterize these features would include: sensitive radio polarimetry to more conclusively establish whether the radio emission is synchrotron or thermal, sensitive optical spectroscopy to provide velocity information and search for any emission within the jets, and theoretical modeling of expansion into a variable interstellar medium to see if such features can be produced with reasonable physical parameters.

Another supernova remnant, MSH 14 − *63*, shows a very different sort of apparent breakout. There is a bright ridge of H_α and [S II] emission from filaments in radiative equilibrium running along the northern side of this remnant and then another broken ridge about 15% of the remnant's radius further out [23]. At first sight this might be thought to show the projection of different parts of the shell of the SNR onto the plane of the sky but closer inspection of only the radiative filaments (there are some Balmer-dominated non-radiative filaments in that ridge as well) reveals that the outer filaments are present only at positions lined up presidely outside definite sharp gaps in the inner ridge. It is difficult to envision a geometry which produces several gaps in the shell all extending to the same distance where a new broken shell is seen. Again, velocity information and modeling would be valuable in explaining this peculiar configuration of filaments.

FILAMENTS IN OLDER SNRS

The filaments seen in the shells of old SNRs are very thin and often break up into substructures with high resolution. There is a one-to-one correspondence between the filaments observed in optical recombination lines and in radio synchrotron emission [20, 24]. The optical emission is proportional to the square of the density while the radio emission depends on the density of relativistic particles and the magnetic field strength. We thus conclude that the relativistic particle density and/or magnetic fields follow the thermal particle density. Measurements of the ratio of the two lines of the [S II] doublet at 671.6 and 673.1 nm give typical densities of 200 cm^{-3}, *e.g.*, [9], in these filaments indicating that they are in radiative equilibrium and compressing as they cool to maintain pressure balance.

The magnetic fields in the filaments are studies by radio polarimetry of the synchrotron radiation which gives us information on both the magnetic field strength and its orientation in the plane of the sky. The procedure is very difficult at high resolution, however, because the emission is faint and the polarized intensity is only a few percent of the total intensity. The limited results to date do not show a consistent pattern. In some places in the adolescent remnant IC 443 the field aligns along the axis of a filament but in others it appears to be directed across the filament [29]. Perhaps theoretical modeling of the compression process in the presence of a magnetic field can tell us how the fields should align.

The morphology of the filaments also needs more investigation. While there are cases of filaments appearing to extend across the full face of a SNR, such as one in the Cygnus Loop when seen at low resolution (Green, 1990) most of them consist of multiple small arcs such as seen in a section of the shell of IC 443 in Figure 1. This is an H_α image taken with the 1-m Prairie Telescope of the University of Illinois with a point spread function of about 2 arcsec. Most of these arcs have a convex shape with a smaller radius of curvature than the overall shell. The emission also appears to become less sharp and more diffuse toward the center if the SNR.

Hester [14] has modeled these filaments in the Cygnus Loop as crinkled sheets seen from different perspectives. A long filament across the face of CTB 1 shows a similar pattern at both optical and radio wavelengths [31, 7] and it might also be represented by such a characterization. This picture seems to work well for filaments on the face of a remnant but it doesn't show the convex pattern of filaments near the rim nor the nearly uniform radius of curvature for individual arcs as seen in Figure 1. The remnant S 147 vividly shows the same pattern of parts of small circular features [31]. Many of these arcs look like parts of bubbles with their centers in the outer parts of the SNR. Figure 2 shows such a model of thin sections of hemispherical shells with the radii, cutoffs,

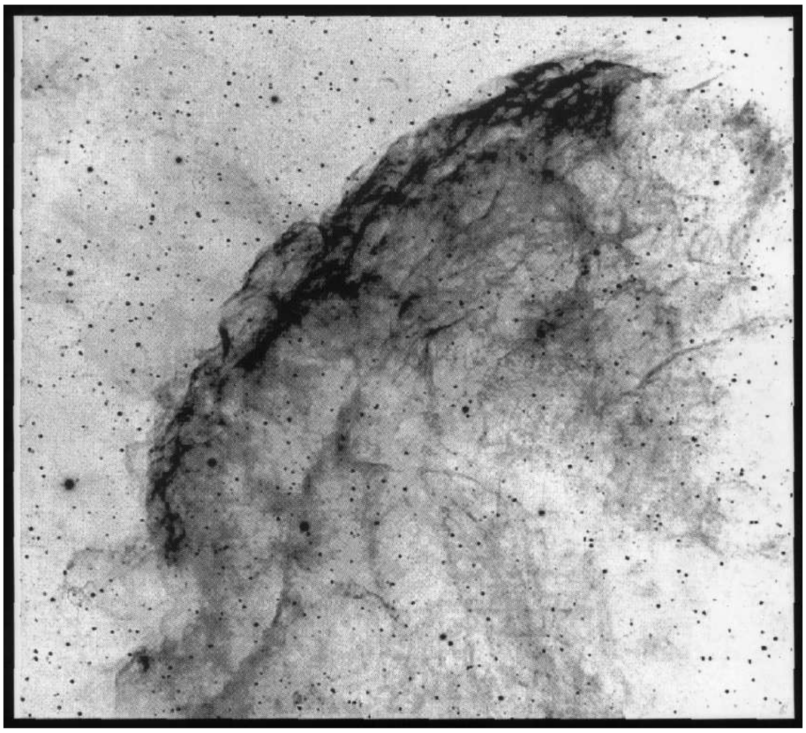

Figure 1: H_α image of filaments in the northeastern section of the supernova remnant IC 443

and locations in the shell set by random numbers. It does quite a good job near the edge but is not as good as the crinkled-sheet model on the face of the remnant. A combination of both effects may be able to reproduce the complex observed patterns.

