Dual Epoch HST Imaging of Kepler's Supernova Remnant

Bright Knot Variability and Search for a Possible SN Progenitor Companion

Ilija Medan (USRA), Ravi Sankrit (SOFIA, USRA), William Blair (JHU), Kazimierz Borkowski (NCSU), Knox Long (STScl), John Raymond (SAO), and Brian Wiliams (STScl)

Kepler's SNR (G4.5+6.8) is the remnant of SN 1604. The strong Fe emission and lack of O emission in Chandra spectra confirms a Type 1a classification (Reynolds et al. 2007, Yamaguchi et al. 2014). The distance to Kepler's SNR is 5 kpc (Sankrit et al. 2016, Ruiz-Lapuente 2016).

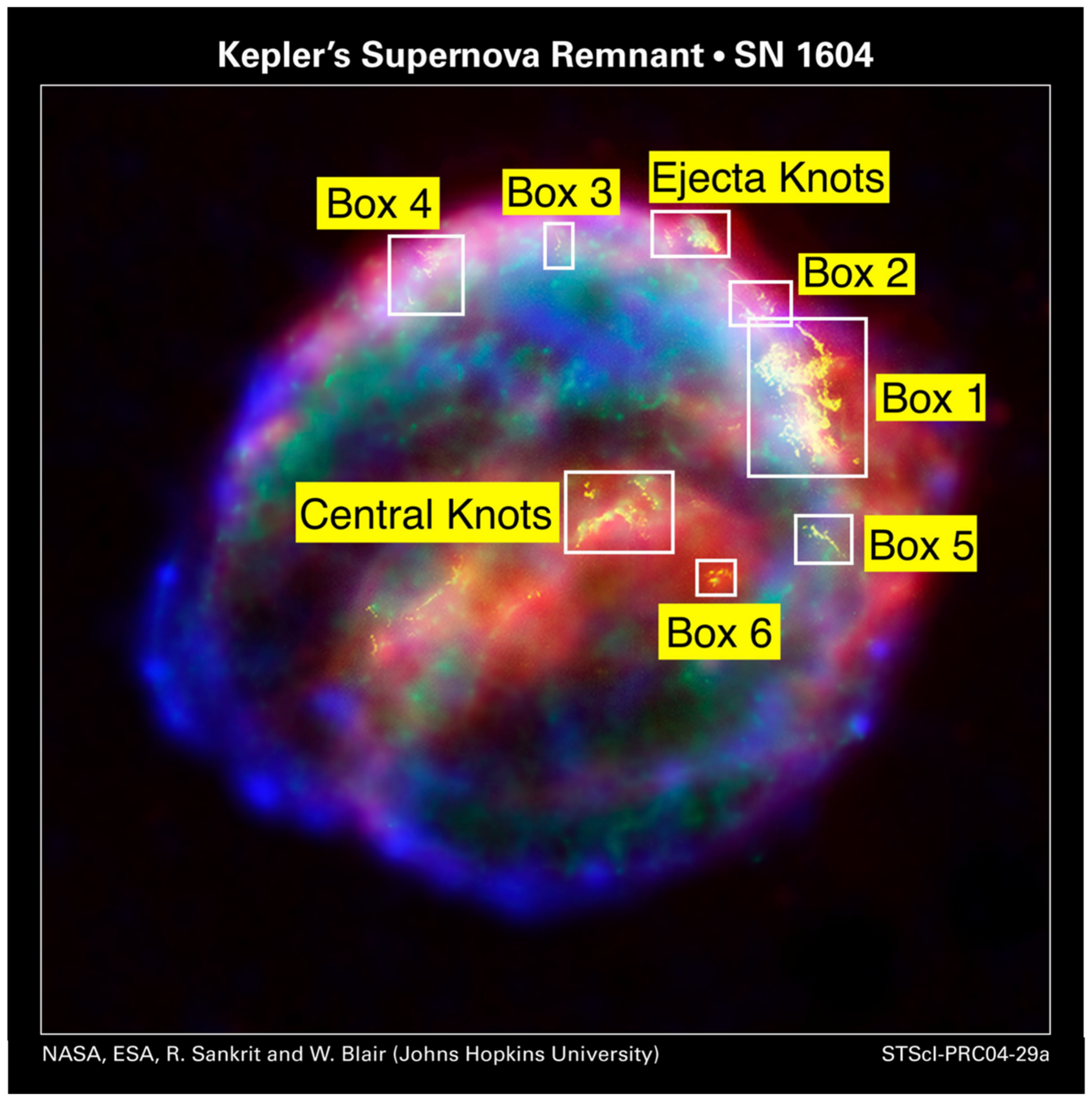
In the image to the right, the hard X-ray (blue) shows the location of the primary shock front, the soft X-ray (green) is dominated by Fe and Si ejecta, the optical Hα+[NII] (yellow) traces both radiative and non-radiative shocks and the infrared 24 μm (red) is thermal dust emission from the shocked gas.

