A DEEP CHANDRA OBSERVATION OF KEPLER’S SUPERNOVA REMNANT: A TYPE Ia EVENT WITH CIRCUMSTELLAR INTERACTION

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ABSTRACT

We present initial results of a 750 ks Chandra observation of the remnant of Kepler’s supernova of AD 1604. The strength and prominence of iron emission, together with the absence of O-rich ejecta, demonstrate that Kepler resulted from a thermonuclear supernova, even though evidence for circumstellar interaction is also strong. We have analyzed spectra of over 100 small regions, and find that they fall into three classes. (1) The vast majority show Fe L emission between 0.7 and 1 keV and Si and S Kα emission; we associate these with shocked ejecta. A few of these are found at or beyond the mean blast wave radius. (2) A very few regions show solar O/Fe abundance ratios; these we associate with shocked circumstellar medium (CSM). (3) Otherwise O is scarce. (3) A few regions are dominated by continuum, probably synchrotron radiation. Finally, we find no central point source, with a limit ~100 times fainter than the central object in Cas A. The evidence that the blast wave is interacting with CSM may indicate a Ia explosion in a more massive progenitor.

Subject headings: ISM: individual (G4.5+6.8 (SN 1604)) — supernova remnants — supernovae: general — X-rays: ISM

1. INTRODUCTION

Kepler’s supernova of 1604 (Kepler 1606) was the most recent well-observed Galactic supernova. The supernova type has been controversial for decades; the Galactic latitude (b = 6.8°) implies a distance above the Galactic plane of 470 pc for a distance of 4 kpc (Sankrit et al. 2005), arguing for a Type Ia (Population II) progenitor, but optical observations (Blair et al. 1991) show radiative shocks in dense knots, suggestive of circumstellar material (CSM) shed by the progenitor. Bandiera (1987) proposed that the progenitor was a massive runaway star with a strong wind; Kepler’s bright north rim suggests a bow shock directed away from the Galactic plane.

X-ray observations of young supernova remnants can give powerful constraints on progenitor models and explosion mechanisms; whether Kepler had a Type Ia or core-collapse origin, the detailed distribution of ejected material and the composition of CSM could be used to test supernova (SN) models. We undertook a long observation of Kepler with the Chandra X-Ray Observatory to study the composition and distribution of ejecta and CSM, to search for any compact object, and to search for convincing evidence of the SN type.

2. OBSERVATIONS AND RESULTS

We observed Kepler’s SNR for 741 ks with the Chandra X-Ray Observatory ACIS-S CCD camera as a Large Project in six installments between 2006 April and July. In all six, Kepler was positioned (slightly differently) on the S3 back-illuminated chip. Data were processed using CIAO version 3.4 and calibrated using CALDB version 3.1.0. A large background region to the north of the remnant (covering most of the remaining area on the S3 chip) was used for almost all spectra except when local backgrounds were called for, as described below. Spectral analysis was performed with XSPEC version 12 (Arnaud 1996). We used the nonequilibrium-ionization (NEI) version 2.0 thermal models, based on the APEC/APED spectral codes (Smith et al. 2001) and augmented by addition of inner-shell processes (Badenes et al. 2006).

We obtained about 3 × 107 source counts, with fewer than 3% background (although some of those may be dust-scattered source photons). S/N permitting, spectra were extracted between 0.3 and 8 keV. Images were smoothed using platelets with a default smoothing parameter γ = 1/2 (Willett 2007).

Figure 1 shows the full observation, with red for energies between 0.3 and 0.7 keV (including primarily O), green for 0.72–1.7 keV (primarily Fe L-shell transitions, also including Ne and Mg Kα complexes), and blue for 1.7–8 keV (with a strong contribution from Si Kα). Immediately evident is the absence of dominantly soft-spectrum regions, and the hardness of emission at the periphery. A few regions do show reddish colors; representative spectra are discussed below.

No central point source is obvious. The bright central knot is resolved, and several fainter central knots, although perhaps unresolved, also have spectra of shocked gas. A faint source could be concealed under bright extended emission. Our conservative estimate assumes a high total background of 860 counts per ACIS S3 pixel, appropriate for the bright central band of emission. A 5σ detection of a point source within the 80% encircled power radius of 0.685” (6 pixel area) would require 400 counts, or 6 × 10−5 counts s−1. The compact central object in Cas A (Pavlov et al. 2000), if placed within Kepler and using the absorbing column density determined below, would produce 0.18 counts s−1. We conclude that we would detect such a source even if its luminosity was ~100 times fainter.

