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A COMPACT CENTRAL OBJECT IN THE SUPERNOVA REMNANT KESTEVEN 79

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ABSTRACT

A *Chandra* X-ray observation has detected an unresolved source at the center of the supernova remnant Kes 79. The best single-model fit to the source spectrum is a blackbody with an X-ray luminosity of $L_X(0.3\text{–}8.0\ \text{keV}) = 7 \times 10^{33}$ ergs s^{-1}. There is no evidence for a surrounding pulsar wind nebula. There are no cataloged counterparts at other wavelengths, but the absorption is high. The source properties are similar to the central source in Cas A even though the Kes 79 remnant is considerably older.

Subject headings: ISM: individual (Kesteven 79) — stars: neutron — supernova remnants — X-rays: stars

1. INTRODUCTION

Source 79 in the radio catalog of Kesteven (1968) lies directly in the Galactic plane, 33° northeast of the Galactic center. It is a moderately large supernova remnant (SNR) and is sometimes called G33.6+0.1. Radio observations (Velusamy, Becker, & Seward 1991) show an outer shell, 11′ in diameter, which is approximately circular over the southwest half of the remnant but with large indentations in the northern and eastern boundaries. The brightest part of the radio remnant is an interior region with a shell-like form. The southern part of this "inner shell" has the highest surface brightness in the remnant. The distance has been determined by neutral H absorption measurements to be 10 ± 2 kpc by Frail & Clifton (1989).

The first X-ray detection of Kes 79 was made using the *Einstein Observatory* (Seaquist & Gilmore 1982; Velusamy et al. 1991) and showed amorphous structure with a bright center. This inspired a *ROSAT* observation (Seward & Velusamy 1995) to search for Crab-like structure in the interior. The results, however, showed no indication of a central pulsar or pulsar wind nebula (PWN). The southern arc of the inner ring was found to be bright in X-rays and faint emission was observed from the outer shell, particularly close to the eastern indentation. Assuming a thermal spectrum, analysis of the *ROSAT* data indicated an age of $6\text{–}12 \times 10^3$ yr, an X-ray luminosity of $\sim 10^{36}$ ergs s^{-1}, and an energy release of 5×10^{50} ergs in the supernova (SN) explosion. Subsequent observations with *ASCA* (Sun & Wang 2000) showed that the spectrum was indeed thermal, with strong lines from Mg, Si, and S. The global spectrum was fitted well by a single nonequilibrium ionization model. Seward & Velusamy (1995) speculated that this remnant might be younger and closer than believed and the result of a Type Ia supernova. As evidence they cited the circular shell, the fact that the absorption was the same as that in the path to W44 (1° distant in the plane of the sky and only 3 kpc distant from the Sun), and the lack of an observable pulsar. The *Chandra* observation described here shows that this is not the case.

In this paper we report the detection of a pointlike source at the center of the remnant, which is likely to be a neutron star created in the SN explosion. We discuss the spectrum, the apparent absence of any surrounding synchrotron emission, and briefly compare the source with similar objects. Discussion of the SNR shell is deferred to a subsequent publication.

2. *CHANDRA* OBSERVATION

Chandra observed Kes 79 on 2001 July 31. The observation was undertaken to better determine the shell-like structure and to measure spectra from different regions. An exposure of 30 ks was obtained, and there were no "flares" from particle-induced background. The remnant was centered in the ACIS-I array and consequently spread over the four, 8 arcmin^2 chips comprising the detector. The telescope was dithered and images are exposure corrected so the gaps between chips do not appear in the images. Because of the CTI degradation of the detector (*Chandra* X-ray Center 2001), the spectral resolution is better along the northeast and southwest edges of the remnant than at the center. We took this into account using appropriate tasks from the CIAO software, version 2.1, which was used for data analysis.

Figure 1 shows the *Chandra* image. The data have been adaptively smoothed (with the *csmooth* algorithm) and show the bright inner shell of the remnant. Emission from the outer shell is weak and is hard to see (except in the eastern indentation) in this figure. Five unresolved sources are easily seen, including three within the shell. The brightest, by an order of magnitude, is the source at the middle, which is the subject of this paper. The sources are labeled 1–5 in Figure 1, and Table 1 lists their properties. The 2002 May *Chandra* aspect solution was used. For sources within 2′ of the telescope axis the 90% certainty radius in the *Chandra* position is 0″.6. Positions were compared with the Guide Star Catalog 2.2 (STScI 2001).[1] Sources 3 (7′ off-axis) and 4 (3′ off-axis) are probably stars; the X-ray spectra are soft and the X-ray source positions are 0″.9 and 0″.2 from optical counterparts, which shows the accuracy of the aspect determination for these parts of the field.