The main problem with these geometrical models is what physical structures and conditions can cause these collections of mini-expansion centers plus some long kinks in apparent sheets toward other parts of the shell? Again, magnetic fields might give the answer. The magnetic pressure in young SNRs is well below the thermal pressure [19, 6] but it is likely to track the compression and become stronger in the filaments in older remnants [8]. The magnetic fields could then provide the effective surface tension to hold the expanding shock into curved shells as it threads its way past clumps in the surrounding medium and also to tie individual pieces into longer consistent structures.

It is clear that the super sensitivity of the Square Kilometer Array of radio telescopes (SKA) currently being planned is needed to allow accurate magnetic field mapping of these objects. The SKA will have a sensitivity improvement of greater than a factor of 100 over current telescopes which means that we can do high resolution polarimetry of these faint, thin filaments for the first time. Continually improving computer capacity also allows more detailed three-dimensional magnetohydrodynamic modeling of these expansion processes to provide a true physical basis to our understanding. We hope that these developments will take place within the next two decades.

COLD ATOMIC GAS

The distribution and temperature of atomic gas in the interstellar medium remains an important parameter in our understanding of the energetics of the galaxy. A basic question is whether most of the gas is cold material in the vicinity of molecular clouds or warmer material associated with H II regions. While the 21-cm hydrogen line can measure the total gas content along a line of sight, it cannot distinguish different temperatures unless there are absorption components in front of a bright background source. After the discovery of radio recombination lines of carbon near 25 MHz (quantum number about 640) using the UTR-2 telescope of the Institute of Radio Astronomy in Kharkiv [17], it was realized that they offer a valuable tool to probe this gas.

The lines are seen in absorption below about 150 MHz and then in emission at higher frequencies [21]. The absorption lines generally appear wider than the Doppler widths for the temperature of the gas, suggesting pressure broadening. The inclusion of some hydrogen ionization as well at these relatively high pressures and low temperatures also requires consideration of dielectric recombination to assess the properties of the material

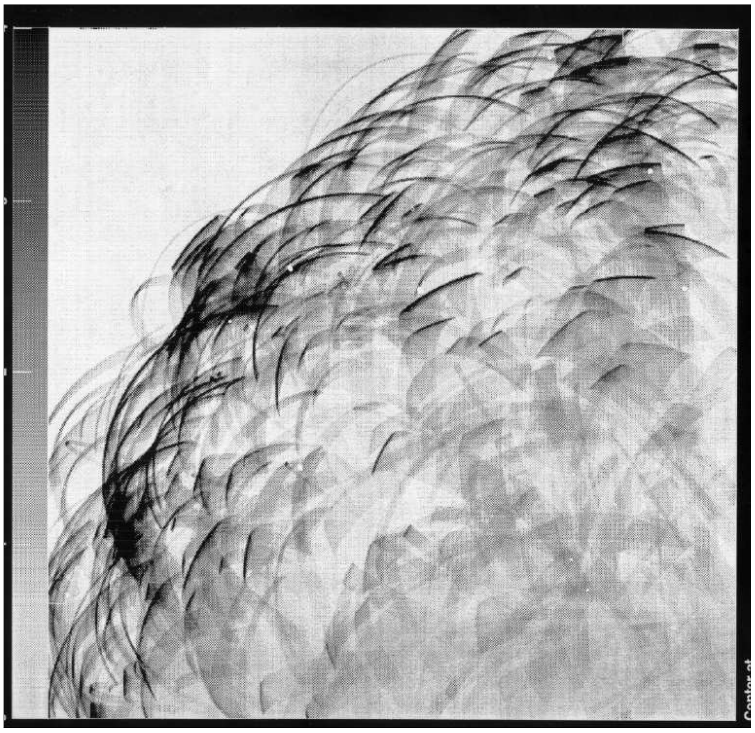

Figure 2: Model image of sections of hemispherical shells centered around the edge of an SNR shell similar to IC 443

[27]. In addition, the presence of emission lines near 322 MHz (quantum numbers of about 275) in the direction of the strong source Cas A indicates that stimulated emission must be present [21].

The observations [18, 10, 21, 16] tend to favor gas in the temperature range of 50–100 K toward most directions in the galactic plane but none of the models incorporating all of the relevant physics fully match the data [1]. In one case toward the dust cloud L1407 it is found that 20 K gas gives a more acceptable fit to the data [11].

A major problem in sorting out the actual temperature and distribution of this gas is that the poor angular resolution available to date at these long wavelengths does not allow determination of the sizes of the clouds producing the lines nor the evaluation of confusion along the line of sight. There may be several components within the observed beam. We need more complete surveys with high angular resolution at a range of wavelengths covering the transition between absorption and emission to sort out the full range of conditions throughout the galaxy. Another new radio telescope currently being discussed, LOFAR, will operate in the meter and decameter wavelength bands and should make vital contributions toward understanding this cold gas.

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