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## Kepler’s Supernova Remnant: The View at 400 Years

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**Abstract.** October 2004 marks the 400th anniversary of the sighting of SN 1604, now marked by the presence of an expanding nebulosity known as Kepler’s supernova remnant. Of the small number of remnants of historical supernovae, Kepler’s remnant remains the most enigmatic. The supernova type, and hence the type of star that exploded, is still a matter of debate, and even the distance to the remnant is uncertain by more than a factor of two. As new and improved multiwavelength observations become available, and as the time baseline of observations gets longer, Kepler’s supernova remnant is slowly revealing its secrets. I review recent and current observations of Kepler’s supernova remnant and what they indicate about this intriguing object.

### 1. Introduction

Four hundred years ago, when Johannes Kepler and others observed the “new star” of 1604, those observing the event had no concept of what it was that they were observing. Today we know that supernovae are exploding stars and that they even come in different varieties. The type Ia SNe, which have become so important for cosmology because they are standard candles, arise from the incineration of white dwarf stars. The other main class, core collapse SNe, come from more massive stars and produce the sub-classes called type Ib, type Ic, and type II. Of the six historical SNe in our Galaxy that have occurred over the last millennium (including Cas A for which the SN itself apparently escaped detection), only Kepler’s SN has remained uncertain as to the type of the star that exploded.

Today of course, what we observe is the expanding young supernova remnant (SNR) that resulted from the explosion. By studying this SNR across the electromagnetic spectrum, modern astronomers are still trying to discern a clear picture of the precursor star of this event. In doing so, they are hindered by the lack of an accurate distance to the object, which makes the derivation of even basic properties like the diameter or mean expansion velocity uncertain. In this paper, I will review the current observational status of this enigmatic object and point out some of the apparent inconsistencies in existing interpretations.

### 2. Observational Parameters

Kepler’s SNR is located at galactic coordinates  $l = 4.5^\circ$  and  $b = 6.8^\circ$  (i.e., nearly directly toward the galactic center from the sun but significantly out of the plane). The full extent of the remnant is most visible in radio and X-ray

regimes, where a circle of diameter  $200''$  encompasses the entire shell except for two “ears” of emission on the east and west sides (see Figure 1).

Unfortunately, the distance to Kepler’s SNR is only poorly constrained by observations to date. Most recent literature cites the study by Reynoso & Goss (1999) and adopts a distance near 5 kpc. However, a careful reading of this paper shows that many authors misquote or misunderstand Reynoso & Goss’s result. These authors use the H I kinematics with a galactic rotation model to place a rather inaccurate “lower limit” of  $4.8 \pm 1.4$  kpc on the distance, and independently place an “upper limit” of 6.4 kpc based on the proposed association of the SNR with an H I cloud. Kinematic distances are inherently uncertain along the line toward the galactic center. Table 1 shows how some basic parameters for the SNR depend critically on the assumed distance. In particular, note that the larger distances imply a very large distance off the galactic plane and, when combined with the observed current shock velocity, apparently require a very significant deceleration, which is not consistent with the absence of a well-defined reverse shock in the X-ray data.

Table 1. Kepler’s SNR: The Affect of the Distance Uncertainty

Parameter	D=3.0 kpc	D=4.5 kpc	D=6.0 kpc
Z Distance (pc)	355	533	710
Radius (pc)	1.45	2.18	2.90
$\langle V_{exp} \rangle$ (km s $^{-1}$ )	3540	5310	7080

In Figure 1, I show 6 cm VLA radio (DeLaney et al. 2002) and 0.2 - 10 keV *Chandra* X-ray observations (Hwang et al. 2000) of Kepler’s SNR. The overall similarity is striking, showing a roughly spherical thick shell of emission brightest in the north. The apparent band of emission cutting across the middle from NW to SE is largely an illusion, caused by projection effects from material on the front and back sides of the shell (see optical section below).

