THE METAL-ENRICHED THERMAL COMPOSITE SUPERNova REMNANT KESEVEN 41 (G337.8–0.1) IN A MOLECULAR ENVIRONMENT

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ABSTRACT

The physical nature of thermal composite supernova remnants (SNRs) remains controversial. We have revisited the archival XMM-Newton and Chandra data of the thermal composite SNR Kes 41 (G337.8–0.1) and performed a millimeter observation toward this source in the 12CO, 13CO, and C18O lines. The X-ray emission, mainly concentrated toward the southwestern part of the SNR, is characterized by distinct S and Ar He-like lines in the spectra. The X-ray spectra can be fitted with an absorbed nonequilibrium ionization collisional plasma model at a temperature of 1.3–2.6 keV and an ionization timescale of 0.1–1.2 × 10^{12} cm^{-3} s. The metal species S and Ar are overabundant, with 1.2–2.7 and 1.3–3.8 solar abundances, respectively, which strongly indicate the presence of a substantial ejecta component in the X-ray-emitting plasma of this SNR. Kes 41 is found to be associated with a giant molecular cloud (MC) at a systemic local standard of rest velocity of ≳50 km s^{-1} and confined in a cavity delineated by a northern molecular shell, a western concave MC that features a discernible shell, and an H I cloud seen toward the southeast of the SNR. The birth of the SNR in a preexisting molecular cavity implies a mass of \textasciitilde18 M\odot for the progenitor if it was not in a binary system. Thermal conduction and cloudlet evaporation seem to be feasible mechanisms to interpret the X-ray thermal composite morphology, and the scenario of gas reheating by the shock reflected from the cavity wall is quantitatively consistent with the observations. An updated list of thermal composite SNRs is also presented in this paper.

Key words: ISM: individual objects (G337.8–0.1 = Kes 41) – ISM: molecules – ISM: supernova remnants

1. INTRODUCTION

Massive stars rapidly evolve to the end of their nuclear-burning lifetimes and explode as core-collapse (CC) supernovae before they can move far away from where they formed. Dozens of CC supernova remnants (SNRs) have been found to be interacting with molecular clouds (MCs; see Jiang et al. 2010 and references therein). Such SNRs are a crucial probe for hadronic interactions between the shock-accelerated protons and the associated MCs, and many detections of them have been made based on \(\gamma\)-ray observations in the current Fermi and HESS era. Among them are a number of so-called thermal composite (Jones et al. 1998; Wilner et al. 1998) or mixed-morphology remnants (Rho & Petre 1998); this class of SNRs is characterized by the coexistence of radio shells and centrally brightened thermal X-ray emission. The large majority of thermal composite SNRs have been found to be interacting with adjacent MCs (Green et al. 1997; Yusef-Zadeh et al. 2003). Unlike the regular composite-type SNRs, in which the central X-ray emission is clearly known to be powered by pulsars, the nature of the X-ray kernel in the thermal composites remains a controversial issue.

Several attempts have been made to interpret the X-ray morphology of the thermal composites, and some mechanisms to explain the center-filled X-ray morphology have been proposed, including a hot interior with radiatively cooled rim, thermal conduction in the interior hot gas, gas evaporation from the shock-engulfed cloudlets, projection effects of the one-sided shock–cloud interaction, metal enrichment in the interior, and a shock reflected inward from a wind-blown cavity wall, among other proposed mechanisms (see a summary in Chen et al. 2008 and references therein). More studies of thermal composite SNRs are needed to test these mechanisms. For this purpose, we here investigate the properties of the interior hot gas and the environs of SNR Kes 41 (Kes 41 for the remainder of this paper).

Kes 41 (G337.8–0.1), a southern-sky SNR first discovered with the Molonglo Observatory Synthesis Telescope (MOST) at 408 MHz (Shaver & Goss 1970), is shown to be centrally brightened in X-rays within a distorted radio shell by an XMM-Newton observation and is therefore classified as a thermal composite SNR (Combi et al. 2008). In a spectral analysis, the X-ray emission was suggested to arise from a hot (\(~\sim 1.4\) keV) gas of normal metal abundance; however, only the MOS data of the XMM-Newton have been analyzed so far (Combi et al. 2008). Presently, the available X-ray observations allow a more thorough analysis of the physical properties of Kes 41.

Moreover, Kes 41 has been found to be interacting with an adjacent MC, as indicated by the 1720 MHz hydroxyl radical (OH) maser emission detected on the radio shell (Koralesky et al. 1998; Caswell 2004). The OH satellite line masers at 1720 MHz are widely accepted as signposts of SNR–MC interaction (Lockett et al. 1999; Frail & Mitchell 1998; Wardle & Yusef-Zadeh 2002). The SNR–MC interaction may probably contribute to the high-energy \(\gamma\)-ray excess near Kes 41 detected by the EGRET (Casandjian & Grenier 2008) and Fermi (Ergin & Ercan 2012) satellites. The distance to the remnant is estimated to be 12.3 kpc from the OH maser detection at the local standard
of rest (LSR) velocity of $-45 \text{ km s}^{-1}$ (Koralesky et al. 1998) and the H I absorption that places it beyond the tangent point at 7.9 kpc (Caswell et al. 1975). As a follow-up study of the association of Kes 41 with an adjacent MC, we have performed a millimeter observation toward Kes 41 of CO transition lines.

In this paper we carry out an X-ray analysis of SNR Kes 41 with archival XMM-Newton (MOS and PN) and Chandra observation data and investigate the ambient interstellar environment as contrasted with the shell-like feature in radio (shown in Figure 1). A broadband (2.0–7.2 keV) X-ray map of Kes 41 is shown in Figure 1. In this image, we have removed the bad particle background subtracted and exposure map correction applied, and adaptively smoothed the image (using the tool fadapt of HEASOFT). It can be clearly seen that the X-ray emission is internally filled without limb brightening, as contrasted with the shell-like feature in radio (shown in Figure 1).

