STRUCTURAL CHANGES IN CAS A, TYCHO AND OTHER YOUNG SUPERNOVA REMNANTS.

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INTRODUCTION

Structural changes have been found and investigated in a handful of young supernova remnants (SNR). The variations in the Crab Nebula (Trimble, 1968) have been known for some time. Here I am concerned with young shell remnants of which the best studied is Cas A. It is, like the Crab nebula, undergoing an overall radial expansion, although other forms of motion have also been observed. Simple expansion has been found in Tycho (3C10) and the remnant of SN 1006. Optical measurements of the remnant of Kepler´s supernova (SN 1604), however, have failed to show motion of the magnitude expected from this relatively young SNR.

PRELIMINARY CONSIDERATIONS

From the following line of reasoning one can infer that motion might be observable in young SNR. A typical member of the class is at least 3´ arc in diameter and has an age of, say, 500 yr. The average expansion speed at the rim is, then, about 100" arc/500 yr = 0."2 arc/yr. If the motion has been undecelerated, this will also be the present speed, a value which can be measured on a time scale of 5-10 yr using modern techniques.

A model applicable to SNR which are strongly interacting with an ambient medium was considered and discussed by Oort (1946). He suggested that nearly circular nebulae like the Cygnus Loop might indeed be remnants of supernovae which are now sweeping up interstellar material like a snow-plow. In this case momentum is conserved, although energy is not (the gas heated at the interaction front is not so hot that radiation losses can be neglected), and it is easy to show that the expansion speed should be one-quarter of the average value.

A third possibility, intermediate to the other two, describes the stage where the kinetic and thermal energies are independently conserved. A similarity solution due to Sedov (1959) treats the case of a spherical shock wave expanding into a uniform medium. The amount of interstellar material encountered much exceeds the ejecta mass, and the shock front moves at two-fifths of the average expansion speed.

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Woltjer (1972) considers these phases to represent the first three stages of SNR evolution (in the final stage the remnant loses its identity and disperses). Of particular interest to SNR motion studies is the proportionality constant, η, in the relationship between the expansion speed, v, the remnant radius, r, and its age, t:

$$v = \eta \frac{r}{t}$$

For the phases of SNR evolution outlined above, we expect (Woltjer, 1972):

Phase I (undecelerated motion): $v = \frac{r}{t}$

Phase II (energy conserving): $v = \frac{2}{5}\frac{r}{t}$

Phase III (momentum conserving): $v = \frac{1}{4}\frac{r}{t}$

A primary goal of motion studies is to test these relationships in the light of other information about a given remnant, and in particular determine the value of η.

INDICATORS OF MOTION IN SNR

The evidence for motion in SNR falls into two categories: direct and indirect. In the former a property is measured which directly gives a speed, while the latter involves measurements from which one can infer that different parts of the remnant are in relative motion.

Direct evidence

(a) Determine the displacement of identifiable features. A major advantage of this approach is that a single measurement near the limb of an SNR is sufficient to determine the expansion rate. Furthermore, the fact that shell remnants have a sharp, prominent outer boundary makes them particularly well-suited for such measurements. However, the time required for the SNR boundary to advance by a detectable amount usually dictates considerable patience in the observer. It may, in turn, lead to difficulties if identifiable features change on a similar time scale, which is a major pitfall.

(b) Spectroscopic determination of velocity. The advantage of this technique over a proper motion measurement is that one obtains the velocity instantaneously. However, conclusive evidence for motion requires that different velocities be found in a remnant or that we have at least an indication of its systemic velocity. An unambiguous determination of the expansion speed requires that spectra be obtained from material near the remnant's center in both the approaching and receding hemispheres. For many shell remnants such material is difficult to observe.

It may be worth noting that techniques (a) and (b), if reliably applied to a single SNR, can be used to determine its distance. This has been done by Van den Bergh (1971) for Cas A. Its inherent uncertainty

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lies in the tacit assumption of a uniformly expanding spherical shell.