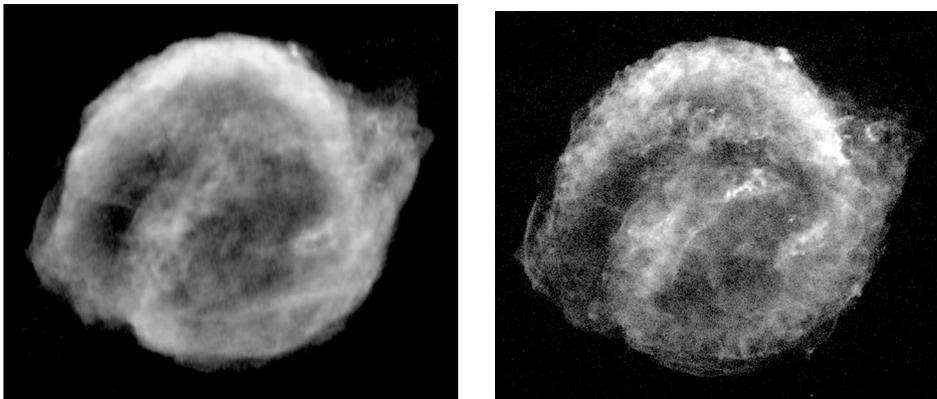


Figure 1. (left) VLA 6 cm radio map of Kepler’s SNR, from DeLaney et al. (2002). (right) *Chandra* 0.2 - 10 keV X-ray data from Hwang et al. (2000).

However, this apparent similarity may be deceiving. Flat and steep radio spectrum deconvolutions look quite different from the total intensity maps, and soft (0.3 - 1.4 keV) and hard (4 - 6 keV) X-ray bands, either from *Chandra* or *XMM-Newton* (Cassam-Chenaï et al. 2004) also show different structures. (In particular, the harder X-rays form a distinct outer rim likely associated with the primary shock wave.) Also, when one looks at the dynamics of the SNR, discrepancies are seen. Both radio and X-ray observations extend over a long enough baseline that expansion of the SNR has been measured. Hughes (1999) finds an X-ray expansion rate of  $R \propto t^{0.93}$ , which is nearly free expansion. This is almost twice that found in the radio ( $R \propto t^{0.50}$ , Dickel et al. 1988; DeLaney et al. 2002). The reason for this discrepancy is not understood.

Optical observations (Blair, Long, & Vancura 1991) are brightest in the NW, with the northern cap and isolated central patches of emission also visible (see Figure 2). The optical data indicate substantial and variable foreground extinction, with  $E(B-V) = 1.0 \pm 0.2$ , consistent with and X-ray determined  $N(H) = 5.0 \times 10^{21} \text{ cm}^{-2}$ . Bandiera & van den Bergh (1991) performed a careful study of the space velocity of the object, finding a value of  $278 \text{ km s}^{-1}$  toward the NW, which is away from the galactic plane. Assuming this motion is due to the precursor star, this would account for the large angular distance off the galactic plane and the observed morphology in all bands, showing the brightest emission in the N and NW.

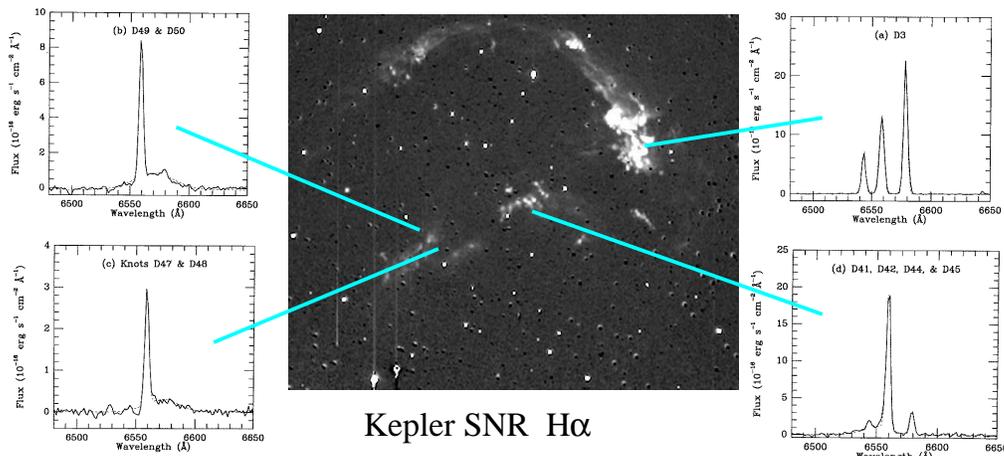


Figure 2. Ground-based  $H\alpha$  image of Kepler's SNR (from Blair et al. 1991) is shown. A continuum image has been subtracted although some stellar residuals remain. Insets show  $H\alpha + [N II]$  region optical spectra of the regions indicated. Note the broad and narrow components on the  $H\alpha$  line at some positions. Blue-shifted broad components indicate approaching (near side of shell) emission while red-shifted material is from the back of the shell.