Kepler's SNR is surrounded by Circumstellar Material (CSM) suggesting a single-degenerate supernova explosion. We have cataloged the bright stars in the field of view to search for the surviving companion of the progenitor (see below). We have used the stellar catalog and unsupervised machine learning (Meingast et al. 2017) to map the extinction in the WFC3 field of view of the remnant.

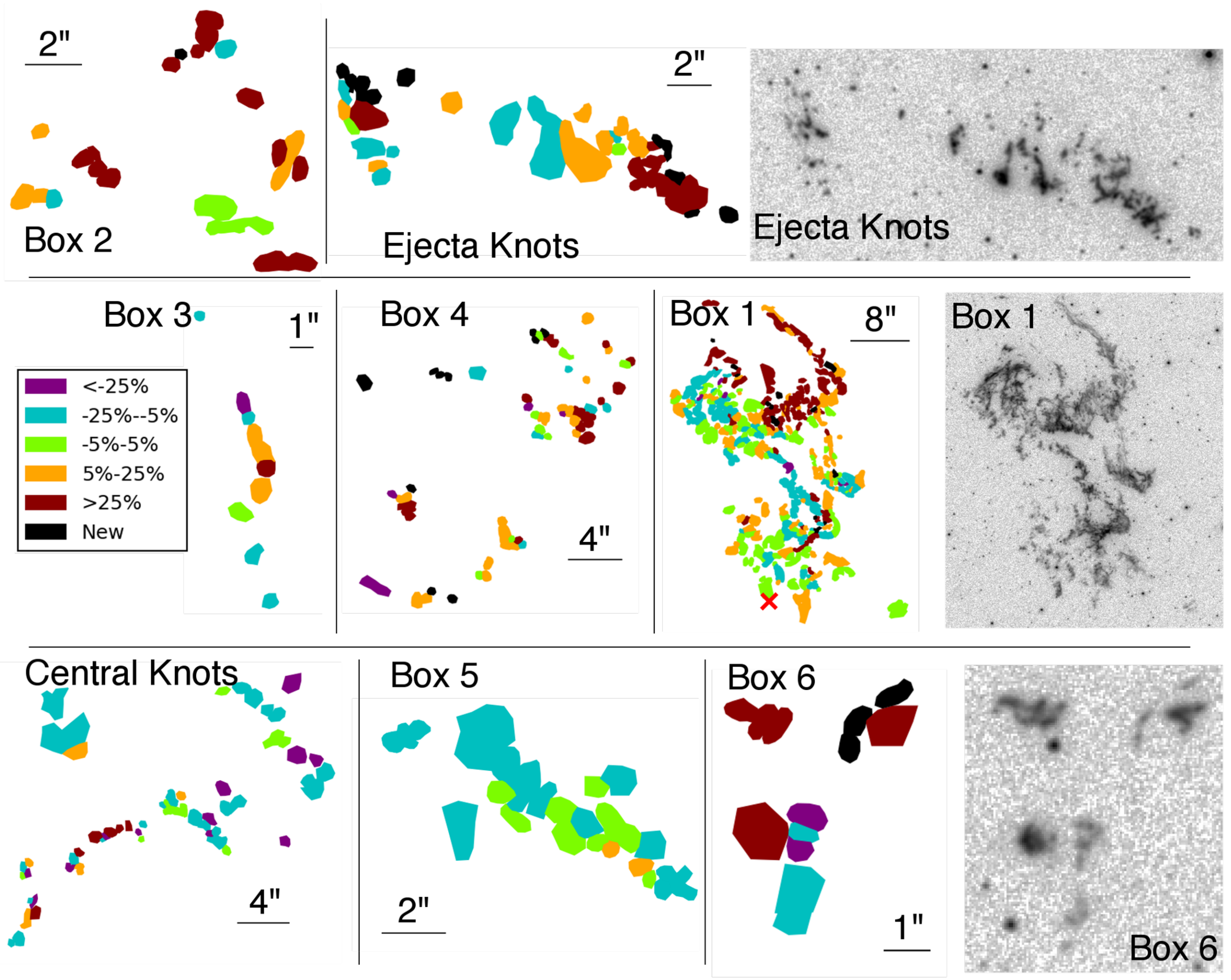
We have also cataloged all the bright knots in the remnant and measured their surface brightnesses. Changes in the [NII] fluxes between the two epochs of observation are presented here (see far-right).

