# THE EXPANSION OF THE X-RAY REMNANT OF TYCHO'S SUPERNOVA (SN 1572)

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**Abstract**

The angular expansion rate of the X-ray remnant of the supernova (SN) observed by Tycho Brahe in AD 1572 has been determined using observations by *ROSAT*. From two High Resolution Imager (HRI) pointings separated in time by 4.5 yr, I determine a mean expansion rate for the blast wave of $0.42 \pm 0.06''$ yr$^{-1}$, which is larger than published results from optical and radio observations. The X-ray expansion is consistent with the dynamical evolution expected from a young ejecta-dominated remnant which has experienced only modest deceleration. I find evidence for differential expansion in that the interior of the remnant appears to be expanding at a somewhat slower rate. The expansion rate varies significantly with azimuth as well. In particular, I find that two small knots in the southeastern part of Tycho are moving more rapidly than any other feature in the X-ray image. Previous work has established that these knots are clumps of highly enriched stellar ejecta with very different abundance distributions. This is the first evidence for ejecta "bullets" in the remnant of a Type Ia SN.

## 1. Introduction

The gaseous remnants of historical supernova explosions provide astronomers with a valuable class of objects for investigating the dynamical evolution of supernova remnants (SNRs). For these remnants one knows the average expansion rate and thus a determination of the current expansion rate yields an indication of the remnant's deceleration. However the expected motions are small, $<1''$ yr$^{-1}$, and thus significant measurements of current expansion rates in SNRs require high angular resolution, long time baselines, and deep observations.

Tycho's SNR is an ideal target for such studies. Indeed, the expansion of Tycho's SNR has been measured previously in both the optical (Kamper & van den Bergh 1978) and radio bands (Tan & Gull 1985). The observed proper motion of the optical filaments indicate expansion rates ranging from $0.18''$ yr$^{-1}$ to $0.28''$ yr$^{-1}$. Since the amount of material probed by the optical emission is a tiny fraction of the total mass of Tycho's SNR and filaments appear only toward the north and east near the remnant's periphery, observations in the optical band are unable to provide a comprehensive picture of the expansion of the remnant. Radio data reveal a nearly circular, limb-brightened, clumpy shell of emission. The overall expansion of the entire radio remnant has been determined to be $0.113 \pm 0.006$ % yr$^{-1}$, although azimuthal sectors of the remnant are observed to expand at rates varying from $\sim$0.05 % yr$^{-1}$ to $\sim$0.15 % yr$^{-1}$ or more. Again, the radio band probes material different from that in the X-ray or optical: in this case regions of compressed magnetic field and relativistic electron acceleration.

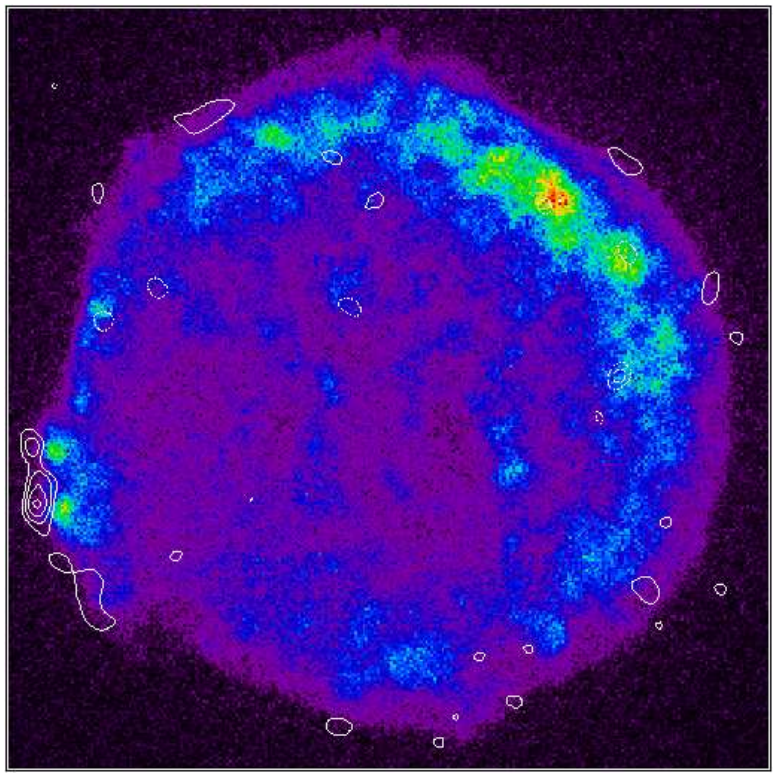

Fig. 1. Deep *ROSAT* HRI soft (0.2– 2 keV band) X-ray image of Tycho's SNR. Solid (dashed) contours show regions of increased (decreased) flux when this image is compared to one taken 4.5 years earlier. The contour levels are in units of $\sigma$ and the ones shown correspond to values of $-4$, $-3$, 3, 4, 5, and 6.