The optical emission comes from two components: radiative shocks into dense, knotty structures (presumably circumstellar mass loss), and smoother filamentary emission visible only in  $H\alpha$  from so-called nonradiative shocks (e.g. Blair et al. 1991; Sollerman et al. 2003). The radiative knots show enhanced  $[N II]/H\alpha$ , indicative of probable enrichment from the precursor. Interpretation

of the broad line components in the nonradiative shocks (e.g. Chevalier, Kirshner, & Raymond 1980) indicate a current shock velocity of about  $1750 \pm 250$  km s<sup>-1</sup>.

Relatively little information is available in the infrared. The SNR is small enough in angular size that *IRAS* data are not useful. However, Douvion et al. (2001) observed Kepler's SNR with the *Infrared space Observatory's* ISOCAM (see Figure 3). The morphology of the  $\sim 12$   $\mu$ m emission is very similar to the optical, and 6 - 16  $\mu$ m spectra are well-fitted by shock-heated dust models with  $T_{dust} = 95 - 145$  K,  $n_e$  of several thousand (similar to optical [S II] densities), and  $T_e$  of several hundred thousand K. This makes it very likely that the *ISO* emission arises primarily from dust heated directly by the primary shock front. SCUBA sub-mm observations at 450  $\mu$ m and 850  $\mu$ m by Morgan et al. (2003) were interpreted as indicating a large mass ( $\sim 1 M_\odot$  of cold ( $T = 17$  K) dust in the remnant, but this result has been called into question (Dwek 2004). Upcoming *Spitzer Space Telescope* observations may resolve this issue.

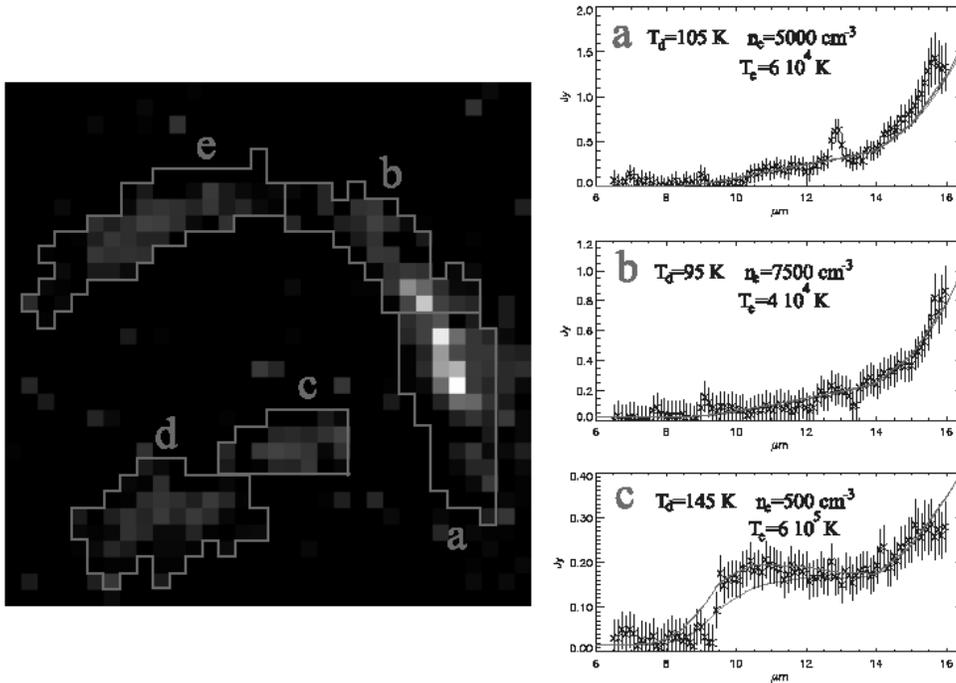


Figure 3. ISOCAM 14 - 16  $\mu$ m image of Kepler's SNR (from Douvion et al. 2001). Boxes mark regions for extracted spectra, which show warm (95 -145 K) thermal dust emission. The emission in boxes a-e accounted for 92% of the detected emission. Note the similarity to the distribution of optical emission in Figure 2.

### 3. Whither the SN Type?

The literature is extremely confusing on the issue of the SN type. Baade (1943) reconstructed the historical light curve and claimed a type Ia designation, a

result that is still quoted in many recent papers. However, Doggett & Branch (1985) showed consistency with a type II-L light curve, and Schaefer (1996) has also called the historical curve and type Ia designation into question.