For spectral analysis, we fixed the absorbing column density at NLH = 5.2 × 1021 cm−2, a value we found by fitting lineless regions in the southeast with an absorbed synchrotron model srctt using Wilms et al. (2000) abundances. We used the three-color image of Figure 1 to aid in identifying small, relatively homogeneous regions of contrasting spectral character. We identified and examined about 100 regions. The vast ma-
Fig. 1.—Merged image between 0.3 and 8 keV. Red: 0.3–0.72 keV; green, 0.72–1.7 keV; blue, 1.7–8 keV. All three images were smoothed using platelet smoothing (Willett 2007). Image size is $4.7' \times 3.9'$. Regions from which spectra of Figs. 2 and 3 were extracted are shown.

Majority show prominent lines of Fe L-shell transitions, He-like Si, S, Ar, and Ca, and Fe Kα, and a handful had contrasting properties. We found that the spectra can be separated into three main classes. Over 90% of the regions showed Fe- and Si-rich spectra; we identify these with SN ejecta. A few regions showed spectra with O and Mg emission consistent with solar- or near-solar abundances; we identify these with CSM. Finally, a few regions showed continuum-dominated spectra.

Examples of ejecta spectra (regions 1–3 in Fig. 1) are shown in Figure 2 and the top spectrum (Fe L region, 6) in Figure 3. In particular, Figure 2 shows spectra of three outer knots, where we might expect to find the lightest nucleosynthetic products at the largest distances, specifically the O that should indicate a CC explosion. All of them, however, show strong Si, S, and Fe L emission; prominent Ar, Ca, and Fe Kα lines are also present in the bright north knot 1. The western and southern knots 2 and 3 have comparable Si and S emission, but they differ in their Fe L-shell emission.

Knot 3 is well modeled by a heavy-element plane shock (Hendrick 2003) with velocity $v_s$ of 1010 km s$^{-1}$ [(889, 1120) km s$^{-1}$ 90% confidence interval], shock ionization age $\tau = 2.69$ (2.32, 3.18) $\times 10^{10}$ cm s$^{-1}$, and Si/Fe and S/Fe ratios (by number) of 2.64 (2.35, 2.92) and 2.24 (1.59, 2.87), respectively. The knot is clearly composed of ejecta. A trace amount of Mg [Mg/Fe = 0.052 (0.003, 0.10)] has been included, because it formally improves the fit, but its presence is much in doubt in view of deficiencies in Fe L atomic data. A synchrotron component (constrained by the absence of radio flux from the knot; DeLaney et al. 2002) improves the fit quality. We assumed no collisionless heating at the shock; if such heating were present, $v_s$ could be substantially less. Si and S are the primary constituents of the southern knot, but a significant (1/4 by mass) amount of Fe is present.

In the western knot 2, the shock speed is lower [$v_s = 500$ (360, 830) km s$^{-1}$] and the ionization age is longer [$\tau = 4.8$ (2.7, 14) $\times 10^{10}$ cm$^{-3}$ s$^{-1}$], but most significant are much higher Si/Fe and S/Fe ratios, 11.6 (8.9, 14.5) and 14.7 (10.2, 21.1), respectively. There is noticeably less Fe (6% by mass) in this knot; different Fe contents of knots 2 and 3 partially account for their different Fe L-shell emission strengths. Finally, in knot 1 the relative strengths of Si, S, and Fe L-shell emission are similar, so this is also a Si- and S-rich knot containing Fe. (Because a simple plane shock model failed to provide a satisfactory fit at high energies, we have not attempted a detailed abundance analysis for knot 1.)