Below is a table showing the HST filters used and the data acquired from these images.

Epoch	Date	Instrument	Filter	Data Acquired
Epoch 1	August 2003	ACS WFC	F550M	Proper Motion
			F658N	[NII]+[Hα]
			F660N	[NII]
Epoch 2	July 2013	WFC3 UVIS	F336W	U
			F438W	B
			F547M	V, Proper Motion
			F814W	I
			F656N	[Hα]
			F658N	[NII]



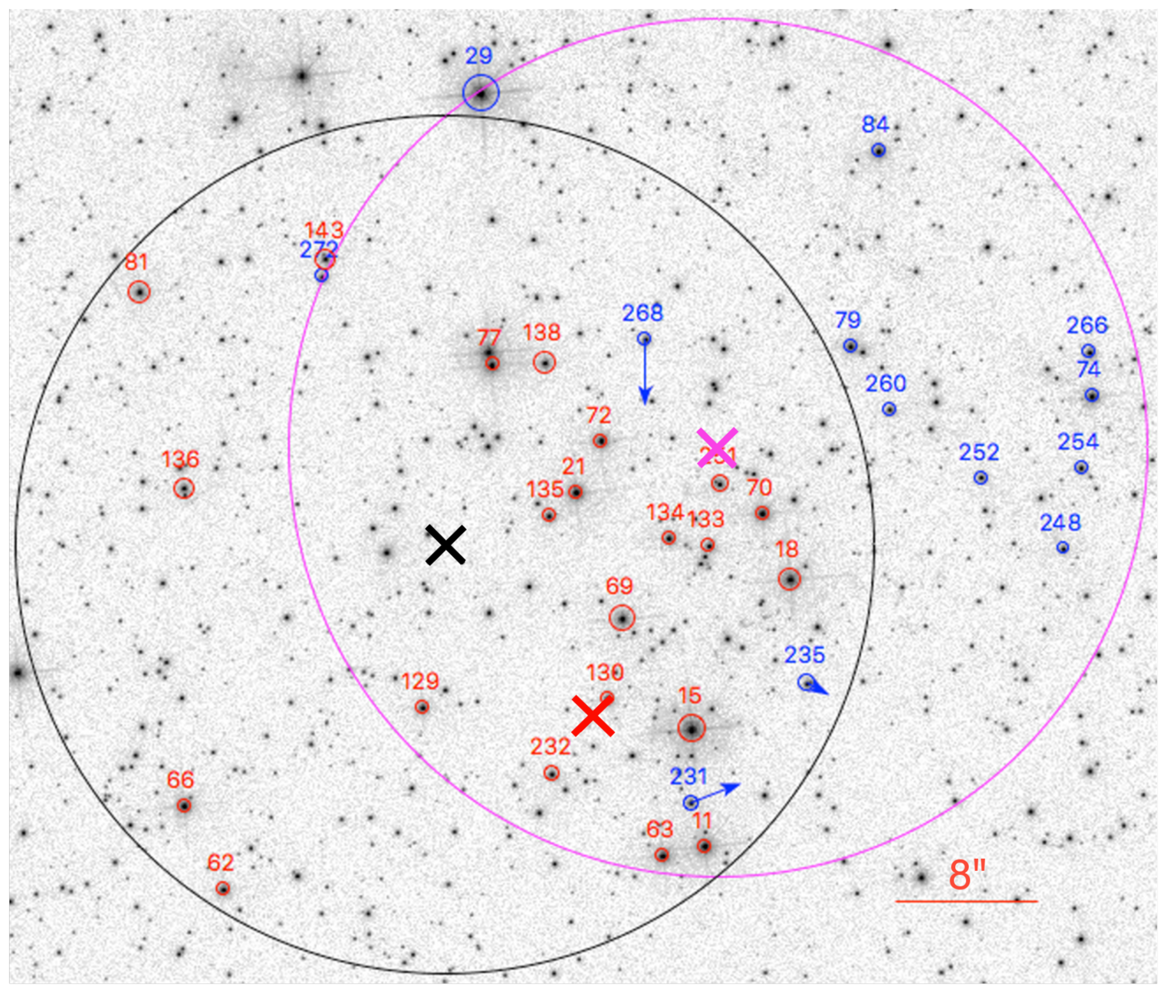
WFC3 658N	Box 1	Box 2	Ejecta Knots	Box 3	Box 4	Central Knots	Box 5	Box 6
Knots Total, New Knots	330, 17	21, 1	39, 11	11, 0	64, 11	58, 0	22, 0	13, 3
Area Median, [Min, Max] (″^{2})	0.36 [0.036, 4.1]	0.22 [0.041, 0.62]	0.20 [0.049, 2.7]	0.33 [0.041, 2.9]	0.11 [0.028, 0.51]	0.17 [0.025, 3.6]	0.26 [0.064, 1.2]	0.16 [0.042, 0.62]
SB Median, [Min, Max] ($10^{-15} ergs\ cm^{-2} s^{-1} {''}^{-2}$)	5.3 [1.6, 70]	2.7 [1.5, 5.4]	4.0 [1.6, 20]	1.8 [1.1, 3.1]	2.0 [1.2, 5.8]	2.5 [1.2, 14]	1.9 [1.4, 3.7]	2.9 [1.5, 9.7]



The [NII] 6548 A emission fluxes were calculated for the knots in the WFC3 F658N image using the standard header keyword PHOTFLAM value. Kepler has a radial velocity of -185 km/s, and this places the [NII] line center on the blueward shoulder of the ACS F660N throughput curve, and makes the flux conversion highly uncertain. To evaluate the [NII] fluxes in the ACS image, we used a scaling factor based on a set of knots that were found to not be changing in brightness by Bandiera and van den Bergh (1991). The median scaling constant (counts to flux units) towards these 18 knots was found to be 2.05E-16, with a spread of 1.35E-16 to 2.37E-16. We chose one of these knots (marked with a red X in box 1) to have a change of exactly 0% resulting in a scaling constant of 2.15E-16, which was then applied to all the knots in the ACS image. Note that significant differences in the radial velocities of knots relative to the systemic velocity of Kepler will show up as brightness changes in the plots above. This is very likely the effect seen in the Central Knots region where it is known that many individual knots are red- and blue-shifted.

