AN ASTROPHYSICS DATA PROGRAM INVESTIGATION OF SPATIAL STRUCTURE OF SUPERNOVA REMNANTS

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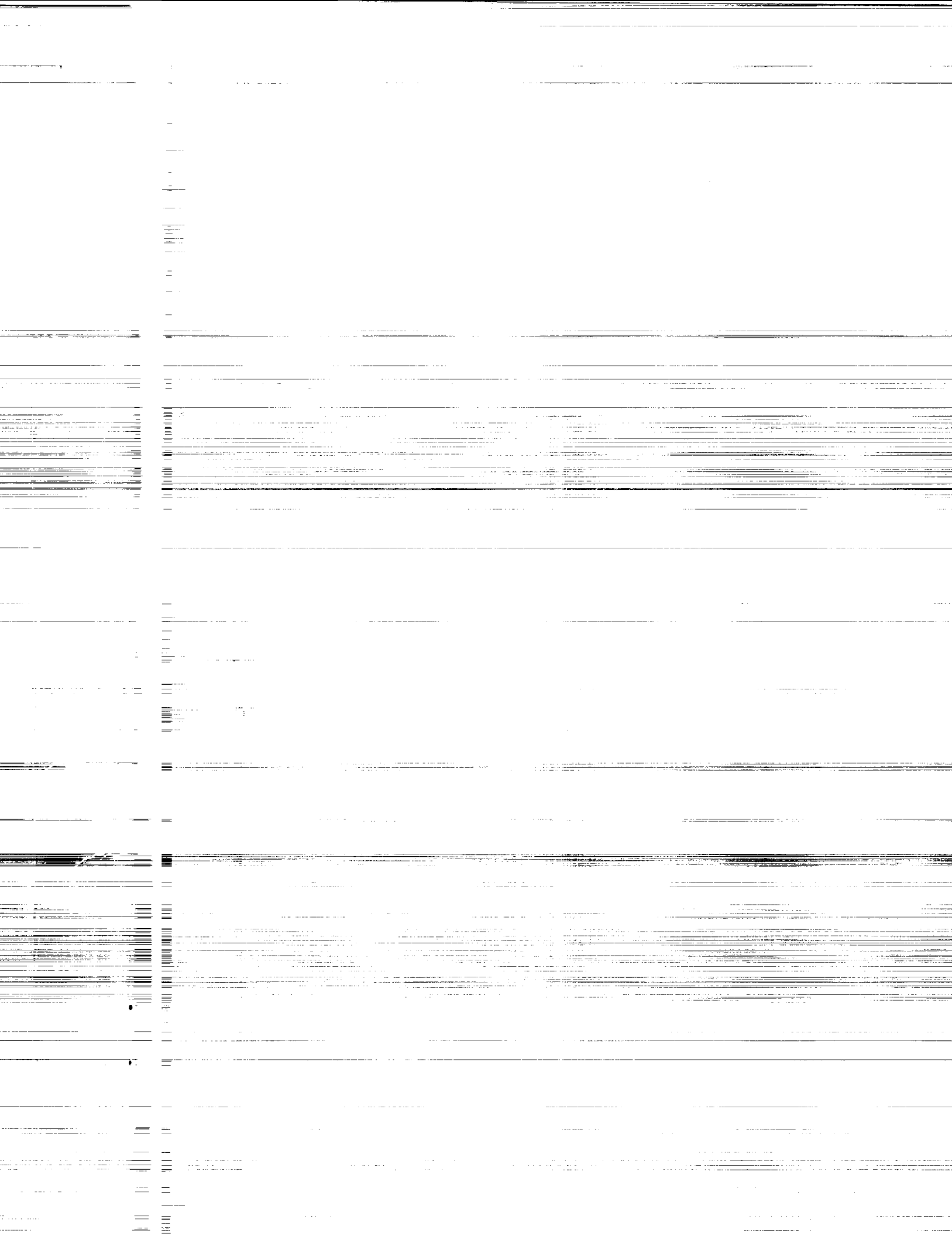

The goal of the project was the study of the spatial structure of supernova remnants (SNRs) as observed in the X-ray band. A number of software tools were developed for the analysis: (1) a program to fit various geometric models to high resolution X-ray data, and (2) programs for Fourier Transform analysis of clumping in SNRs. These programs were applied to high resolution imager (HRI) data on the young galactic SNRs Tycho and Kepler with some success.

Figure 1 shows the power spectral density function (PSDF) of the *Einstein* HRI image of Tycho's SNR calculated in the spatial domain and radially averaged. The key to interpreting this function in terms of clumped ejecta lies with first determining a model for the smooth unclumped (or unresolved) emission. The first program mentioned above can perform fits to X-ray imaging data of projected geometric models (with almost arbitrary complexity), using, as the figure-of-merit function, a maximum likelihood statistical estimator explicitly derived for Poisson distributed data. The PSDF of the smooth, unclumped thin-shell geometric model which fits the Tycho imaging data is shown as the histogram in Fig. 1. The detailed structure in the PSDF at low wavenumbers arises from the overall geometry of the SNR (note the local peak at $0.006 = 1/170''$, which is roughly the radius of the inner edge of the shell of ejecta). I stress that the model shown here was the best-fit to the surface brightness data and not the PSDF and, in fact, no free parameters were used in comparing the PSDF with the model. The excess power in the image appearing at spatial scales between $15''$ and $60''$ can be modeled quite well by including with the smooth component, a clumped component with $\sim$100 clumps all of the same scale-size ($\sim 10''$) containing about 25% of the counts in the image. In this case the clumps were included in a statistical fashion, by randomly placing them within the volume of the SNR shell. The PSDF derived from the current data is just not of sufficient statistical level to be able to reveal the presence of clumps with smaller scale size.