Indirect evidence

(a) Changes in flux density or surface brightness. Such variations can imply compression or expansion of a gaseous component, and hence motion. The best example is probably the adiabatic expansion of the relativistic plasma responsible for radio emission from young SNR, which should, as Shklovsky (1960) correctly predicted, produce a measurable decrease in the flux density of Cas A. The observational confirmation (Högbom and Shakeshaft, 1961) provided early evidence that Cas A probably was expanding. The Shklovsky model assumes that the adiabatic losses dominate and that the relativistic particles have no source of additional energy; even in the case of Cas A it was evident from the start that this is probably not true.
(b) Frequency changes in spectral line features. If it can be shown that such a change occurs in one spatial component (and is not due to, for example, brightness changes in a blend or superposition of features) then it implies acceleration of the gas and thereby motion.
(c) Changes in the radio polarization. Polarized radiation at long wavelengths is, through the Faraday effect, quite sensitive to changes in the magnetoionic medium through which it propagates. The observation of variations in the linearly polarized component may indicate changes in the density of material and hence motion within the remnant.
(d) In general, any temporal change observed in an SNR makes it a candidate for motion studies.

MOTION IN CAS A

The wealth of observational information which has been collected on Cas A is largely due to the efforts of Sidney van den Bergh and his coworkers over many years. Starting with plates taken by Baade they have obtained data of high uniform quality spanning well over a quarter of a century. The existence of this optical treasure-trove has no doubt helped spur researchers in other wavelength bands to peruse their data for corresponding changes.

Optical studies

The situation through the mid-1970s has been summarized by Kamper and Van den Bergh (1976). From the standpoint of motion in Cas A, there are two populations of filaments: the fast-moving knots, and the quasi-stationary flocculi. The former indicate an expansion lifetime for the remnant of some 300 yr, while the latter suggest a dynamical age some 35 times larger. In their analysis of the fast-moving knots, Kamper and Van den Bergh find a close correlation between position and velocity. This smooth linear relationship means, they argue, that there has been essentially no deceleration of this component, although there are small systematic differences between groups of filaments such as the "flare" to the northeast, which is moving faster than the rest.

In their latest analysis, Kamper and Van den Bergh (reported

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elsewhere in this volume) find that the longest lived knots, if their motions are linearly extrapolated back in time, yield a date for the supernova explosion of 1658±3 yr. The finite lifetimes of the knots - both increases and decreases in brightness have been observed, and the changes are consistent with an e-folding time of 25 yr - provide a not insignificant obstacle to analyses of the dynamics. Brightness and shape changes in individual filaments certainly can be a source of error.

Radio Studies

As with the optical filaments, radio knots in Cas A also exhibit substantial brightness changes over similar time scales. Furthermore, radio velocity determinations which different investigators using a variety of instruments have made disagree as to whether overall expansion is present, although they all find evidence for motion.

Before considering the attempts to observe expansion in Cas A it may be useful to remember that the steady decline observed in flux density (Högbom and Shakeshaft, 1961), which predates the synthesis maps, provides strong circumstantial evidence that the remnant is indeed expanding in accordance with Shklovsky's (1960) model calculation. In addition, reports of a low frequency "flare" (Erickson and Perley, 1975; Read, 1977a, 1977b) with a time scale of 2-6 yr suggest activity, if not motion, in Cas A.

Bell (1977) used maps made five years apart with the Cambridge One-Mile and 5-km telescopes to observe changes in some thirty compact knots at a frequency of 5 GHz. He found evidence for expansion although there was large scatter and a substantial degree of tangential motion.

Shortly thereafter, Dickel and Greisen (1979) using 2.7 GHz observations made with the NRAO three element interferometer in 1967 and 1976, were unable to find evidence for systematic expansion in the pattern of essentially random motions they observed. The result was, however, not fully inconsistent with Bell's determination considering the formal errors. Dickel and Greisen suggest that the discrepancy may be (partially) attributed to brightness changes in blends of multiple knots which give rise to apparent motion if the angular and temporal sampling are not propitious for resolving this effect.

