3-D Mapping of X-ray Emitting Ejecta in Kepler's Supernova Remnant

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Introduction

- **Kepler's Supernova Remnant** (SNR) is the leftover cloud of multi-million-degree hot debris gas from a massive stellar explosion seen in 1604, now emitting strong radiation in the X-ray band. (Fig. 1)
- We use NASA's **Chandra X-ray Observatory** (Fig. 10) to study the remnant and understand how these explosions evolve over time.
- As a direct expansion of our previous work [4], we focus on measuring how fast chunks of metal-rich debris (ejecta) are moving in different directions.
- We do this by combining two types of X-ray data:
  - **High resolution X-ray spectroscopy:** 7 days of our Chandra observations taken in 2016 and 2022.
  - **High resolution X-ray imaging:** 12 days of archival Chandra data spanning 22 years of time baseline.
- Our goal is to create a **comprehensive 3-D structure of stellar debris** and to help theoretical modeling of dynamics of thermonuclear explosion of a sun-like star. (Fig. 9)

Methodology

- **Spectral Analysis:** Identify bright regions in X-ray images and determine if they are from the exploded star or surrounding gas by analyzing their chemical makeup. (Fig. 3 & 4)
- **Radial Velocity:** Measure how fast debris is moving toward or away from us by measuring Doppler shifts in bright X-ray emission lines. [4] (Fig. 5)
- **Transverse Velocity:** Track how debris moves across the sky by measuring positional changes of individual small clumps of stellar debris gas based on Chandra images taken over 22 years. [4] (Fig. 6, 7 & 8)
- **3D Velocity Mapping:** Combine both motion measurements to create a 3D map of how the explosion's debris is expanding. [4] (Fig. 2, Table 1)

Fig 1: Kepler's SNR X-ray + Optical Image[1][2]

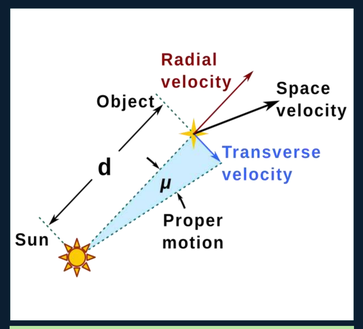

Fig 2: Measuring Space Velocity[3]

Data Analysis

Fig 3: Kepler's SNR X-ray Image (0.3-10 keV) [1]

- Example of 3 characteristic small clumps of stellar debris gas:

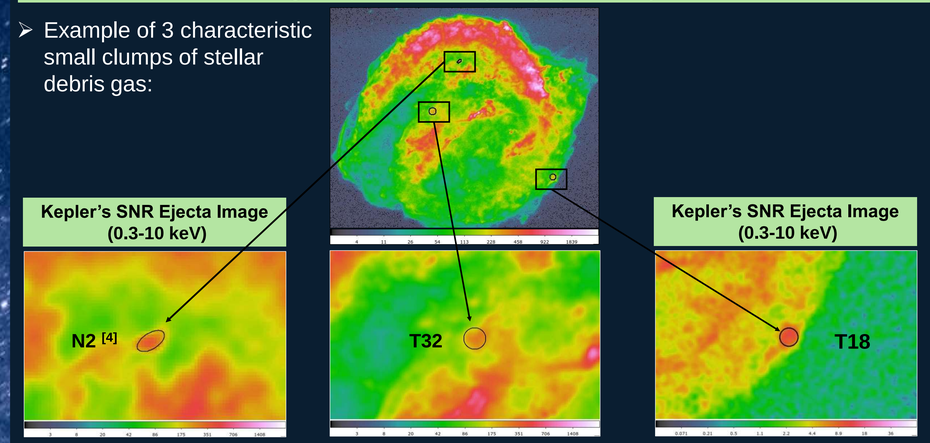

Fig 4: Broadband (0.3-7.0 keV photon energies) X-ray spectrum of above 3 example features