In our search for the progenitor companion, we first compiled a catalog of stars. Magnitudes (U, B, V, I) and proper motions for 2985 sources detected at greater than 3-sigma significance in the WFC3 F547M image were derived from the images using source detection and aperture photometry routines found in the Python package PHOTUTILS and the standard conversion from HST filters to magnitudes. We considered all the stars within 24" of two possible centers - one proposed by Kerzendorf et al. (2014), henceforth K14, in their search for the progenitor companion, and the other 15% of the radius towards the NW based on dynamical models of the remnant (Borkowski, Williams et al. priv. comm.) - and found from color-magnitude diagrams (U and V against B-V) that none of the bright stars are particularly hot compared to the rest of the stars in the remnant.

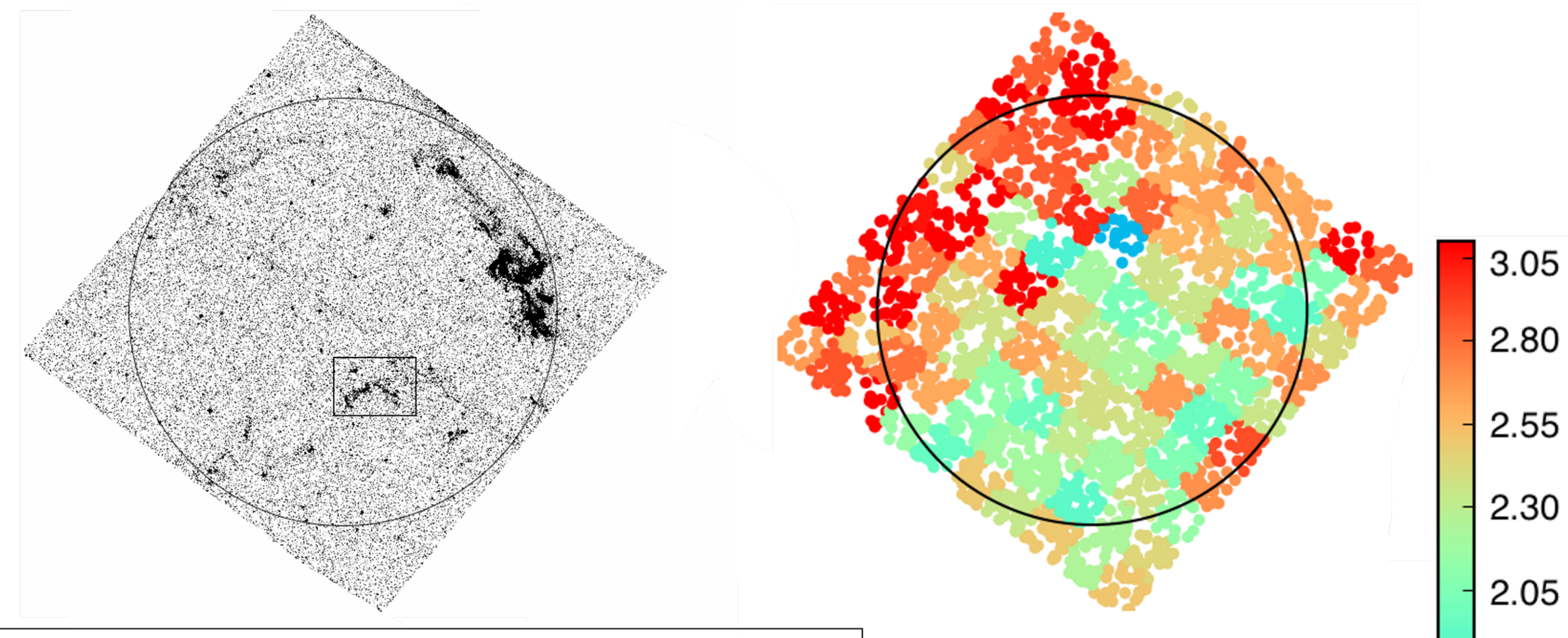
The figure shows the F547 image of a ~70"x54" region around the remnant center. The black "X" is the center assumed by K14, the pink "X" is the 15% NW position, and the red "X" is the geometric center (shown for reference). Circles with 24" radii are shown around each of the two centers considered, and all the stars with V<20 lying in these circular regions are labeled. The 24 stars considered and ruled out as progenitor companions by K14 are shown encircled in red, while the others are encircled in blue.