Various criticisms can be levelled at both sets of measurements. The most significant are that Bell compared data obtained from two different instruments, while Dickel and Greisen used measurements which did not sample the visibility plane well. Of these, the latter may be the most telling. Nevertheless, it is worth noting that both studies agree that the fine scale structure in Cas A is in motion, and that it has a substantial, if not dominant, random component.

The most extensive and determined effort to study motion in Cas A, which avoids both of these deficiencies, has now been carried out by Tuffs (reported elsewhere in this volume). Using 5 GHz observations made with the Cambridge 5-km telescope in 1974 and 1978 he has determined the motion of nearly 350 compact features as well as several extended ridges. The main result is that an overall pattern of expansion is clearly present despite a very considerable random component, confirming Bell's main conclusion. The mean radial expansion speed for all measured

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compact features corresponds to an expansion "age" (ignoring deceleration) of 950 yr. The upper envelope in a radial velocity vs. distance from center diagram - the expansion of the fastest radio features - is in reasonable agreement with the motion observed in the system of fast moving optical filaments. This suggests that if the observed motion of radio features corresponds to material transport, we are witnessing acceleration and/or deceleration in Cas A on a large scale. The implications are discussed in greater detail in Tuffs' contribution.

The episode would thus appear to be neatly concluded and the dispute settled, were it not for observations recently carried out with the VLA. Angerhofer and Perley (1982) have begun a program to monitor changes in Cas A. In their first results, based on a comparison of observations separated by 21 months, they have measured the displacement of some 120 radio knots. They find radial and tangential motions of about the same magnitude, but observe no pattern of overall expansion, a conclusion which appears to be in qualitative agreement with Dickel and Greisen, but not with Bell or Tuffs.

A definitive resolution of this discrepancy will probably be forthcoming only if the different groups are able to compare their measurements of the same radio features. Such a comparison cannot be done in more than a limited way with the existing data which were obtained at different (and not necessarily overlapping) times over intervals ranging from less than 2 to more than 9 yr. The pair of American determinations suffer from an undersampling of the visibility plane, and as a result they observe only a fraction of the emission from Cas A. Considering both this effect and the difference in epoch, it is not too much of an exaggeration to maintain that the Cambridge and American groups have not actually been studying the same thing. This is surely the best place to start searching for the cause of the discrepancy.

Though the problem may not be resolved, it is clear from all the radio studies that the radio knots do not generally share the motion of the fast moving optical filaments. A detailed radio-optical comparison would nevertheless be fruitful, even if it were to do no more than demonstrate that none of the features is spatially coincident. With the resolution which synthesis telescopes now achieve such a comparison is feasible.

Ultimately, we will want to know the relationship of the radio and optical emission to the shock front(s) which bound Cas A, for it is only the velocity of the latter which we can simply apply to the equations of motion. It seems a safe bet to assume that the shock is moving at least as fast as the fastest filaments, but an unambiguous determination of shock velocity must await an X-ray proper motion study. Thus far, the only changes which have apparently been observed in the X-ray are possible brightness variations (Murray et al., elsewhere in this volume). An improvement in this situation will probably have to await an X-ray observatory with high resolution imaging capability which remains in orbit for at least five years.

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MOTION IN THE REMNANT OF SN 1572 (TYCHO)

The situation in Tycho's remnant (3C10) is refreshing in its simplicity when contrasted with the complexity observed in Cas A. This difference may not be too surprising for although both objects are young shell SNR, they differ significantly in many radio and optical properties. In fact, both optical (Kamper and Van den Bergh, 1978) and radio (Strom et al., 1982) measurements show clear expansion in 3C10 and are in good agreement.

Optical expansion

The optical determination is based upon a series of Hale 5 m telescope plates beginning with one obtained by Baade in 1949. Kamper and Van den Bergh (1978) have analyzed observations spanning 28 years. Although the filaments are quite faint, they do lie near the limb so their speed should directly give the rate of expansion. Motion can, in fact, be readily seen in the brightest filaments along the eastern rim. The analysis involved determining the radial position (with respect to the center of 3C10) of the nebulosity at locations where it is sufficiently sharp, from which the weighted mean was taken. The solution is thus strongly influenced by the brightest filaments, a point which I will return to shortly.