## 2. X-ray Observations

Figure 1 shows a 104 ks observation of Tycho taken by the HRI in February 1995. This image is about five times deeper than any previous high resolution X-ray image and it reveals interesting new features. Most notable is the weak rim of emission seen clearly around the entire remnant, which is believed to be the blast wave propagating through the surrounding circumstellar medium. The time baseline between this pointing and the first epoch one (done in July 1990) was about 4.5 years, roughly 1% of the SNR's age. A number of techniques were developed to estimate background (made difficult by the strong grain scattering halo from Tycho), generate exposure maps (including telescope vignetting and spatial variations of the HRI quantum efficiency), correct for aspect drift, and finally align the images. The contours on the image show small-scale-size regions where a significant change in X-ray flux has occurred in 4.5 years. Notice that the increased brightness regions (solid contours) are distributed around the periphery of the remnant, while the regions of dimming (dashed contours) appear further in. Simulations were used to assess the significance of these features and I find that most of the flux changes are real and represent evidence for expansion of Tycho's SNR.

I determined the expansion rate by examining the count rates in azimuthal sectors of a thin radial region at the edge of the remnant. Quantitative results were obtained by shifting the first epoch image along the direction of the center of each sector until the count rates in the old and new images, from that azimuthal region, were the same. The X-ray expansion rates as a function of azimuthal angle are shown in Figure 2 along with radio and optical results for

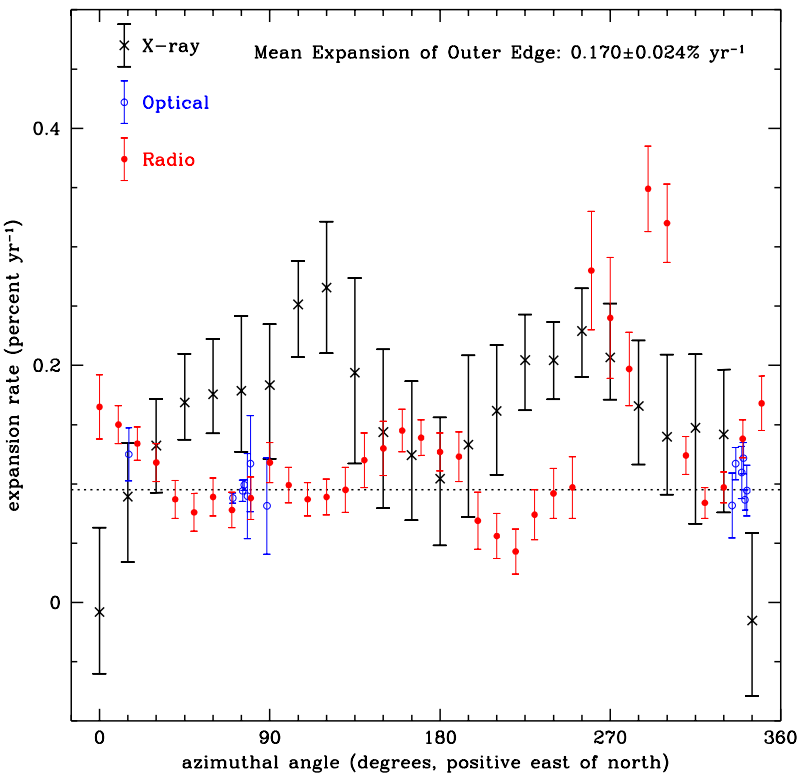


Fig. 2. Expansion of Tycho's SNR in the X-ray, optical, and radio bands. The rate corresponding to the Sedov expansion law ($n = 0.4$) is shown as the horizontal dashed line. The X-ray points at 105° and 120° include the location of the bright knots in the southeastern quadrant of Tycho. Note that these points are consistent with undecelerated motion (a value of 0.24% yr$^{-1}$).

comparison. Note that each azimuthal sector was 30° wide, although we show results for sectors with centers separated by 15°.

The azimuthally-averaged current expansion rate of the outermost rim of the X-ray remnant is $0.42 \pm 0.06''$ yr$^{-1}$ (90% confidence level errors). For a radial region that is slightly interior to this but which still precedes the brightest ring of emission, I find a slower expansion rate $0.23 \pm 0.09''$ yr$^{-1}$. When the age, $t$ of a remnant is known, it is possible to express its expansion rate in terms of $n \equiv t\dot{\theta}/\theta$, where $\theta$ is the angular size. The mean radii of the selected radial regions in Tycho are $248.9''$ and $238.2''$ so the expansion rates are $n = 0.72 \pm 0.10$ (outer edge) and $n = 0.41 \pm 0.16$ (inner edge). The radio data, as analyzed by Tan & Gull (1985), give an average expansion rate of $n = 0.462$. One possible explanation for the difference with the X-ray results may be that the radio expansion was obtained over the entire radial extent of the remnant. This would tend to "dilute" the effect of the fastest moving material at the outermost rim of the remnant.