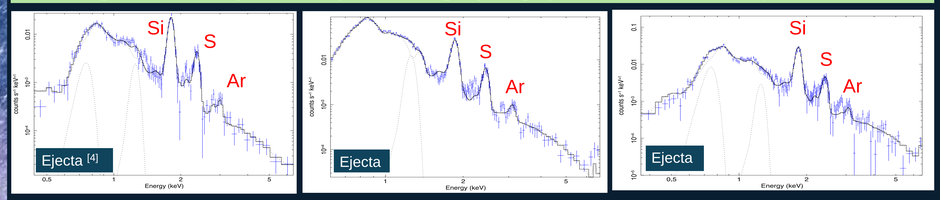

Fig 5: Narrow band (0.60 – 0.75 nm) high resolution X-ray spectrum of above 3 example features to show our Doppler shift measurements of X-ray emission lines from He-like Si ions

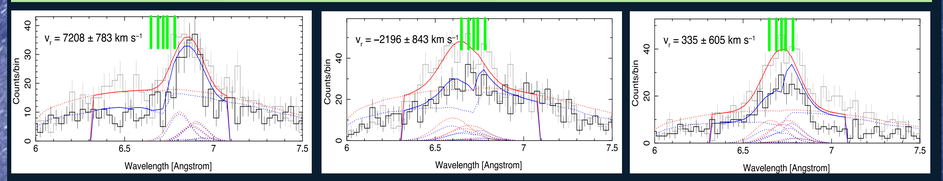

Fig 6: Proper Motion of N2
Reference Image: 2006 in white cross

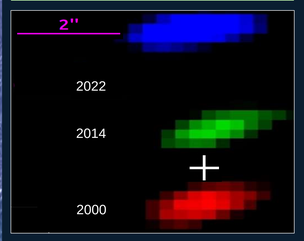

Fig 7: Proper Motion of T32
Reference Image: 2006 in white cross

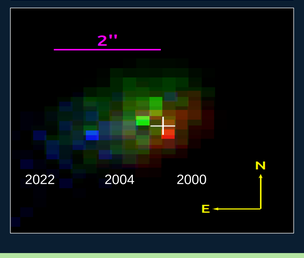

Fig 8: Proper Motion of T18
Reference Image: 2006 in white cross

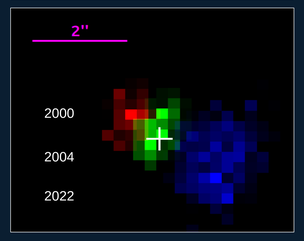

Table 1: Space Velocity Measurements

Region	Radial Velocity	Transverse Velocity	Space Velocity
T18	335^{+605}_{-605} km/s	2814^{+1584}_{-1584} km/s	$\mathbf{2834^{+1572}_{-1572}}$ km/s
T32	-2196^{+840}_{-846} km/s	1751^{+1615}_{-1615} km/s	$\mathbf{2809^{+1203}_{-1205}}$ km/s
N2	7208^{+772}_{-794} km/s	3265^{+1544}_{-1544} km/s	$\mathbf{7912^{+964}_{-949}}$ km/s

3D Map of Stellar Debris: Our Initial Results

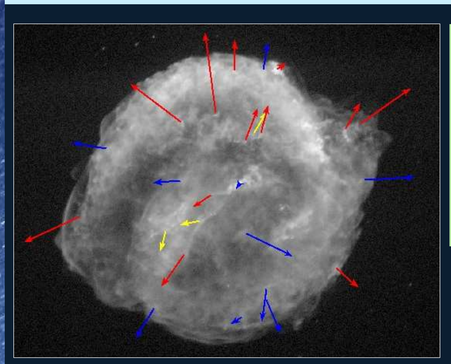

Fig 9: Kepler's SNR X-ray Broadband Image 2022
Space Velocities of debris: blue and red colors are strongly blue and red shifted emission features, respectively, showing fast moving stellar debris gas. Yellow arrows indicate shocked CSM regions showing negligible Doppler shifts, thus no significant motion.

- **Space velocities of Ejecta debris:** 2000 – 8000 km/s
- **Space velocities of CSM :** < 2000 km/s

Summary & Future Work

- We have measured space velocities of **~30 regions** so far.
- We will expand our sample size of space velocity measurements for clumpy stellar debris to **~100** in the next year.
- We will particularly focus on revealing any significant deviation of spatial and velocity distributions of stellar debris off the spherically-symmetric stellar explosion, which may provide specific observational constraints for modeling true 3D nature of stellar explosion physics.

References

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Fig 10: Chandra Space Telescope 1999 – Present [5]