The average expansion speed found is 0."21 arc/yr. This agrees well with the value predicted by the Sedov solution for a 400 yr old shell provided the shock radius can be ascertained from the size of the radio remnant. Such an assumption is necessary because the nebulosity is so irregular, and is distributed along less than half of the limb, that an optical determination of the radius would be quite uncertain. In the same vein, it is interesting to note that the radio map (Duin and Strom, 1975) was also used to determine the geometrical center which was an essential reference point for intercomparing the optical plate material. In several respects, then, radio data played a significant role in interpreting the optical measurements.

Radio expansion.

A prime reason for carrying out a radio study of motion in 3C10 is the symmetry and hence apparent completeness of the shell, and the strength and sharpness of the outer rim. While this contrasts favorably with the optical situation, a disadvantage is the lower radio angular resolution. Nevertheless, Strom et al. (1982) have determined the expansion rate at regular intervals around the limb of 3C10 from 1.4 GHz observations made eight years apart with the Westerbork Synthesis Radio Telescope (WSRT). The result of these measurements is summarised in Fig. 1, where the optical determinations are also shown for comparison.

It is clear from Fig. 1 that the optical and radio measurements are in good agreement, and that several values in the east are significantly low. Ignoring the lowest radio point, one obtains an average expansion speed of 0."26 arc/yr. This is higher than the optical value of 0."21 arc/yr because of the low points in the east, suggesting that the

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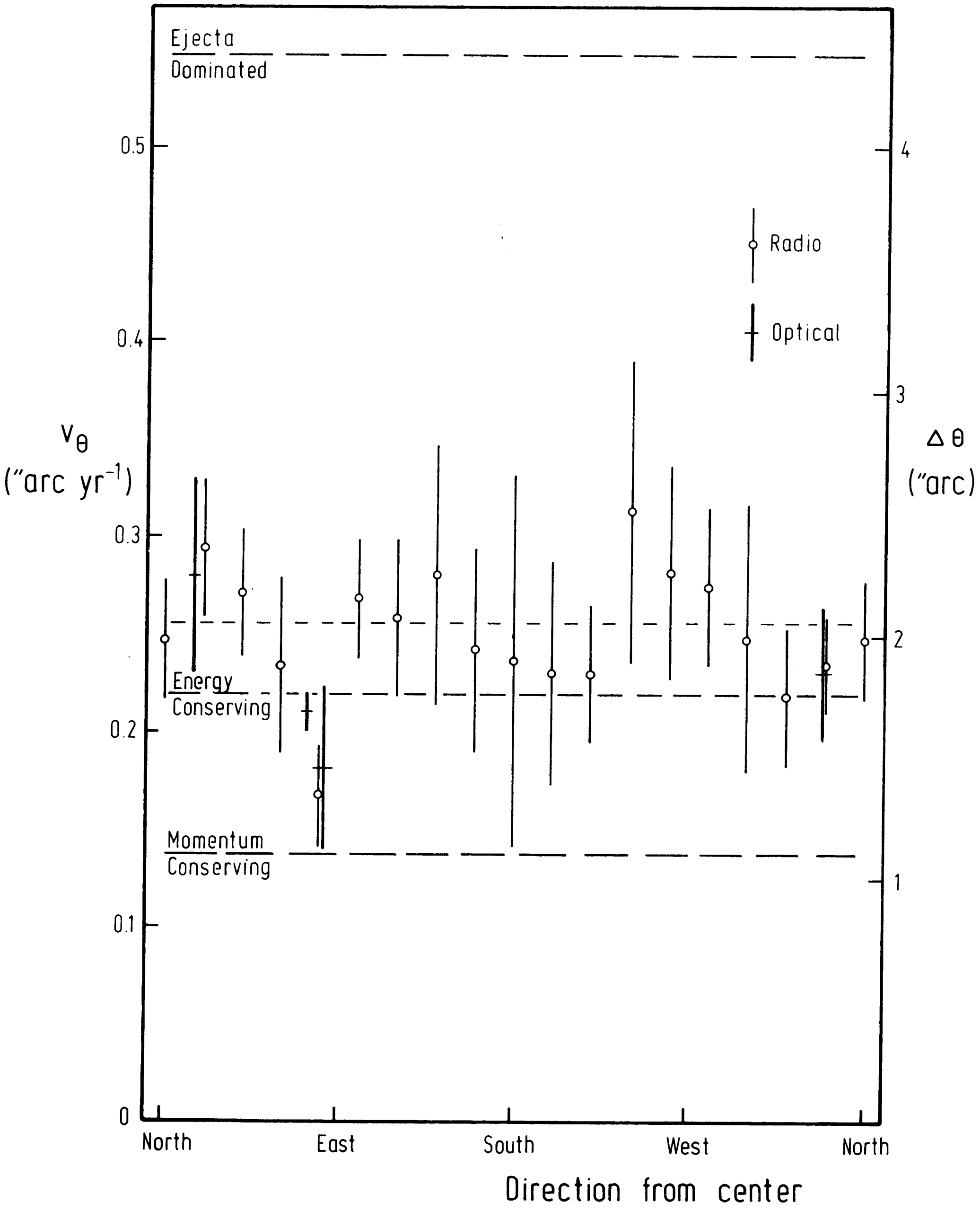