Table 1

| Obs. ID | R.A.          | Decl.          | Observation Date | Exposure (ks) | CCD Chips | Good Exposure (ks) | Spectral Analysis |
|---------|---------------|----------------|------------------|---------------|------------|---------------------|------------------|
| 12513   | $1\text{h}39\text{m}53\text{s}81$ | $-46^\circ57^\prime45^\prime0$ | 2011 June 27 | 20.4         | 10         | 20.2                | Yes              |
| 12514   | $1\text{h}39\text{m}01^\prime38$ | $-46^\circ49^\prime45^\prime8$ | 2011 June 10 | 20.0         | 11         | 19.8                | No               |
| 12516   | $1\text{h}39\text{m}06^\prime95$ | $-46^\circ06^\prime42^\prime5$ | 2011 June 11 | 19.8         | 12         | 19.5                | No               |
| 12517   | $1\text{h}38\text{m}14^\prime49$ | $-46^\circ58^\prime42^\prime0$ | 2011 June 11 | 19.8         | 13         | 19.5                | Yes              |
| 12518   | $1\text{h}38\text{m}19^\prime33$ | $-47^\circ15^\prime38^\prime8$ | 2011 June 13 | 19.6         | 52         | 19.3                | No               |
| 12520   | $1\text{h}37\text{m}27^\prime34$ | $-47^\circ07^\prime37^\prime0$ | 2011 June 13 | 19.6         | 53         | 19.0                | Yes              |

Notes.

- a Indicates which observations featured data that were extracted for spectral analysis.
- b Indicates which observations featured data that were extracted for spectral analysis.

7 See http://xmm.esac.esa.int/sas/
8 See http://cxc.harvard.edu/ciao/
9 See http://heasarc.gsfc.nasa.gov/lheasoft/
10 See http://www.atnf.csiro.au/computing/software/livedata/
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40.0 20.0 16:39:00.0 38:40.0 -46:52:00.0 54:00.0 56:00.0 58:00.0 -47:00:00.0

Figure 1. Tricolor image of Kes 41 in multiwavelengths. Blue: XMM-Newton X-ray image (2.0–7.2 keV) obtained by combining the EPIC-PN and MOS data. Green: $^{12}$CO($J=1$–$0$) integrated map ($V_{\text{LSR}} = -70$ to $-40$ km s$^{-1}$). Red: H$\text{I}$ line emission from the SGPS integrated map ($V_{\text{LSR}} = -55$ to $-50$ km s$^{-1}$). The image is overlaid with MOST 843 MHz radio contours (at seven linear scale levels between 0.00 and 0.79 Jy beam$^{-1}$; from Whiteoak & Green (1996)). The white cross indicates the location of the 1720 MHz OH maser (Koralesky et al. 1998) in this SNR.

Figure 2. XMM-Newton (MOS+PN) X-ray images of Kes 41 in energy bands 2.0–2.8 keV, 2.8–3.5 keV, and 3.5–7.2 keV, with radio contours (the same as in Figure 1) overlaid.

white contours). The centroid of the X-ray emission sits in the southwest (SW) region of the northeast–southwest elongated extent of the SNR.

In Figure 2, we present X-ray images that are produced in the 2.0–2.8 keV, 2.8–3.5 keV, and 3.5–7.2 keV energy ranges, respectively, following a procedure similar to that of the broadband image. These images illustrate the photon energy dependence for broadband intensities. The narrow bands correspond to the sulfur line, argon line (see Section 3.1.2), and higher energy emission, respectively. In both the soft (2.0–2.8 keV) and hard (3.5–7.2 keV) images, there are two X-ray brightness peaks located in the geometric center and the southwestern region. The hard X-ray image looks relatively bright in the SW compared with that in the NE.

All six short sections of the Chandra observation described in Table 1 are also used to generate a merged broadband image of Kes 41, but the location of the SNR is near the edge of the CCD chips in each section of observation, resulting in a decrease of the angular resolution. The Chandra X-ray image of the SNR shows no significant difference from the XMM-Newton image and is not presented here.

3.1.2. Spectral Analysis

Figure 3 shows the simultaneous fit of the XMM-Newton and Chandra spectra of Kes 41. The spectral extraction regions for the diffuse emission source and the local background are defined in Figure 4 with all of the detected point sources removed. The spectral extraction is such as to include the brightest portion of the diffuse X-ray emission, which is located in the southwestern part of the SNR and is within the FOVs of all of the XMM-Newton MOS and PN and Chandra-ACIS detectors. Because of the insufficiency of event counts in each spectrum of the XMM-Newton EPIC-MOS and Chandra observations, we merge the MOS1 and MOS2 spectra using the HEASOFT tool addascaspec and merge three Chandra spectra (see Table 1) using combine_spectra in CIAO 4.5 to increase the statistical
distinct line features, to vary and set the abundances of the other spectral fit, we allow the abundances of S and Ar, which have been adapted to achieve a background-subtracted signal-to-noise ratio of three per bin. They are jointly fitted using the same absorbed vnei model, and the lines with different colors are fitted model lines matching the same color data points separately.

The other three sections of the Chandra observation hardly cover the main area of the X-ray emission and are thus not considered. The spectra are all adaptively regrouped to achieve a background-subtracted signal-to-noise ratio of three per bin. In these spectra, there are apparent emission line features of metal elements S (∼2.43 keV) and Ar (∼3.16 keV), as well as a hint of Ca (∼3.9 keV), which confirms the thermal origin of the X-ray emission. There is no emission below ∼2.0 keV, which indicates a large value of line-of-sight (LOS) hydrogen column density \(N_H\).

The XMM-Newton and Chandra spectra can be jointly fitted with an absorbed (using XSPEC model phabs) single-temperature, nonequilibrium ionization (NEI) model (vnei, version 2.0), and the results are summarized in Table 2. In the spectral fit, we allow the abundances of S and Ar, which have distinct line features, to vary and set the abundances of the other metal elements equal to solar (Anders & Grevesse 1989). The thermal X-ray-emitting gas is at a temperature \(T\) ∼1.3–2.6 keV with an ionization parameter of \(n_e \sim 0.1–1.2 \times 10^{12} \text{cm}^{-3} \text{s}^{-1}\). The best-fit abundances of the two elements are moderately elevated (∼1.2–2.7 and ∼1.3–3.8 times solar, respectively), indicating that the hot gas is metal enriched.