A decade ago, the preponderance of evidence seemed to point toward a core-collapse event, and much of this evidence is still relevant. A large distance off the galactic plane might be suggestive of a white dwarf precursor, but high space motion away from the plane and N-rich circumstellar material points to a massive runaway star from an earlier SN as the precursor for Kepler's SNR. Borkowski et al. (1992, 1994) developed a massive star model that was consistent with observations available at that time. However, X-ray analyses in particular, from Exosat (Smith et al. 1989; Decourchelle & Ballet 1994; Rothenflug et al. 1994), ASCA (Kinugasa & Tsunemi 1999), *Chandra* (Hwang et al. 2000), and now *XMM-Newton* (Cassam-Chenaï et al. 2004) have alternately claimed better fits to type Ia or core collapse models.

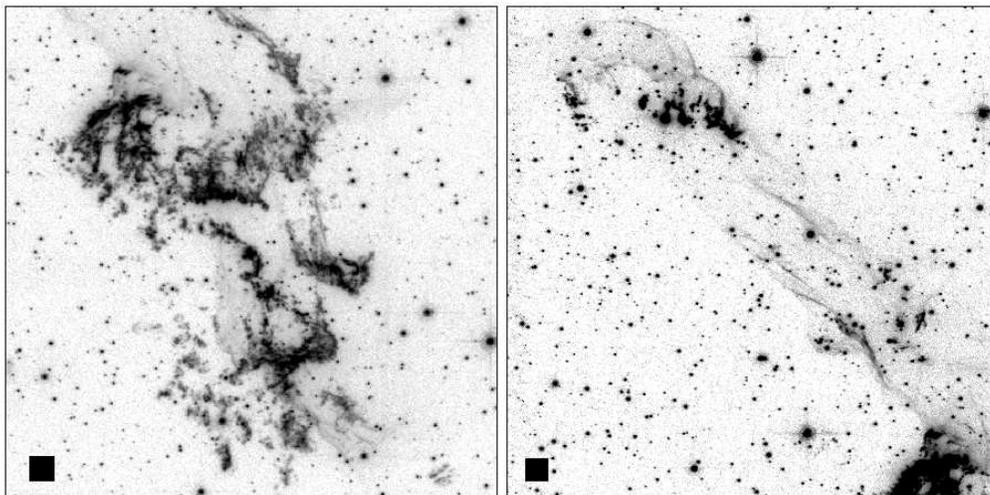


Figure 4. Two sub-fields in the northwestern portion of Kepler's SNR, as seen with the *HST* Advanced Camera for Surveys, using filter F680N ( $H\alpha + [N\ II]$ ). Bright knots (left panel) show the encounter of the blast wave with dense circumstellar knots. The fainter wispy filaments, especially visible at right, are nonradiative shocks delineating the actual shock front position. The black square at lower left in each panel is  $2''$ . Comparison of the motion of the wispy filaments to the ground-based data in Figure 2, with assumptions about the shock velocity, will yield a much better distance estimate in the near future. (Figure courtesy R. Sankrit, JHU.)

The modelling of *XMM-Newton* data by Cassam-Chenaï et al. (2004) is the most careful and accurate to date. Although these authors do not claim to have determined the SN type, their determination of Si and Fe abundances similar to type Ia models and their lack of detection of overabundances of O, Ne, Ar, S as seen in core collapse objects such as Cas A (Hughes et al. 2000), is a strong indicator of a type Ia event. I also note that, even with its exquisite sensitivity and resolving power, the *Chandra* observation has failed to detect any hint of a stellar remnant (quite in contrast to the situation with Cas A!). While the

issue may not be closed, the pendulum has swung back toward a white dwarf precursor star. This is not an entirely comfortable situation. If the type Ia designation is correct, then the closest example of our cosmological standard candle has some very peculiar properties!

At least one significant near term advance is in the offing. Recent optical *HST* ACS images have been obtained (see Figure 4) that not only show the bright optical filaments in exquisite detail, but will permit the proper motion of key filaments to be measured. With a refined estimate of the shock velocity from X-ray and optical data, it should soon be possible to measure the distance to Kepler's SNR with relative precision.

Johannes Kepler was an intriguing personality (Ferguson 2002). He came from extremely humble beginnings, he possessed a fierce and staunch religious faith that was entwined with his world view but at odds with his contemporary culture, and he was a visionary scientist. While understanding the new star of 1604 was a sidelight for him, I think he would be secretly pleased to know that his name has been attached to this equally intriguing supernova remnant.

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