Figure 1. The expansion speed measured around the periphery of Tycho. Short dashes show the average radio value, excluding the anomalous point in the east.

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expansion speed of the brighter nebulosity may be anomalously low. This, in turn, has implications both for optical determinations of SNR expansion speeds and for interpreting the dynamics in Tycho.

Considering this last point briefly, it is probably significant that this eastern region of brighter filaments and low expansion speed coincides with a prominent dent in the otherwise nearly circular radio shell (Strom et al., 1982). The most likely explanation is that we are witnessing an encounter between the shock front and a region of higher than average density, perhaps a discrete interstellar cloud. It will be interesting to see whether other changes can be observed here in coming years.

Further analysis of the existing 1.4 GHz data, although somewhat preliminary, has turned up additional information. New maps have been made in which the longest baselines are not weighted down, so as to obtain higher angular resolution (at the cost of an increased sidelobe level). They show that discrete emission peaks in the interior also participate in the overall expansion, with a speed which appears to increase with distance from the center. Furthermore the polarization maps, while generally in good agreement, show several areas where the position angles appear to have changed substantially over eight years. This work, including a comparison of two 5 GHz maps made with the WSRT, is continuing.

We must now consider how the radio/optical expansion relates to the shock dynamics. In view of the compatibility between the two sets of measurements the conclusions we draw should be less ambiguous than was the case for Cas. Nevertheless, we need to know something about the location of the shock front. In a recent preprint, Seward, Gorenstein and Tucker (see also Gorenstein et al., elsewhere in this volume) present and discuss a high resolution X-ray map of Tycho. The shape of the outer boundary bears a remarkable similarity to the radio map, and a detailed comparison shows that the two images are nearly congruent. This degree of coincidence suggests that the relativistic particles are largely accelerated in, or directly behind, the shock front. If this is correct, the radio expansion measurements of the outer edge should faithfully reflect the shock speed.

The technique used for determining the radio expansion (Strom et al., 1982) is most sensitive to the steepest gradient. As this occurs along the outer boundary, it should ensure that the measurement essentially refers to the motion of that boundary, and hence of the shock. (It should be pointed out that the radio measurements compare the positions of the most recently accelerated particles, and the "motion" observed does not necessarily reflect flow of the relativistic plasma, although it does follow the progression of the shock.) The sharpest optical filaments are found at the very edge of the radio remnant, so it is not surprising that they share the radio expansion observed.

The expected expansion rate for the three phases of SNR evolution - the undecelerated, adiabatic and momentum conserving stages - are indicated on Fig. 1. The observations are clearly only consistent with the adiabatic or energy conserving phase, and Strom et al. (1982), using the calculations of Rosenberg and Scheuer (1973), estimate that the swept-up material exceeds the ejecta mass by a factor of 8. This may

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conflict with the mass ratio of 2 which Seward et al. obtain from their X-ray data, although the uncertainties in that estimate could be as much as a factor 2 in each component.