## 3. Discussion

The Sedov (1959) similarity solution for the dynamical evolution of SNRs predicts an expansion rate of $n = 0.4$. As is well known, this model assumes that the ejecta are dynamically insignificant, so its applicability to Tycho's SNR, where the ejecta are clearly dominant, is questionable. Models where the SN ejecta are important have been developed by Chevalier

(1982) in which the ejecta and the ambient medium are assumed to be in the form of power-law density profiles. For parameters appropriate to Tycho (i.e., a uniform interstellar medium and a steep power law, $\rho \propto r^{-7}$, for the exploded white dwarf envelope), these similarity solutions predict a rate of $n = 0.57$. Neither of these models accounts for differential expansion. Hamilton, Sarazin, & Szymkowiak (1986) proposed a model for Tycho wherein the blast wave was expanding as $n = 0.70$ and the ejecta (specifically the contact discontinuity) were expanding more slowly: $n = 0.60$. The azimuthally-averaged X-ray results presented here are rather consistent with this latter model.

The expansion shows significant azimuthal variation as well. The two small X-ray bright knots in the southeast are particularly interesting, since earlier work (Vancura, Gorenstein, & Hughes 1995) has revealed that these features are almost surely highly enriched knots of SN ejecta with very different abundance distributions. The northern one is apparently rich in Si and S, while the southern one is Fe rich. These knots are moving considerably more rapidly than the rest of the remnant (as shown clearly in Fig. 1), and, in addition, the current expansion rate is consistent with their time-averaged expansion rate, implying that these clumps of ejecta have not been decelerated.

I propose that these are fragments or "bullets" of ejecta formed in the SN explosion, which is believed to be Type Ia. For an assumed distance to Tycho of 2.5 kpc, the transverse velocity of these knots is approximately 8300 km $s^{-1}$. The clump masses are of order $0.002\,M_\odot$ (for the Si+S knot) and $0.0004\,M_\odot$ (for the Fe knot) and the kinetic energies are $2 \times 10^{48}$ ergs $s^{-1}$ and $2 \times 10^{47}$ ergs $s^{-1}$, respectively, again for purely transverse motion. These ejecta fragments in Tycho are similar in many respects to the recently discovered ejecta fragments beyond the apparent boundary of the Vela SN blast wave (Aschenbach, Egger, & Trümper 1995). Although the current velocities of the Vela ejecta bullets are small (390–650 km $s^{-1}$), their angular distance from the estimated site of the SN explosion require large mean transverse velocities: 4000–5000 km $s^{-1}$ as well as significant deceleration. The initial kinetic energy of the Vela knots is in the range $(0.3–5)\times10^{48}$ ergs $s^{-1}$, however, their masses, $0.01–0.5\,M_\odot$, are quite a bit larger than the knots in Tycho.

In summary it appears likely that the rapidly moving, chemically enriched features seen in Tycho's SNR are ejecta fragments being observed at an early stage of evolution before much interaction with the ambient medium has occurred. Since their expansion rate is greater than the rest of the remnant, at some time in the future they will clearly precede the blast wave. Their differing chemical composition require widely different origination sites in the exploded star: the Fe-rich knot must have originated from near the center where explosive Si-burning led to only Fe-group nuclei and the Si+S-rich knot must have come from further out where the flame temperature dropped and explosive O-burning predominated. Whether instabilities of this type prove to be intrinsic to the nature of flame front propagation in Type Ia SNe or arise from Rayleigh-Taylor and other instabilities operating on the expanding ejecta at later times remains to be studied. In any event the results presented here make clear that Type Ia SN explosions are considerably more inhomogeneous than previously thought.

## 4. References

1. Aschenbach, B., Egger, R., & Trümper, J., 1995, *Nature*, **373**, 587.
2. Chevalier, R. A., 1982, *Ap. J.*, **258**, 790.
3. Hamilton, A. J. S., Sarazin, C. L., & Szymkowiak, A. E., 1986, *Ap. J.*, **300**, 713.
4. Kamper, K. W., & van den Bergh, S., 1978, *Ap. J.*, **224**, 851.
5. Sedov, L. I., 1959, *Similarity and Dimensional Methods in Mechanics*, (New York: Academic).
6. Tan, S. M., & Gull, S. F., 1985, *M.N.R.A.S.*, **216**, 949.
7. Vancura, O., Gorenstein, P., & Hughes, J. P., 1995, *Ap. J.*, **441**, 680.

This research was partially supported by NASA *ROSAT* Grant NAG5-2156.