To see where the metal-rich materials’ emission arises, we present the equivalent-width (EW) images of the S and Ar lines in Figure 5. These images are constructed using a method similar to that used in Jiang & Chen (2010) so as to maximize the

**Table 2**

| Parameter | Value |
|-----------|-------|
| Net count rate (10^{-3} counts s) | 28.05 ± 1.60^a |
| 7.86 ± 0.49^b |
| 2.46 ± 0.38^c |
| \(N_H(10^{22} \text{cm}^{-2})\) | 6.75^{+1.27}_{-1.21} |
| \(kT_e (\text{keV})\) | 1.80^{+0.34}_{-0.47} |
| \(n_e(10^{11} \text{~cm}^{-3})\) | 2.06^{+0.87}_{-1.56} |
| \(f_{\text{n}_e n_H V/d_{12}^3(10^7 \text{~cm}^{-3})}\) | 1.46^{+1.17}_{-0.72} |
| \([\text{S}/\text{H}]\) | 1.80^{+0.92}_{-0.65} |
| \([\text{Ar}/\text{H}]\) | 2.40^{+1.42}_{-1.06} |
| Reduced \(\chi^2\) (d.o.f.) | 0.99 (54) |

**Notes.** The abundances of all elements are set to solar abundances, except for S and Ar.

\(a,b,c\) The count rates are from PN, MOS, and ACIS, respectively, with a 1σ error range.
\(d\) The unabsorbed fluxes are in the 0.5–10 keV band.
\(e\) In the estimate of the densities, we assume a volume of a prolate ellipsoid (considering the NE–SW elongated morphology of the SNR) with size 5.8 × 4.2 × 4.2 pc^3 for the elliptical region of X-ray spectral extraction (see Figure 4).

**Figure 3.** X-ray spectra of the region defined in Figure 4 from both XMM-Newton and Chandra observations. Red points show the EPIC-PN data; the black points are from the merged EPIC-MOS1/2 data; the green points show the coadded spectrum made by merging all three Chandra observations that cover the majority of the SNR’s X-ray emission, as described in Section 3.1.2. All of the spectra have been adaptively binned to achieve a background-subtracted S/N (signal-to-noise ratio) of three per bin. They are jointly fitted using the same absorbed vnei model, and the lines with different colors are fitted model lines matching the same color data points separately.

**Figure 4.** Raw images of the XMM-Newton observation (left) and merged Chandra observations (right), with all detected point sources removed. The common ellipse (in blue) is used for source spectral extraction. In the left panel, the dashed boxes, excluding the dashed circle with the crossing line (in red), are used for PN and MOS1/MOS2 background subtraction. In the right panel, the boxes with the numbers denoting the Obs. IDs in Table 1 are used as background regions for the corresponding data. The black contours are from radio observation, with levels the same as in Figure 1.
statistical quality. Assuming that the line-to-continuum ratio is intrinsically invariable for various detectors, we sum the X-ray counts from XMM-Newton EPIC-MOS and PN and Chandra ACIS observations band by band according to componendo. We then rebin the data using an adaptive mesh, with each bin in each narrow-band image containing about 10 counts. The intensity of the line emission with the interpolated continuum component subtracted is used as the numerator of the ratio, and the background (estimated from the region surrounding the SNR) is subtracted from the continuum intensity, which is used as the denominator. Figure 5 shows that the EW values of both the S and Ar lines are only significant in the interior of the southwestern part of the SNR. The caveat here is that the derived continuum images might have lower statistical qualities than the corresponding line emission images, and not all of the bins can reach $3\sigma$ significance, especially outside the X-ray emission region.

3.2. The Interstellar Environment

3.2.1. Spatial Distribution of the Ambient Clouds

The average CO spectra over the FOV are shown in Figure 6. There are a number of spectral components along the LOS at the LSR velocities from $V_{\text{LSR}} = -130$ km s$^{-1}$ to $V_{\text{LSR}} = 0$ km s$^{-1}$. The LSR velocity of the 1720 MHz maser spot, $\sim-45$ km s$^{-1}$, is in the right wing of the line component peaked at $\sim-50$ km s$^{-1}$, which is commonly revealed in the $^{12}$CO($J = 1-0$), $^{13}$CO($J = 1-0$), and C$^{18}$O($J = 1-0$) spectra (see Figure 6). By an examination of the channel maps of the $\sim-50$ km s$^{-1}$ line component, we find a morphological correspondence between the western radio boundary of the SNR and a concave surface of MC seen in the $^{12}$CO emission at velocity interval $\sim-55$ to $-52$ km s$^{-1}$ (see Figure 7). The concaved MC is also remarkable in the integrated $^{12}$CO intensity map in the interval $-70$ to $-40$ km s$^{-1}$ within the velocity range of the line profile (see Figure 1). In $^{13}$CO emission, a bow-like structure at $\sim-50$ to $-48$ km s$^{-1}$ seems to match the western radio shell; furthermore, a molecular shell at $\sim-61$ to $-58$ km s$^{-1}$ perfectly follows the western radio shell of the SNR (see Figure 8). In addition, a section of molecular shell in $^{12}$CO emission at $\sim-47.5$ km s$^{-1}$ is seen to closely follow the northern radio shell (see Figure 7). Such correspondence is actually only seen in this spectral component by examining the data cubes across the entire LSR velocity span. Around the OH maser position, we can also see some dense molecular gas in the intensity maps (Figure 9) of C$^{18}$O emission, which is optically thin and traces molecular cores. The combination of the OH maser and the spatial features of CO emission presented here clearly demonstrates that SNR Kes 41 is in physical contact with the MC at a systemic velocity $V_{\text{LSR}} \sim -50$ km s$^{-1}$ in the west and the north, although the broadened CO line profiles of the $\sim-50$ km s$^{-1}$ molecular component due to shock disturbance cannot be discerned because of line crowding along the LOS.

It is noteworthy that a dense HI cloud at $V_{\text{LSR}} \sim -52$ km s$^{-1}$ is situated to the southeast of the SNR (see Figure 1, where the HI intensity image is presented in the velocity interval $-55$ to $-50$ km s$^{-1}$), and the southeastern radio shell of the SNR seems...
Figure 7. $^{12}$CO($J=1-0$) intensity maps integrated each 1 km s$^{-1}$ in the velocity range $-70$ to $-40$ km s$^{-1}$ in a linear scale, overlaid with the MOST 843 MHz radio continuum contours (at seven linear scale levels between 0.07 and 0.88 Jy beam$^{-1}$). The cross indicates the location of the OH (1720 MHz) maser spot. The color bar of the last row of panels is different from those of the other rows because of the relatively low brightness. The dashed lines in the $-54.5$ k ms$^{-1}$ panel depict the two diagonals of the FOV along which the column density distribution $N$(H$_2$) of the molecular gas in velocity range $-70$ to $-40$ km s$^{-1}$ is measured. The intersection of the diagonals is used as the reference point (see Figure 10). The dashed box in the $-53.5$ km s$^{-1}$ panel depicts the region where we derive the parameters of the interacting MC.