The ratio of instantaneous to average speed found by Strom et al., $\eta = 0.47$, is larger than the value of 0.4 predicted from the Sedov solution by a marginally significant amount. If the effect is real, it may mean, as suggested by the mass ratio estimate mentioned above, that the amount of swept-up material is not quite sufficient to bring Tycho fully into the energy conserving phase. There are, however, other possibilities.

Chevalier (1982) has shown how a power law density profile for the outer atmosphere of the supernova precursor will modify the value of η in a Sedov-like solution. For a Type I supernova like Tycho he suggests a value somewhat in excess of 0.4. Another possible modification to the dynamics would be caused by the evaporation of dense cloudlets behind the SNR shock front (McKee and Ostriker, 1977). This gives a value of between 0.4 and 0.6, although the number of evaporating cloudlets encountered by a young remnant may be too small to have much effect.

MOTION IN OTHER YOUNG SHELL REMNANTS

For two other shell remnants - those of SN 1006 and SN 1604 (Kepler) - the association with a historical supernova is convincing. Both have been the subject of optical motion studies with markedly different results. Van den Bergh and Kamper (1977) find very little evidence for expansion in Kepler, the velocities being much smaller than expected and not conforming to an overall pattern. They suggest a dynamic age which, as in the case of the quasi-stationary flocculi in Cas A, is a great deal larger than the probable age of the remnant.

In the remnant of SN 1006, Hesser and Van den Bergh (1981) have measured the speed of sharp filaments along the limb. Their result gives $\eta = 0.47$, suggesting that this remnant is also in the Sedov phase. In neither SN 1006 or Kepler has it been possible to carry out radio motion studies. Their southern declinations have so far made them inaccessible to high resolution synthesis telescopes, all of which are sited in the northern hemisphere.

CONCLUSIONS

It should be clear from this brief review that attempts to measure and interpret motion in young SNR have achieved a considerable degree of success. An optimist might be tempted to emphasize that in two of the objects, the remnants of SN 1006 and SN 1572, effective agreement is found between the measured expansion rate and the Sedov prediction. He might also point out that nothing in the X-ray data suggests that either remnant is in anything other than the adiabatic phase, and in Tycho the optical and radio determinations of expansion agree well.

Regrettably, I must warn against such a sanguine attitude. Even attributing the deviations in average expansion speed from the expected Sedov behavior to measuring uncertainties, we are still faced with real velocity differences within Tycho. The mechanisms for producing the

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radio and optical emission are so different that we really do not know whether they should display the same (apparent) motion, and if they do we can only guess why. Moreover, the expansion observed in SN 1006 is solely based on optical observations of nebulosity in one limited area; we have no way of knowing to what extent this is representative of the global motion.

In point of fact of the four young shell remnants in which motion studies have been attempted, one produces a confusing picture of both moving and nearly stationary features, one shows practically no motion at all, while the other two are roughly doing what we expect. A pessimist could be forgiven for saying that we have almost as many types of motion as objects studied, a dismaying state of affairs. How might this be rectified?

On the observational side I think that both the Cas A and especially Tycho studies demonstrate the value of radio expansion determinations. Kepler and SN 1006 should be the subject of similar measurements - both can be observed with the VLA. Work on Cas A and Tycho should continue, in coordination where possible with new optical measurements; for Cas A this is particularly important. Where feasible more velocities via spectroscopy ought to be obtained to enable exploration of the velocity field. Improved instrumentation and the Space Telescope should create new opportunities here. It goes almost without saying that X-ray motion studies are sorely needed, but they are probably some years in the future.

On the theoretical side there are at least as many problems to be tackled. Where (not to say how) does particle acceleration occur, and how should the synchrotron volume emissivity vary with distance from the shock? Where does the optically emitting material lie with respect to the shock? Young shell remnants appear to be in either the undecelerated or energy conserving phase. We need more work on the transition between these two evolutionary stages. Finally, observers in particular are keen to know which measurable quantities provide a crucial test for theoretical models.