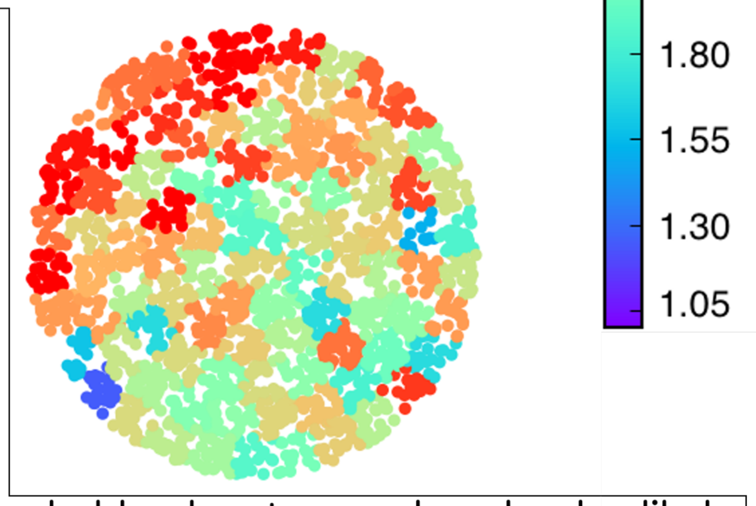


Our study supports the K14 result: in addition to their colors being normal, none of these stars has a high proper motion. Three other stars in the region show higher-than-normal proper motion - 231, 235 and 268. However, 235 is too far away from the center, and 231 and 268 are moving in directions not compatible with them being the progenitor companion.

In summary, we have compiled a catalog of the bright stars towards Kepler's SNR but our search for the progenitor companion has yielded a null result.

The crowded star field in the direction of Kepler's SNR and the WFC3 continuum images allow us to estimate the extinction using an unsupervised machine learned algorithm, PNICER (Meingast et. Al 2017). Using source colors and a set extinction law, PNICER creates all possible color-color diagrams, plots the extinction vector for each source and from this creates a probability density function for each color combination. The final extinction is chosen from the combination of colors which minimizes the population variance. A control sample of about 50 stars was used and constrained to have the same proportion of stars in four brightness bands as well as a fixed proportion of main sequence and giant branch stars. Extinction to each source was estimated using four extinction laws (Cardelli, Clayton & Mathis 1989, henceforth CCM, O'Donnell 1994, Calzetti 2000 and Fitzpatrick 1999) and assuming Av=2.8 and Rv=3.1 (Reynolds et al. 2007). The process was carried out 10 times. Thus, for each source, we obtained 10 estimations of extinction for each extinction law.





The extinction maps shown to the right use estimates from the CCM trials. Although each star with an extinction estimate is shown, the values assigned to them are medians over equal area regions. The map at the top has 100 square regions with sides along the WFC3 image edges (see F656N image above). The map at the bottom has 96 polar regions made from 6 equally spaced circles from the center out (outermost circle shown on images above). The trend of higher extinction towards the north, particularly the north-east, is clearly seen. It should be noted that most of the extinction towards Kepler is probably due to nearby clouds, likely within 2 kpc from us. The center of each plot is at 17:30:40.82, -21:28:52.23, and the Central Knots box is overlaid on the image above for reference.

Summary

1. There are a higher fraction of brightening knots, and new knots at the perimeter of the remnant from northeast to northwest.
2. The region in box 6 appears to be undergoing significant brightening, along with the appearance of new knots.
3. The highest extinction towards the remnant is in the northeast region.
4. About 3000 stars towards Kepler's SNR have been cataloged with no clear identification of a progenitor companion.

References

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