[1] Available at http://www-gsss.stsci.edu/gsc/gsc2/GSC2home.htm.

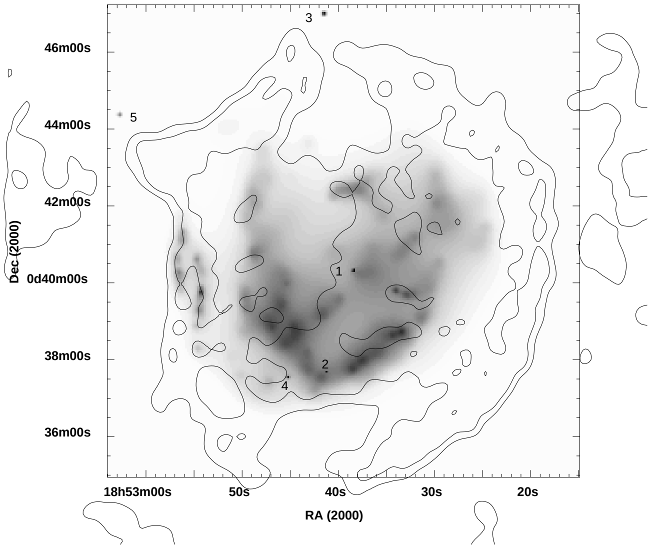

FIG. 1.—*Chandra* image of Kes 79 in the energy range 0.8–8 keV. Data have been adaptively smoothed. The gray-scale X-ray emission comes largely from the bright inner ring of the remnant, a region with dimensions $5' \times 6'$. Unresolved sources are labeled 1–5. Source 1 is centered in the remnant and is, by a factor of 10, the brightest pointlike source in this field. The radio remnant is indicated by three brightness contours at relative surface brightness levels of 1, 2.24, and 5.

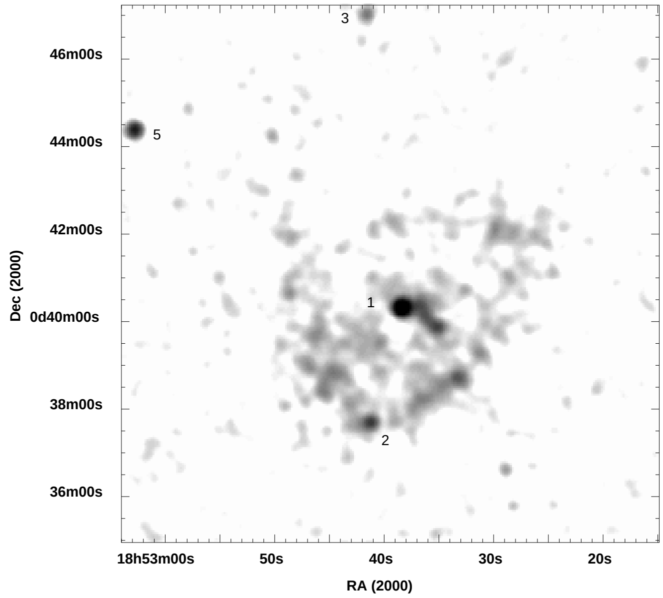

FIG. 2.—*Chandra* image of Kes 79 in the energy range 3–5 keV. Data have been smoothed with a Gaussian of FWHM = $12''$. Four of the unresolved sources are still visible.

Hardness ratios are given for eventual comparison with two surveys of serendipitous *Chandra* sources, extragalactic (P. Green et al. 2002, in preparation) and Galactic (J. Grindlay et al. 2002, in preparation). The hardness ratio is $\mathrm{HR} = H - S/H + S$, where S is the number of counts from 0.3 to 2.5 keV and H is the number of counts from 2.5 to 8 keV. There is no counterpart brighter than R magnitude 19 for the central source (source 1) or for sources 2 and 5. Because the spectra of sources 2 and 5 are hard, they are probably background active galactic nuclei (AGNs).

The radial profile of the central source is consistent with the expected *Chandra* point-spread function. Any extent is less than $1\farcs0$. Thinking this is likely to be an isolated neutron star, we searched for time variability and pulsations. The light curve is constant within statistics $-2\,\sigma$ fluctuations $\leq 20\%$ on an hourly basis. The search for periodicity was limited to periods longer than 6.4 s because the ACIS instrument, in normal mode, integrates for 3.2 s. A fast Fourier transform analysis showed no coherent power significantly above the noise, giving an upper limit of $\approx 30\%$ for pulsed power in this range.