The striking lack of obvious O features in the vast majority of the regions we examined led us to search specifically for soft-spectrum regions that might be expected to have a different composition. We found a few (all showing a pink color in Fig. 1) with discernible O features; two are shown in Figure 3. They constitute our second class of spectral region. The central knot has optical and IR counterparts (Blair et al. 1991, 2007), implying that it is composed of ambient CSM. We obtained the spectrum shown in Figure 3 after subtracting a local background from the knot; different Fe contents of knots 2 and 3 partially account for their different Fe L-shell emission strengths. Finally, in knot 1 the relative strengths of Si, S, and Fe L-shell emission are similar, so this is also a Si- and S-rich knot containing Fe. (Because a simple plane shock model failed to provide a satisfactory fit at high energies, we have not attempted a detailed abundance analysis for knot 1.)
bright east-west band nearby. In the plane-shock model fit shown in Figure 3, we allowed the abundances of Ne, Mg, Si, and Fe to vary (with S and Ni tied to Si and Fe, respectively). The poor spectral resolution of CCDs and the uncertain calibration at low energies, combined with deficiencies in Fe L atomic data, do not allow us to determine reliable absolute abundances with respect to H and He, or even a relative N abundance, but supersolar abundances for all elements except N are ruled out. We assumed near solar composition by setting the O abundance to its solar value, and determined relative abundances with respect to O. We assumed a supersolar (by a factor of 3; Blair et al. 2007) N abundance. We obtained a temperature $kT = 0.64$ keV (0.59, 0.70), $\tau = 2.7$ (1.8, 3.6) $\times 10^{11}$ cm$^{-3}$ s, and abundances with respect to solar of Ne = 0.64 (0.41, 0.91), Mg = 0.83 (0.61, 1.1), Si (tied to S) = 1.4 (1.0, 1.9), and Fe (tied to Ni) = 1.1 (0.94, 1.4). When N was allowed to vary, the best-fit N abundance is 3.2 (1.9, 4.6), where errors do not include systematic uncertainties particularly important at low photon energies. The model underestimates the continuum near the Si and S $\alpha\pi$ lines, most likely because of the presence of multitemperature plasma in the central knot, so abundances of these elements may be somewhat overestimated. The central knot spectrum is consistent with the same N-enhanced near-solar abundance composition found from optical spectra of the CSM in Kepler. Figure 3 also shows another soft-spectrum knot, 5; its spectrum is consistent with that of the central knot.

Finally, a few regions, primarily in the southeast, showed featureless or almost featureless spectra (one example, region 4, is shown in Fig. 3). These are well-described by models of synchrotron emission extending from the radio (Reynolds et al. 2004, is shown in Fig. 3). These are well-described by models of featureless or almost featureless spectra (one example, region 4, is shown in Fig. 3). These are well-described by models of synchrotron emission extending from the radio (Reynolds et al. 2004). Previous work with ASCA and XMM-Newton (Kinugasa & Tsunemi 1999, Cassam-Chenaï et al. 2004) derived substantial masses of shocked Fe, 0.1–0.3 $M_\odot$ (Kinugasa & Tsunemi 1999).

2. Scarcity of O.—By contrast, there is little evidence for O in Kepler’s SNR. It is seen only in a few regions with spectra quite different from the ejecta knots in having relatively weak Fe L emission. Most of these regions are coincident with optical knots which have been identified with CSM of roughly solar abundances except for elevated N. The X-ray knots do not require enhanced N abundance, but are consistent with the optical abundances. In particular, O/Fe is roughly solar. In SN ejecta of Type Ia, O/Fe is expected to be only 0.3-0.7 by number, whereas in CC explosions, it is about 70 (e.g., Iwamoto et al. 1999). None of the spectra we examined had the high O/Fe ratios required for CC ejecta. (Several poorly-understood luminous Type Ib/c SNe listed by Richardson et al. (2006) could be an exception, because their O/Fe ratios are much less than typical for CC explosions. Without detailed explosion models for these SNe confirming their CC origin, we cannot exclude such possible extreme CC events on the basis of the O/Fe ratio alone, but they are ruled out by arguments below.) We conclude that regions with detectable O are CSM.

3. Central source.—No central point source is seen, with a limit at least 100 times fainter than the source in Cas A.

We find the X-ray evidence for Kepler’s origin in a thermonuclear event to be compelling. However, additional evidence can be found from optical observations.

4. Balmer-dominated shocks.—Blair et al. (1991) discovered substantial emission from nonradiative, Balmer-dominated shocks. Such shocks demand the presence of partially neutral upstream material, ruling out most CC scenarios. A hot (i.e., compact) progenitor of a stripped CC Type Ib/c SN would have a strong ionizing flux before the explosion, while a cooler star would be larger at the time of the explosion, resulting in a large ionizing flux at shock breakout. The presence of neutral H sets an upper limit to the progenitor radius $R_*$ of $26\alpha^{0.575}(E/10^{51}$ ergs)$^{0.23}(M_{\text{CSM}}/M_\odot)^{0.657}(M/M_\odot)^{0.25}$ $R_*$ (Chevalier 2005), where $13.6\alpha$ eV ($\alpha > 1$) is the mean energy of an ionizing photon, and $M_{\text{CSM}}$ and $M_\odot$ are the shocked CSM and ejecta masses. Since $M_{\text{CSM}}$ is only $\sim 1 M_\odot$ (Blair et al. 2007), explosions of red supergiants with $R_* \sim 600 R_\odot$ are ruled out, including not only Type IIP and Type III SNe with full and partially-stripped H envelopes, respectively, but also Type IIn SNe such as 1993J with only a residual (0.2 $M_\odot$) H envelope left on its He core (Woosley et al. 1994). While an exotic stripped CC event, resulting from a star with a residual hydrogen envelope of low ($<0.2 M_\odot$) mass but large radius, might avoid ionizing the CSM before or during the explosion, such events become even less probable than a Type Ia with CSM interaction. An additional problem with a stripped CC progenitor is a large expected mechanical luminosity of its stellar wind, since radio observations of circumstellar interactions in Type Ib/c SNe are consistent with WR winds (e.g., Chevalier 2007). A powerful WR-like wind would have accelerated and swept away any dense CSM to distances of many pc from the SN, in obvious conflict with observations.