3.2.2. Parameters of the Ambient Clouds

We estimate the gas parameters of the $-50$ km s$^{-1}$ molecular component in the velocity range $-70$ to $-40$ km s$^{-1}$ with which to follow the surface of the H I cloud. SNR Kes 41 appears to be confined in a cavity enclosed by the MC in the west and northwest and the H I cloud in the southeast. The archival data show that this H I cloud has an angular size of $\sim$18$''$. 

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Figure 8. Intensity maps of the $^{13}$CO($J=1$–0) observation between $-66$ km s$^{-1}$ and $-41$ km s$^{-1}$ in a linear scale. The contours and cross are the same as those in Figure 7. Note the difference in color bars for different rows.

the SNR is interacting, and the results are listed in Table 3. The column density and mass of the molecular gas derived may be an upper limit because there may be irrelevant contributions in the complicated line profiles in $^{12}$CO and $^{13}$CO emission. For the estimate, we adopt a box region that includes the main part of the MC in the FOV (see the $-53.5$ km s$^{-1}$ panel of Figure 7). Three methods have been utilized to estimate the average molecular column density $N$(H$_2$), which give a similar value of $N$(H$_2$) $\sim 3$–$5 \times 10^{22}$ cm$^{-2}$. In the first method, we use the mean CO-to-H$_2$ mass conversion factor (known as the X factor) $1.8 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km$^{-1}$ s (Dame et al. 2001) to calculate the molecular column density based on the $^{12}$CO($J=1$–0) emission. In the second method, the $^{13}$CO column density is converted to the H$_2$ column density using $N$(H$_2$)/$N$(^{13}CO) $\approx 6.2 \times 10^5$ (Nagahama et al. 1998), and in the third method, the relation $N$(H$_2$)/$N$(C$^{18}$O) $\approx 7 \times 10^6$ (Warin et al. 1996) is used for the conversion from C$^{18}$O column density to H$_2$ column density. In the second and third method, we have assumed a local thermodynamic equilibrium and that the $^{12}$CO($J=1$–0) line is optically thick, with an excitation temperature of 12.9 K (as obtained from the line peak of $^{12}$CO($J=1$–0)).

Prior to deriving the column densities of $^{13}$CO and C$^{18}$O, we have derived the optical depths $\tau^{(13)}$CO $\approx 0.6$ and $\tau^{(C^{18}O)}$ $\approx 0.1$, and therefore we treat the $^{13}$CO and C$^{18}$O emissions as optically thin. The $N$(H$_2$) value obtained from the third method, $\sim 5.1 \times 10^{22}$ cm$^{-2}$, is a little greater than those obtained from the other two methods, and it is probably because C$^{18}$O traces denser clouds.
Corrected to the radiative temperature.

We use the same LSR velocity range and this range likewise includes the main part of the H\(_i\) column density of 12 kpc.

The archival data show that the H\(_i\) cloud southeast of Kes 41 that is adopted as the LOS size of the ~9' (a lower limit given by the FOV and using the molecular column density \(N(\text{H}_2) \sim 3\times10^{22} \text{ cm}^{-2}\), we estimate the molecular density as \(n(\text{H}_2) \lesssim 310-510d_{12}^{-1} \text{ cm}^{-3}\), where \(d_{12} = d/(12 \text{ kpc})\) is the distance to the MC associated with the SNR in units of the reference value estimated from the maser observation (Koralesky et al. 1998).

Another density estimate can be made from the excavation of the molecular gas in the SNR extent, following the method used in Jiang et al. (2010). We plot the molecular density distributions of the \(^{12}\text{CO}\) line complex in the interval ~70 to ~40 km s\(^{-1}\) along the two diagonals of the FOV using the X-factor method (see Figure 10). As can be clearly seen, \(N(\text{H}_2)\) generally increases both from the southeast to the northwest and from the northeast to the southwest. Notably, there are peaks or bumps in column density just outside the SNR boundary, which is consistent with the molecular shells described in Section 3.2.1.

Outside the bumps of both \(N(\text{H}_2)\) curves, there are platforms at ~4 x 10\(^{22}\) cm\(^{-2}\); just inside the opposite boundaries, there are lower platforms (wide in the left panel and narrow in the right panel), both at ~2.9 x 10\(^{22}\) cm\(^{-2}\). The common difference of column density ~7.1 x 10\(^{22}\) cm\(^{-2}\) can be explained with the removal of molecular gas from the SNR region. Thus, the molecular gas originally in the excavated region has a number density \(n(\text{H}_2) \sim 140d_{12}^{-1} \text{ cm}^{-3}\), assuming that the mean LOS length of the excavated region is similar to the minor axis of the elongated SNR.

If the apparent size of the southeastern H\(_i\) cloud—that is, ~18' (see Section 3.2.1)—is adopted as the LOS size of the cloud, then the number density of the neutral gas can be estimated from the neutral column density as \(n(\text{H}_i) \sim 36d_{12}^{-1} \text{ cm}^{-3}\).

Our analysis has revealed that SNR Kes 41 is confined in a cavity enclosed by MCs in the west and north and an H\(_i\) cloud in the southeast (Section 3.2.1). Some shell-like features of molecular gas also appear to follow the periphery of the SNR. We can give some crude estimates on the gas density of the complicated surrounding environment.
\[ V = \frac{5.8 \pm 0.8 \times 10^3 \times d_{12} \text{ yr}}{r} \text{ (where } r = 13d_{12} \text{ pc is the mean radius), and the supernova explosion energy would be } E = (25/4\xi)4n_0m_pv^2 \sim 2d_{12}^{3} \times 10^{53} \text{ erg or } 2d_{12}^{3} \times 10^{44} \text{ erg, for ambient density } n_0 = 40 \text{ cm}^{-3} \text{ (for H gas) and } 280 \text{ cm}^{-3} \text{ (for molecular gas), respectively, where } \xi = 2.026. \text{ Such estimates are highly unphysical because the explosion energy is much higher than the canonical value of } 10^{51} \text{ erg. Moreover, the molecules in the surrounding molecular shell (Section 3.2.1) could not survive if the shell were swept up by the SNR shock, given the high shock velocity. Therefore, the assumption of Sedov evolution of Kes 41 in a uniform medium is problematic.}

### 4.2. SNR Physics

#### (i) Some Physical Parameters

The density of the X-ray-emitting gas interior to the SNR can be estimated using the volume emission measure obtained from the spectral analysis. Based on the assumption \( n_i \approx 1.2n_0 \) for the densities of electrons and hydrogen atoms, we get \( n_i \approx 0.2-0.4f^{-1/2}d_{12}^{-1/2} \text{ cm}^{-3} \), where \( f \) is the filling factor of the hot gas. We estimate the ionization age \( t_i \approx 4 \times 10^3-1.1 \times 10^5 f^{1/2}d_{12}^{1/2} \text{ yr} \) by using the best-fit ionization parameter \( n_i f \) (also see Table 2).