The global structure of Kepler's SNR is quite different from that of Tycho's. There is a strong asymmetry (an increase in surface brightness from the southeast to the northwest) in the X-ray (White and Long 1983) and radio images (see, *e.g.*, Dickel *et al.* 1988) which we have been able to model using the software developed under this project in terms of a gradient in the gas density within the SNR shell. Results from this global model are being used to constrain some of the details of the current evolutionary scenario for Kepler's SNR and its progenitor star (Bandiera 1987, Borkowski *et al.* 1992). Because of the high statistical signal of the Kepler ROSAT HRI data, it was also possible to carry out direct fits to of order 25 individual bright clumps in the image. The mean size of the clumps is $\sim 8''$, they are overdense (relative to the unclumped component) by factors of 1.5 to 3, and together produce 25% of the total counts in the image. The model PSDF (the histogram in Fig. 2) is from the image made by summing the smooth density-gradient-model and

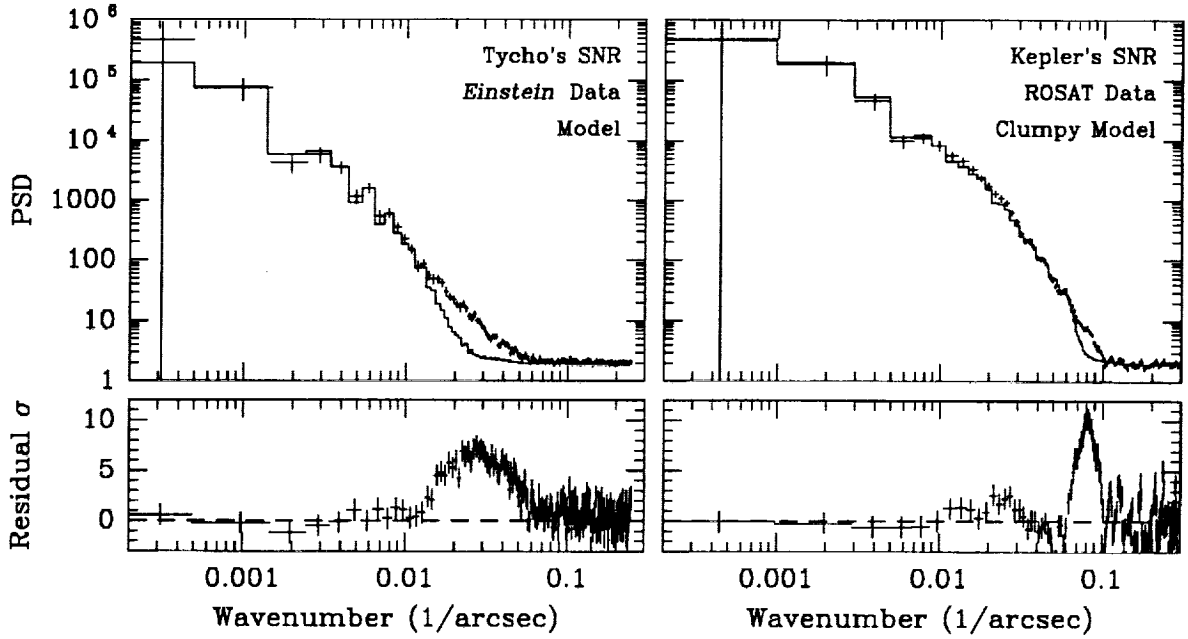

Figure 1 (Left) – Fourier power spectral density (PSD) function of the Tycho *Einstein* HRI data compared to the unclumped thin-shell geometric model, which describes the average X-ray surface brightness. Residual plot shows significant power in the image at scales between 15″ and 60″, which can be modeled as clumpy ejecta. At high wavenumbers the PSD function is dominated by the Poisson noise in the image (*i.e.*, the flattening of the PSD at the value 2).
Figure 2 (Right) – PSD of the Kepler ROSAT HRI data compared to model with smooth and clumped components. Additional power at high wavenumbers indicates presence of clumping at even smaller size scales.

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the directly fit clumped component. The residuals show significant excess power at even smaller spatial scales (approaching clump radii of 4″), which may need to be included in a statistical fashion, like for the Tycho result above.

The grant supported a Harvard student (David Yoon) for two summers. The work done during these summers as well as during the school year resulted in two Harvard University Honors Theses:

"Modeling the Gross and Small Structures of the Tycho Supernova Remnant," David Yoon, Harvard University Junior Thesis, May 1990.

"The Global Structure of Kepler's Supernova Remnant," David Yoon, Harvard University Senior Thesis, May 1991.

The structure fitting program and Fourier Transform analyses programs were used in a recent analysis of ROSAT HRI data on Kepler's SNR:

"ROSAT High Spatial Resolution Observations of Kepler's Supernova Remnant," P. Slane, and J. P. Hughes, *Bull. Amer. Astr. Soc.*, **24**, 1196 (1992).

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