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DISCUSSION

WOLTJER: What can you say about changes in the total flux and in the polarization of Tycho?

STROM: As reported in our paper on the 1.4 GHz expansion (Strom et al., 1982), we find an insignificant decrease of -0.23 ± 0.19 per cent/yr in the flux density of Tycho. The Shklovsky model based on adiabatic expansion and magnetic flux conservation predicts a decrease of -0.49 per cent/yr. Our results are thus marginally inconsistent with a situation in which expansion losses dominate.

Turning to the polarization changes, our preliminary results show significant position angle differences in a few regions although the two maps are generally in good agreement. The most substantial changes are found in the northeast quadrant, approximately where the brightest nebulosity occurs. A rough calculation suggests a change in the product of electron density, magnetic field strength and path length of at most about 20 cm^{-3} G pc. This is comparable to the changes between adjacent regions found by Duin and Strom (1975) in their analysis of cellular structure observed in the polarization distribution.

McKEE: Theories of relativistic particle acceleration by a first order Fermi process in shocks suggest a precursor of relativistic particles extending ahead of the shock. Electrons in such a precursor could radiate in the interstellar magnetic field. What limits can be set on the intensity of such emission around bright radio-emitting SNRs?

STROM: The best limits to halo emission around the brighter remnants are, as far as I am aware, about 1% of the peak brightness, although Wilson and Weiler have recently set better limits to extended emission around the Crab Nebula. Using the WSRT in redundancy mode and applying closure phase we can now improve upon this by a factor of between 10 and 100. For a bright remnant such as Cas A we should be able to detect emission with a surface brightness of 2-10 mJy/beam (for a 12" arc synthesized beam at 21 cm). For a weaker remnant such as Tycho the measurement would be noise limited to a few tenths of a mJy/beam (depending on the amount of observing time invested).

TUFFS: There have now been four measurements of the radio expansion

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of Cas A. The Cambridge results, by Bell and myself show that the remnant is expanding with a time scale of 1000 yrs, whereas the results of Dickel, with the NRAO interferometer, and more recently Angerhofer & Perley, with the VLA show only random motions for the radio morphology. I should like to point out that there are significant differences between the sampling in the aperture plane of the various surveys which points to the Cambridge results being more reliable. Both my observations, and those of Bell, are well oversampled in the aperture plane, and both Cambridge 5 km observations had exactly the same telescope configuration. The NRAO observations also had the same telescope configuration for both epochs, but were severely undersampled in the aperture plane, thus necessitating the use of clean. Clean is a somewhat risky technique to use on Cas A, as the broad scale structure dominates the visibility function. In fact the compact features on 5 km maps contribute only 1/40 of the total flux of Cas, and extreme care is obviously necessary when cleaning the map. This is particularly relevant to the measurement of proper motions when the grid point separation on the map is much greater than the proper motions, as is the case for Cas A.

I have also measured the proper motion of extended shell features in Cas A (up to 1 arc minute in size) and these show the same overall expansion as for the compact features, with a true time scale of ~1000 yr. There is no question, therefore that the proper motion is dependent on the morphology of the radio features; it is not.

DICKEL: I think the major difference between the NRAO and Cambridge results could be, as suggested by Strom, that the ones taken at NRAO (by Greisen and myself with the 3 element interferometer and also with the VLA by Angerhofer and Perley) do miss the short spacings responsible for the diffuse component and so we see only the small scale features. The Cambridge ones include the diffuse component which is probably 2/3 of the total flux density.

The VLA data are well sampled and so can be further processed by "clean" plus other algorithms and the 3 element interferometer data show the same results for the original or "dirty" results.

GULL: I would be intrigued to know the 5 GHz flux of the point source at the centre of 3C10 (it is 4.0 mJy at 2.7 GHz).

STROM: In our recent 5 GHz map we find a flux density for this object of about 2.7 mJy, so there seems to be nothing remarkable about its spectrum.

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