In the X-ray spectral analysis, the spectral extraction region covers the main part of the X-ray emission. The mass of the hot gas in the region is \( \sim 2-4f^{3/2}d_{12}^{-2/3}M_\odot \), which can be regarded as a lower limit. If the hot gas pervades the whole interior of the remnant, we obtain an upper limit of the mass of the hot gas, \( \sim 18-37f^{1/2}d_{12}^{1/2}M_\odot \), assuming a prolate ellipsoid volume \( (12.6 \times 8.4 \times 8.4d_{12}^{3/2}) \text{ pc}^3 \) for the remnant.

#### (ii) Sedov Evolution

Kes 41 has been shown to be surrounded by molecular gas of density \( n(H_2) \sim 140-350\text{ cm}^{-3} \) and H1 gas of density \( n(HI) \sim 40\text{ cm}^{-3} \). If the SNR follows the Sedov (1959) evolution in the dense ambient gas, and the hot gas temperature obtained from the X-ray spectral fit, \( kT_x \), is taken to be the emission-measure-weighted mean temperature, then the postshock temperature would be \( kT_x = kT_i/1.27 \) and the expansion velocity would be \( v_x = (16kT_i/3\mu m)\bar{\mu}_i^{1/2} \sim 1.1^{+2.2}_{-0.1} \times 10^3 \text{ km s}^{-1} \), where the mean atomic weight \( \bar{\mu}_i \approx 0.61 \) is used. The dynamic age would be \( t = 2r/5V_0 \approx 5.8^{+0.8}_{-1} \times 10^3d_{12} \text{ yr} \) (where \( r = 13d_{12} \text{ pc} \) is the mean radius), and the supernova explosion energy would be \( E = (25/4\xi)4n_0m_pv^2 \sim 2d_{12}^{3} \times 10^{53} \text{ erg or } 2d_{12}^{3} \times 10^{44} \text{ erg, for ambient density } n_0 = 40 \text{ cm}^{-3} \text{ (for H gas) and } 280 \text{ cm}^{-3} \text{ (for molecular gas), respectively, where } \epsilon = 2.026. \text{ Such estimates are highly unphysical because the explosion energy is much higher than the canonical value of } 10^{51} \text{ erg. Moreover, the molecules in the surrounding molecular shell (Section 3.2.1) could not survive if the shell were swept up by the SNR shock, given the high shock velocity. Therefore, the assumption of Sedov evolution of Kes 41 in a uniform medium is problematic.}

#### (iii) Evolution in the Radiative Phase

The radiatively cooled rim is one of the scenarios invoked to explain the X-ray thermal composite morphology. If Kes 41 is not considered to be in a preexisting cavity, then the radiative pressure-driven snowplow (PDS) stage begins at a radius (Cioffi et al. 1988) \( r_{\text{PDS}} = 2.9E_{51}^{2/7}(n_0/40\text{ cm}^{-3})^{-3/7}\xi_5^{-1/3}\text{pc} \) and an age \( t_{\text{PDS}} = 3.6 \times 10^3E_{51}^{3/14}(n_0/40\text{ cm}^{-3})^{-4/7}\xi_5^{-5/14}\text{yr} \), where \( E_{51} \equiv E/(10^{51}\text{ erg}) \) and the \( \xi_5 \) metallicity factor are of order unity. If \( n_0 = 280 \text{ cm}^{-3} \) for the detected molecular gas, then \( r_{\text{nuv}} \sim 1.3\text{ pc} \) and \( t_{\text{nuv}} \sim 1.8 \times 10^4 \text{ yr} \). Compared to the mean radius \( \sim 13\text{ pc} \) and the ionization age \( \sim 2\text{ kyr} \), these estimates indicate that the SNR may have entered the radiative phase at an early time. In this scenario, the present velocity of the blast wave is \( v_\nu = 21[E_{51}(n_0/40\text{ cm}^{-3})^{-36/31}\xi_5^{-5/3}(r/13\text{ pc})^{-98/31}]^{1/2} \text{ km s}^{-1} \) (Cioffi et al. 1988; Chen & Slane 2001), which would be \( \sim 4\text{ km s}^{-1} \) for an ambient molecular gas with \( n_0 = 280 \text{ cm}^{-3} \), where \( E_{51} \sim 1 \) and \( \xi_{5} \sim 1 \) are assumed for simplicity. With such a shock velocity, the molecular shell can plausibly be explained to be the material swept up by the SNR blast wave. The dynamic age of the remnant is thus given by \( t = 3.3 \times 10^4(r/14\text{ pc})(v_\nu/413\text{ km s}^{-1})^{-1}[3 + \xi_{5}^{-10/3}(r/14\text{ pc})^{-10/3}(v_\nu/413\text{ km s}^{-1})^{10/3}] \text{ yr} \) (Cioffi et al. 1988; Chen & Slane 2001), which yields \( t \sim 1.8 \times 10^5 \text{ yr} \) for a preshock atom gas with \( n_0 \sim 40\text{ cm}^{-3} \) or \( 1.0 \times 10^6 \text{ yr} \) for a molecular gas with \( n_0 \sim 280\text{ cm}^{-3} \), respectively.

---

11 See http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
In Kes 41, the S and Ar emissions contribute 7% and 2%, respectively, to the broad energy ranges 0.5–10 keV, and the extra abundances of these two metals contribute 3% and 1%, respectively.