5. Light curve.—Stephenson & Green (2002) summarize the historical data. Kepler’s observed peak magnitude of $m \sim 3$ gives $M_V = -18.8$ (using the observed $E_{B-V} = 0.9$ to obtain $A_V = 2.8$), brighter than most CC events but typical for SNe Ia (e.g., Hamuy et al. 1996). The light curve, although resembling a normal Ia, could also describe a SN IIL (but see...
above). SN 1987A–like events (fairly compact blue stars with massive H envelopes) produce light curves that are far too broad, and are subluminous as well.

4. DISCUSSION AND CONCLUSIONS

We believe that X-ray and optical evidence points compellingly to the conclusion that Kepler resulted from a thermonuclear event. However, our deep Chandra observations also confirm that Kepler’s blast wave is encountering material with at least solar metallicity, coincident with optically emitting N-enhanced material—most likely circumstellar material lost by a fairly massive star, either the progenitor of the white dwarf or the companion, or both. Interaction with CSM is unexpected for Type Ia events. Some Type Ia SNe have shown signs of CSM interaction in the form of narrow H lines, such as SN 2002ic (Hamuy et al. 2003) and SN 2005gj (Aldering et al. 2006), but the interpretation of these objects remains controversial (Benetti et al. 2006; but see Prieto et al. 2007). Patat et al. (2007) give spectroscopic evidence that SN 2006X is a normal Type Ia SN with CSM interaction. Evidence for CSM interaction in SNRs appears to be relatively more widespread, and in some cases can be associated with Type Ia events. Prominent Fe emission in DEM L238 and DEM L249, two LMC SNRs, indicates a Type Ia origin. However, the brightness and location of that Fe, at small radii with a large ionization age, cannot be explained with standard Type Ia explosions into a uniform ISM (Borkowski et al. 2006); interaction with a nonuniform CSM seems to be required. Relatively bright central emission dominated by Fe is common in LMC SNRs (Nishiuchi et al. 2001; van der Heyden et al. 2004), suggesting that this class of SNRs is not a negligible population. N103B (Lewis et al. 2003) also shows evidence for CSM interaction in SNRs appears to be relatively more widespread. Of important SNRs, indicates a Type Ia origin. However, the brightness and location of that Fe, at small radii with a large ionization age, cannot be explained with standard Type Ia explosions into a uniform ISM (Borkowski et al. 2006); interaction with a nonuniform CSM seems to be required. Relatively bright central emission dominated by Fe is common in LMC SNRs (Nishiuchi et al. 2001; van der Heyden et al. 2004), suggesting that this class of SNRs is not a negligible population. N103B (Lewis et al. 2003) also shows evidence for CSM interaction in SNRs. Kepler’s SNR could just be the nearest example of a class of thermonuclear supernovae interacting with dense CSM from the progenitor system.

The required CSM might indicate an origin in a younger, more massive population. Three recent studies of extragalactic SNe Ia (Mannucci et al. 2006; Sullivan et al. 2006; Aubourg et al. 2007) propose the presence of a “prompt” population (delay ≲ 5 × 10^8 yr) in addition to an “old” population (delay ≳ 1 Gyr) in later type galaxies. If stars with initial masses less than about 8 M_☉ produce white dwarfs, the minimum latency for a thermonuclear supernova would be only about 50 Myr. A substantial number of remnants of Type Ia supernovae should come from the “prompt” population.

However, Kepler’s origin remains problematic. The elevated CSM abundances rule out a very old population, but the systemic velocity (>200 km s^-1; Blair et al. 1991) seems to indicate either a halo population, inconsistent with the abundances, or a runaway, probably inconsistent with a binary system. The Galactic bulge population would not extend to Kepler’s Galactocentric distance of 4.5 kpc.) The total CSM mass of ≳ 1 M_☉ (Blair et al. 2007) requires too large an initial mass for an extreme halo population. Could Kepler have resulted from the thermonuclear explosion of a single star? Current conventional wisdom requires that all AGB stars eject most of their envelopes to leave a sub-Chandrasekhar white dwarf; if that ejection were occasionally impeded, a single-star Type Ia supernova might result (e.g., Tout 2005). If Kepler’s progenitor were a single star liberated from the Galactic plane by the core-collapse explosion of its companion about 3 Myr ago, its maximum lifetime would only be of order 50 Myr, also arguing for a more massive progenitor.