Since many young pulsars are embedded in diffuse synchrotron radiation from a surrounding PWN, we searched for such a PWN at high energies. In the range of 5–8 keV, the central source is still visible but diffuse emission is absent, both from the bright inner shell and from the vicinity of the central source. In the range of 3–5 keV, shown in Figure 2, the inner ring is discernible and there is a small feature adjacent to the central source and extending southwest. The spectrum of emission from this southwesterly feature shows Mg and Si lines, indicating that much of the emission is thermal. Since there are only 300 counts from this feature, model parameters cannot be accurately determined from spectral fits. By subtracting the thermal spectrum observed elsewhere in the remnant, we estimate that up to about $\frac{1}{3}$ of the emission from this $\sim 0\farcm6 \times 0\farcm6$ feature could be nonthermal. Assuming a power-law spectrum with photon index = 2 (like the Crab Nebula), the upper limit to the luminosity of a PWN at this location is calculated to be 1.5×10^{33} ergs s^{-1}. This upper limit is about $\frac{1}{4}$ the luminosity of the pointlike source. We note that a PWN is usually more luminous than the pulsar itself (20 : 1 for the Crab pulsar: Toor & Seward 1977; 1.3 : 1 for the Vela pulsar: Helfand, Gotthelf, & Halpern 2001).

TABLE 1
PROPERTIES OF SERENDIPITOUS SOURCES

Source	R.A.	Decl.	ACIS (Counts)	Hardness Ratio	R Magnitude	Optical Counterpart
1, central source	18 52 38.56	+00 40 19.84	723	-0.49 ± 0.04	>18.5	None
2	18 52 41.35	+00 37 42.5	60	0.37 ± 0.14	>18.5	None
3, star?	18 52 41.66	+00 47 01.4	61	-0.39 ± 0.19	16.0	N020120163554
4, star?	18 52 45.38	+00 37 34.1	47	-0.83 ± 0.19	16.3	N020120158710
5	18 53 02.87	+00 44 22.9	68	0.70 ± 0.14	>18.5	None

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

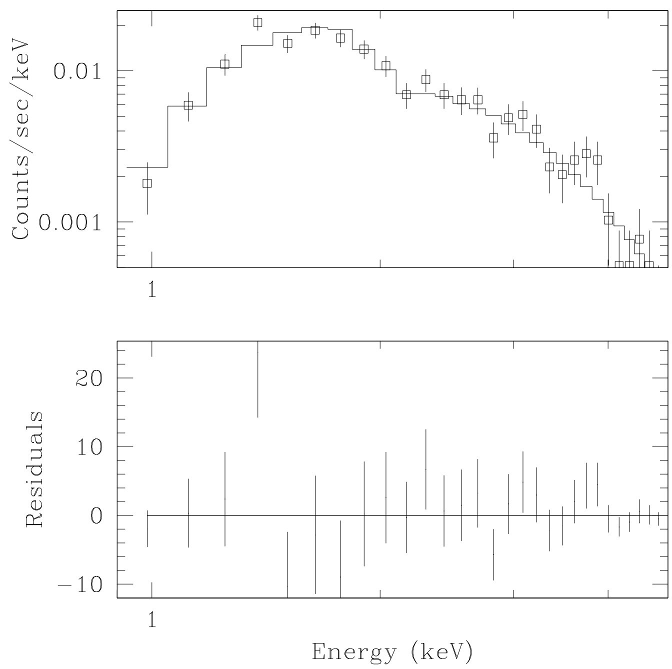

FIG. 3.—X-ray spectrum of the central source. A small background has been subtracted. The solid histogram is the result expected from a blackbody spectrum with temperature $kT = 0.48$ keV.

The spectrum of the central source is shown in Figure 3, and Table 2 lists the results of spectral fits. We extracted 723 counts from a circle of radius 4″, grouped over nine ACIS energy channels, and restricted to the energy band 0.8–4.7 keV. The SHERPA software was used for spectral fitting. A power law gives a fit that, although it produces an acceptable $\chi^2 = 1.2$, is obviously too weak in the range of 2–4 keV and too strong in the range of 4–6 keV. Furthermore, the photon index, $\gamma = 4.2$, is higher than observed for most cosmic sources, and the value for absorption is high. The *ASCA*-measured $N_{\rm H}$ was $(1.75 \pm .07) \times 10^{22}$ atoms cm^{-2}, and spectral fits to the bright thermal emission in our *Chandra* data yield $N_{\rm H} \approx 1.8 \times 10^{22}$ atoms cm^{-2}. The central source spectrum is soft, softer than expected from an AGN ($\alpha \approx 1.7$) or from a PWN ($\alpha \approx 1.5$–2.5; e.g., Slane et al 2000).