4.2.3. Effect of Preexisting Cavity

(i) Shock Reflection. Thermal composite SNRs are usually associated with dense material (especially MCs), and therefore their progenitor stars are likely to have created a cavity in the dense environment with energetic stellar winds and ionizing radiation. Actually, about 10 thermal composites have been found or suggested to evolve in cavities (see Table 4). When the supernova blast wave hits the cavity wall, a reflected shock can be expected to be sent back inward and reheat the interior gas including the ejecta to a higher temperature. This is the case suggested for the thermal X-ray composite morphology to SNR Kes 27 (Chen et al. 2008). A similar explanation is also proposed for the thermal composite SNR 3C 397, which is embedded in the edge of a giant MC and confined by a sharp molecular wall (Jiang et al. 2010). The thermal composite X-ray W44 appears to be confined in a molecular cavity that is delineated by sharp molecular “edges” in the east, southeast, and southwest, as well as molecular filaments and clumps in other periphery positions (Seta et al. 2004). The metal-enriched X-ray-emitting gas in the interior of the SNR may have been reheated by the shock reflected from the cavity wall (which is at least represented by the sharp “edges”).

Kes 41 has been demonstrated here to also be confined in a cavity in a molecular environment. As shown above (Section 4.2.1), both the Sedov and radiative-phase evolution in a uniform, dense molecular/H I gas will lead to unreasonable physical parameters, and hence the cavity is not blown by the SNR itself. A collision of the SNR shock with the preexisting cavity wall thus cannot be ignored. The forward shock of the SNR is drastically decelerated upon the collision. Assuming that the density ratio between the cavity and the wall is much smaller than one and adopting the cavity radius \( r_c \sim 13 \text{ pc} \), the shock velocity upon the collision can be essentially estimated as (Chen et al. 2003)

\[
v_{r}(r_c) = \left[ \frac{E}{2\pi(1.4n_0m_p)r_c^2} \right]^{1/2},
\]

which is \( \lesssim 20E_{21}^{1/2} \) and \( 50E_{51}^{1/2} \) km s\(^{-1} \) for \( n_0 \gtrsim 280 \text{ cm}^{-3} \) (for molecular gas) and \( n_0 \approx 40 \text{ cm}^{-3} \) (for H I gas), respectively. Such low velocities indicate that Kes 41 has entered a radiative stage right after the blast wave struck the cavity wall. This effect readily explains the lack of X-ray emission in the SNR rim.

The interior gas remains hot and is elevated to a higher temperature by the heating by a reflected shock. This scenario can be tested in combination with the observation result and simplified theory presented by Sgro (1975). For a shock reflection at a dense wall, the temperature ratio between the post–reflected-shock gas and the post–transmitted-shock gas is given by

\[
\frac{T_r}{T_i} = \frac{A}{A_r},
\]

where \( A \) is the density contrast between the post–reflected-shock gas and the post–incident-shock gas, and \( A \) is the wall-to-cavity density contrast, which in turn is a function of \( A_r \), specifically.

\[
A = \frac{3A_r(4A_r - 1)}{[(3A_r(4 - A_r))]^{1/2} - \sqrt{5(4A_r - 1)^2}}.
\]
### Table 4

List of Known Thermal Composite SNRs

| SNR Name           | Enriched Metal Species | Temperature $kT_1$ (keV)$^a$ | Ionization Parameter $n_eT_e$ (s cm$^{-3}$)$^b$ | MC Interaction$^c$ | Preexisting Cavity/Shells (Radius/pc) | Progenitor's Mass ($M_⊙$) |
|--------------------|------------------------|-------------------------------|-------------------------------------------------|--------------------|----------------------------------------|-----------------------------|
| G0.0+0.0 (Sgr A East) | S, Ar, Ca, Fe, Ni [1, 2, 3, 4] | $kT_1 \sim 1$, $kT_2 \sim 5$ [3, 2, 4] | (n$_eT_e$)$_0$ $\sim 1-4 \times 10^{11}$ [6, 7, 8] | Y, OH             | Y (5) [5]                             | $\gtrsim 12^f$               |
| G6.4–0.1 (W28)     | ...                    | $kT_1 \sim 0.4$, $kT_2 \sim 0.6$ [6, 9] | $\sim 9 \times 10^{11}$ [6, 9]                  | Y, OH             |                                       |                             |
| G21.8–0.6 (Kes 69) | ...                    | $\sim 0.8$ [10, 11, 12]        |                                                 | Y, OH             | Y ($\sim 13$) [13]                     | $\gtrsim 18^f$               |
| G31.9+0.0 (3C 391)  | ...                    | $\sim 0.5$–0.8 [15, 16, 8]     | $\gtrsim 10^{12}$ [15, 8]                       | Y, OH             | Y ($\sim 5$) [18]                      | $\gtrsim 12^f$               |
| G33.6+0.1 (Kes 79)  | ...                    | $\sim 0.5$–0.6 [17]           |                                                 | Y?                | Y ($\sim 8$) [23, 20]                  | $\gtrsim 14$ [20]            |
| G34.7–0.4 (W44)    | ...                    | $kT_1 \sim 0.3$–0.8, $kT_2 \sim 0.9$–0.4 [24, 8, 28, 25, 27] | $\gtrsim 3 \times 10^{10}$ [24, 8, 25] | Y, OH             | Y ($\sim 30$) [26]                     | 8–15 [27]                    |
| G38.7–1.4          | O, Ne [30]             | $\sim 0.6$ [30]               | $\sim 7 \times 10^{12}$ [30]                   | Y                 | Y ($\sim 6$) [36]                      | $\gtrsim 12^f$               |
| G41.1–0.3 (3C 397)  | O, S, Ca, Fe [31, 32, 33, 34, 35] | $kT_1 \sim 0.21$–0.25, $kT_2 \sim 1.5$–3.5 [31, 35, 34] | (n$_eT_e$)$_0$ $\sim 3 \times 10^{13}$, (n$_eT_e$)$_{11}$ $\sim 2 \times 10^{11}$ [31, 35, 34] | Y                 | Y ($\sim 7$) [23]                     | $\gtrsim 13$ [23]            |
| G43.3–0.2 (W49B)   | S, Si, S, Ca, Fe, Ni [8, 37, 38, 39, 40] | $kT_1 \sim 0.7$–1.05, $kT_2 \sim 1.75$–3.3 [39, 41, 42, 38, 40] | $kT_1 \sim 0.13$–0.3, $kT_2 \sim 1.12$–1.91 [43, 44, 45] | Y?                |                                       | $\sim 25$ [37, 39, 41, 40]   |
| G49.2–0.7 (W51C)   | Ne [46], Mg [46, 47], S [48] | 0.56–0.74 [46, 47, 49, 48]     | 0.8–11$\times 10^{11}$                          | Y, OH             |                                       | $\gtrsim 20$ [46]            |
| G53.6–2.2 (3C 400.2) | Fe? [50]              | $\sim 0.8$ [50]               | $\sim 10^{11}$ [50]                            | Y                 |                                       |                             |
| G65.3+5.7          | ...                    | $\sim 0.25$ [51]              |                                                 |                    |                                       |                             |
| G82.2+5.3 (W63)    | Mg, Si, Fe [52]       | $kT_1 \sim 0.2$, $kT_2 \sim 0.6$ [52, 53] |                                                 |                    |                                       |                             |
| G85.4+0.7          | O? [54]               | 1.0 [54]                      | $8 \times 10^{10}$ [54]                         |                    |                                       |                             |
| G85.9–0.6          | O, Fe [54]            | 1.6 [54]                      | $5 \times 10^{10}$ [54]                         |                    |                                       |                             |
| G89.0+4.7 (HB21)   | Si, S [55, 56]        | 0.62–0.68 [56, 55]            | $\gtrsim 4 \times 10^{11}$ [55, 56]            | Y                 |                                       |                             |
| G93.3+6.9 (DA 530) | Si [57]               | 0.3–0.6 [57, 58]              | $\gtrsim 4 \times 10^{11}$ [57]                |                   |                                       | $\sim 10$ [57]              |
| G93.7–0.2 (CTB 104A)? [53] |                        |                                  |                                                   |                   |                                       |                             |
| G116.9+0.2 (CTB 1) | Mg [55], O, Ne [56]  | $kT_1 \sim 0.2$–0.3, $kT_2 \sim 3$ [56], or $kT_2 \sim 0.8$ [55] | $\gtrsim 1 \times 10^{11}$ [56, 55]           | Y?                |                                       | $\gtrsim 13$ [56]            |
| G132.7+1.3 (HB 3)  | Mg [55], O, Mg, Ne, O [55] | $\sim 0.3$ [55, 53]          |                                                 | Y?                |                                       | $\sim 70$ [59]              |
| G156.2+5.7         | Si, S [60, 61, 62]    | $kT_1 \sim 0.45$, $kT_2 \sim 0.6$ [62, 60, 63, 61] | $\sim 1.5 \times 10^{11}$ [60, 61, 62]        |                    |                                       | $\sim 15$ [61]              |
| G160.9+2.6 (HB 9)  | ...                    | $\sim 0.8$ [64]              |                                                 |                    |                                       |                             |
| G166.0+4.3 (VRO 42.05.01) | S [65]           | $\sim 0.7$ [66, 67]          |                                                 |                    |                                       |                             |
Table 4  (Continued)