Our conclusion that Kepler resulted from a Type Ia event with CSM interaction has important implications. Models of SN Ia progenitor systems make widely varying predictions for the nature of any CSM (e.g., Badenes et al. 2007); these predictions may now be testable. Similarly, SN Ia explosion models can now be tested in detail against the abundances and spatial distribution of elements in Kepler, and can be contrasted with Tycho’s SNR, apparently the result of a conventional SN Ia encountering only low-density, more or less uniform ISM (Badenes et al. 2006). The existence of a more massive subclass of SNe Ia with properties that may be systematically different has obvious important implications for cosmological use of SNe Ia, as it predicts a redshift-dependent mix of the two types. Since the use of SNe Ia for cosmology requires correction of peak magnitudes from light-curve shapes with a relation calibrated locally, the application of that same relation to more distant SNe Ia may raise concerns.

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REFERENCES

Aldering, G., et al. 2006, ApJ, 650, 510
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis and Systems V, ed. G. G. Jacoby & J. Barnes (San Francisco: ASP), 17
Aubourg, E., et al. 2007, ApJ, submitted (arXiv:0707.1328v2)
Badenes, C., Hughes, J. P., Bravo, E., & Langer, N. 2007, ApJ, 662, 472
Badenes, C., et al. 2006, ApJ, 645, 1373
Ballet, J. 2004, in High-Resolution X-Ray Spectroscopy with XMM-Newton and Chandra (London: MSSL)
Bandiera, R. 1987, ApJ, 319, 885
Benetti, S., et al. 2006, ApJ, 653, L129
Blair, W. P., Long, K., & Vancura, O. 1991, ApJ, 366, 484
Blair, W. P., et al. 2007, ApJ, 662, 998
Borkowski, K. J., Hendrick, S. P., & Reynolds, S. P. 2006, ApJ, 652, 1259
Cassam-Chenai, G., et al. 2004, A&A, 414, 545
Chevalier, R. A. 2005, ApJ, 619, 839
———. 2007, Rev. Mex. AA Ser. Conf., 30, 41
Decourchelle, A., et al. 2001, A&A, 365, L218
DeLaney, T. E., et al. 2002, ApJ, 580, 914
Fesen, R. A., et al. 2006, ApJ, 636, 859
Hamuy, M., et al. 1996, AJ, 112, 2391
———. 2003, Nature, 424, 651
Hendrick, S. P. 2003, Ph.D. thesis, North Carolina State Univ
Iwamoto, K., et al. 1999, ApJS, 125, 439
Kepler, J. 1606, De Stella Nova in Pede Serpentarii (Prague: Paul Sessi)

Kinugasa, K., & Tsunemi, H. 1999, PASJ, 51, 239
Lewis, K. T., et al. 2003, ApJ, 582, 770
Mannucci, F., Della Valle, M., & Panagia, N. 2006, MNRAS, 370, 773
Nishiuchi, M., et al. 2001, PASJ, 53, 99
Patat, F., et al. 2007, Science, 317, 924
Pavlov, G. G., et al. 2000, ApJ, 531, L53
Prieto, J. L., et al. 2007, AJ, submitted (arXiv:0706.4088v1)
Reynolds, S. P., et al. 2007, BAAS, 39, 114
Richardson, D., Branch, D., & Baron, E. 2006, AJ, 131, 2233
Sankrit, R., et al. 2005, Adv. Space Res., 35, 1027
Sasaki, M., et al. 2006, ApJ, 642, 260
Smith, R. K., et al. 2001, ApJ, 556, L91
Stephenson, F. R., & Green, D. A. 2002, Historical Supernovae and their Remnants (Oxford: Clarendon), p. 78
Sullivan, M., et al. 2006, ApJ, 648, 868
Tout, C. A., 2005, in White Dwarfs: Cosmological and Galactic Probes, ed. E. M. Sion, S. Vennes, & H. L. Shipman (Dordrecht: Springer), 135
van der Heyden, K. J., et al. 2004, A&A, 421, 1031
Willett, R. 2007, in ASP Conf. Ser. 371, Statistical Challenges in Modern Astronomy IV, ed. G. J. Babu & E. D. Feigelson (San Francisco: ASP), in press (http://www.ee.duke.edu/~willett/pubs.html)
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Woosley, S., et al. 1994, ApJ, 429, 300