| SNR Name | Enriched Metal Species | Temperature $kT_e$ (keV)$^a$ | Ionization Parameter $n_i, T_e$ (cm$^{-3}$)$^b$ | MC Interaction$^c$ | Preexisting Cavity/Shells (Radius/pc) | Progenitor’s Mass ($M_\odot$) |
|----------|------------------------|-----------------------------|---------------------------------|-----------------|--------------------------------|-----------------------------|
| G189.1+5.0 (IC443) | Mg, S [68, 69, 65], Si [68, 69], Ne [65] | $kT_e \sim 0.3$–0.7, $kT_e \sim 1$–1.0 | $(n_i, T_e) \gtrsim 10^{12}$ [68, 69] | Y, OH | Y (~11) [75] | $\gtrsim 15$ [75] |
| R: | Si, S, Ar [72], Ca, Fe, Ni [73] | $\sim 0.65$ [72, 73, 74] | $\sim 9.8 \times 10^{11}$ [73] | | | |
| G272.2-3.2 | O [76], Ne [77], Si, S, Fe [76, 77], Ca, Ni [78] | $\sim 0.7$–1.5 [77, 76, 78, 80] | 2–10$^{10}$ [77, 76, 78, 80] | (SN Ia) [78, 77, 76] |
| G290.1–0.8 (MSH 11–61A) | S, S [81, 82], Mg [81] | $\sim 0.6$–0.9 [82, 81] | $>0.1 \times 10^{11}$ [82] | ? | 25–30 [82] |
| G304.6+0.1 (Kes 17) | Mg? [83, 84, 85] | $\sim 0.7$–1.0 [84, 86, 85] | $\geq 3.7 \times 10^{11}$ [84, 86, 85, 83] | Y | | |
| G311.5–0.3 | ... | $\sim 0.98$ [84] | | | | |
| G327.4+0.4 (Kes 27) | S, Ca [87], Si [8] | $\sim 0.5$–1.2 [87, 53, 88, 89] | $\geq 1 \times 10^{11}$ [87, 8] | Y | Y (~90) | |
| G337.8–0.1 (Kes 41) | S, Ar [91] | $\sim 1.9$ [92, 91] | $\geq 2 \times 10^{11}$ [92, 91] | Y, OH | Y (~13) [91] | $\geq 18^{d}$ |
| G444.7–0.1 | Al, Si, S, Ar, Ca, Fe [93, 94, 95, 96] | $\sim 0.8$–1.8 [96, 95, 94, 93] | 1–4$\times 10^{11}$ [96, 95, 94, 93] | ? | (SN Ia) [93] |
| G346.6–0.2 | Ca [97] | $\sim 1.2$ [97, 98, 84] | $\sim 2.9 \times 10^{11}$ [97, 84] | Y, OH | | |
| R: | ... | $\sim 0.3$ [99] | $\sim 4.8 \times 10^{11}$ [99] | | | |
| G348.5+0.1 (CTB 37A) | Si? [102] | 0.55–0.83 [84, 98, 100, 101, 102] | $>3 \times 10^{10}$ [84, 102] | Y, OH | ? [103] | |
| R: | ... | $\sim 0.5$ [102] | $>1.3 \times 10^{12}$ [102] | | | |
| G352.7–0.1 | Si, S [104, 105, 19], Ar? [19, 104] | 0.8–2.1 [104, 105, 4] | 1–2$\times 10^{10}$ [104, 105, 19] | | | |
| G355.6–0.0 | Si, S, Ar, Ca [106] | $\sim 0.6$ [106, 98] | | | | |
| G357.7–0.1 (Tornado) | ... | $\sim 0.6$ [107, 117] | | Y, OH | | |
| G359.1–0.5 | Si, S [108, 109] | $kT_e \sim 1.1$, $kT_e \sim 2.0$ [109, 111, 108, 112] | Y, OH | Y (~28) [110] | | |
| R: | Si, Mg, S [113] | $\sim 0.3$ [113] | | | | |
We take \( n(H_2) \sim 140 \text{ cm}^{-3} \) as a typical density of the molecular gas and adopt the velocity of the transmitted shock in the molecular cavity wall to be \( \sim 20 \text{ km s}^{-1} \), which corresponds to \( kT_r \sim 2.2 \text{ eV} \). If the observed temperature of the hot gas, \( T_r \), is adopted for \( T_r \), we can calculate the dependence of the wall-to-cavity density \( A \) on \( T_r \) in the uncertainty range 1.3–2.6 keV. Figure 11 shows that \( A \) is in the range 1500–3000. Thus, a cavity density of \( \sim 0.1-0.2 \text{ cm}^{-3} \) is implied. If we adopt the observed upper limit 500 cm\(^{-3}\) for \( n(H_2) \), almost the same cavity density is inferred. Such a cavity density seems to be of an order similar to the observed hot gas density. Here, shock reflection from the dense molecular wall is more efficient than from the \( \text{H} \text{\,i} \) cloud; actually, the centroids of both the diffuse X-ray emission (Section 3.1.1) and the EW maps of \( S \) and \( \text{Ar} \) (Section 3.1.2) in the southwestern half can be consistent with the reheating primarily by the shock reflected from the southwestern dense MC.

(ii) Progenitor’s Mass. The preexisting cavity of Kes 41 should be excavated by the progenitor star, and the progenitor’s mass can be estimated from the cavity size. A linear relation has been found between the progenitor’s mass, \( M_{\text{prog}} \), and the radius, \( R_b \), of the bubble blown by the main-sequence wind in a giant MC (Chen et al. 2013):

\[
R_b \approx (1.22 \pm 0.05)(M_{\text{prog}}/M_\odot) - (9.16 \pm 1.77) \text{ pc}. \tag{4}
\]

If we adopt \( R_b \approx r_c \), the mean radius of the cavity, a stellar mass of \( 18 \pm 2 M_\odot \) is obtained. However, the cavity is not purely confined by molecular gas but by a giant \( \text{H} \text{\,i} \) cloud in the southeastern side, and there seems to be a blow-out morphology in the northeast (see Figure 1). Therefore, this mass estimate should be regarded as a lower limit of the progenitor’s mass if the progenitor was not in a binary system, which implies that the progenitor’s spectral type is no later than B0.

(iii) Ejecta in Cavities. It can be seen in Table 4 that about half of the 36–37 known thermal composite SNRs are interacting with adjacent MCs; moreover, 11 or 12 of them are known or are thought to be evolving in cavities in dense gas, and most of them exhibit an overabundance of metal species. This fact can be explained in the context of the ejecta in preexisting cavities. An appreciable fraction of supernova ejecta, especially some heavy metal species like Si, are expected to expand at a relatively low velocity (e.g., \( \sim 10^3 \text{ km s}^{-1} \); e.g., Ono et al. 2013; J. Mao et al. in preparation); for the ejecta expanding in preexisting cavities, the slow part may not have been substantially mixed or diluted by the interstellar materials by the time the blast shock is reflected backward from the cavity wall. They are not only heated by the reverse shock in the early free expansion phase, but also can very possibly be reheated by the reflected shock. Therefore, the hot interior is thus observed to be metal enriched in X-rays.

4.2.4. Recombining Effect?

A number of thermal composite SNRs have been revealed to contain recombining plasma (see the rows labeled with \( R \) in Table 4). However, the overionization in the case of Kes 41 can be neither proven nor disproven by the spectral fitting because of the lack of obvious radiative recombination continuum (RRC) features and H-like lines of the same metal species in the X-ray spectra with insufficient counts. If there is recombining plasma in the remnant, the temperature obtained here using the vnei model may be an overestimate in view of the “apparent” hard continuum raised by the RRC. Deeper X-ray observations are needed to determine if the X-ray-emitting plasma of Kes 41 is indeed overionized.

5. SUMMARY

We have carried out an X-ray observational analysis by revisiting the archival XMM-Newton and Chandra data of the thermal composite SNR Kes 41. We have also conducted and analyzed an observation toward the remnant in the \( ^{12}\text{CO}, ^{13}\text{CO} \), and \( ^{18}\text{O} \) lines. The main results are summarized as follows.

1. Thermal X-ray emission from Kes 41 is detected above 2 keV, which is characterized by distinct \( S \) and \( \text{Ar} \) He-like lines and a brightening in the SNR interior, with a centroid in the emission toward the southwest portion of the SNR.
2. The X-ray-emitting gas can be described as an optically thin plasma (at a temperature of $1.3-2.6$ keV with an ionization parameter of $0.1-1.2 \times 10^{15}$ cm$^{-3}$ s$^{-1}$) with an NEI model. The metal species S and Ar are found to be overabundant, with abundances 1.2–2.7 and 1.3–3.8 solar, respectively. They may be enriched by the supernova ejecta.

3. The SNR is found to be associated with a giant MC at a systemic LSR velocity $-50$ km s$^{-1}$ and is confined in a cavity delineated by a northern molecular shell, a western concave MC also with a discernible shell, and a southeastern H I cloud. The cavity exists prior to the supernova explosion; it would not be physically realistic to conclude that it was generated by the SNR expansion.

5. Kes 41 seems to have left the adiabatic stage of evolution and entered the radiative phase with an X-ray dim rim just after the SNR shock encountered the dense interstellar medium cavity.

6. Thermal conduction and cloudlet evaporation seem to be feasible mechanisms to interpret the X-ray thermal composite morphology, and the scenario of gas reheating by shock reflected from the cavity wall is quantitatively consistent with the observations.

7. The birth of the SNR in a molecular environment implies a mass $\gtrsim 18 M_\odot$ for the progenitor if it was a single star.

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