A single blackbody spectrum gives a good fit, shown in Figure 3, but with $N_{\rm H}$ a bit lower than expected. It is also not difficult to achieve good fits with two-component spectra. The soft component can be either blackbody or power law and is not well constrained. A power law does not work well as the hard component, and if used as the soft component, only makes a small contribution to the emission. If we require that $N_{\rm H} = 1.8 \times 10^{22}$ atoms cm^{-2}, the absorption observed by *Chandra* for the diffuse part of the remnant, then a two-component spectrum produces a better fit than a single blackbody spectrum, but the relative contribution of the soft component is small. Values of parameters are given in Table 2.

TABLE 2
SPECTRAL FITS TO THE CENTRAL SOURCE

Model	Spectral Index	$N_{\rm H}$ ($\times 10^{22}$ atoms cm^{-2})	Reduced χ^2
Power law	$\alpha = 4.2 \pm 0.25$	2.7 ± 0.2	1.19 (25 dof)
Blackbody........	$kT = 0.48 \pm 0.025$	1.45 ± 0.17	0.92 (25 dof)
2 Blackbody.....	$kT = 0.18 \pm 0.06$	1.8 (fixed)	0.94 (24 dof)
	$kT = 0.47 \pm 0.02$		

The *Chandra* spectra of various parts of the diffuse remnant are all thermal. The Mg, Si, and S lines detected by *ASCA* are prominent, and there is not much variation from region to region. These data and their interpretation will be the subject of a second paper (M. Sun et al. 2002, in preparation).

The radio pulsar B1849−00, proposed to be a high-velocity object associated with Kes 79 (Han 1997), is located just outside the remnant 3′ south of the rim. Frail & Clifton (1989), however, obtained 21 cm absorption data that showed PSR 1849−00 to be considerably farther away than Kes 79. The present discovery of a different object at the center of Kes 79, verifies their conclusion that PSR 1849−00 is not associated with Kes 79.

As a matter of interest, PSR 1849−00 was in the field of view of the ACIS-I detector during our observation and was not detected. An upper limit on the flux is 1×10^{-14} ergs cm^{-2} s^{-1}. If the pulsar were 15 kpc distant, and the transmission of the ISM is $t_{\rm ISM}$, then $L_{\rm X}$ would be less than $2.5 \times 10^{32}\ t_{\rm ISM}{}^{-1}$ ergs s^{-1}. Since $\dot{E}$ is $\sim 4 \times 10^{32}$ ergs s^{-1} for this pulsar, $L_{\rm X}$ is expected to be well below this upper limit.

3. DISCUSSION

The blackbody spectrum strongly suggests that the central point source in Kes 79 is not a foreground star or background AGN, as probably are the other unresolved sources in Figure 1. The central location and similarity to other recently discovered objects (see list below) indicate that this is probably a neutron star—the remnant of the core of the star that exploded to produce Kes 79. It was not detected in previous X-ray observations because the counting rate of the central source is only $\sim 10^{-2}$ that of the entire remnant in the 1–10 keV energy band. The luminosity at 10 kpc distance, in the band 0.3–8 keV, is 7×10^{33} ergs s^{-1}, about 4 times the luminosity of the central object in Cas A (Chakrabarty et al. 2001). The blackbody spectrum and the lack of a PWN favor thermal emission originating from a small region, perhaps on the surface of the star.

Central objects in SNRs were well understood when the only two known were the Crab and Vela pulsars. For each of these objects, the pulsar characteristic age, $P/2\dot{P}$, and the age of the surrounding remnant are about the same (950 yr for the Crab and $\sim 10^4$ yr for the Vela remnant), most of the energy radiated from the vicinity of the pulsar is nonthermal, and spin-down energy is adequate to power all emission from the pulsar and PWN. Now that more objects have been discovered, the situation is complex.

Some putative neutron stars within remnants show no sign of nonthermal emission. There is no PWN, the X-ray spectrum is more blackbody than power law, and no radio or gamma-ray pulsations have been observed. These have been called "radio-quiet" pulsars and/or compact central objects (CCOs). Such objects are found in Cas A (Murray et al. 2002; Chakrabarty et al. 2001), Pup A (Zavlin, Truemper, & Pavlov 1999), PKS 1209−51/52 (Zavlin et al. 2000; Pavlov et al. 2002b), and G347.3−0.5 (Slane et al. 1999). Properties of these objects are reviewed by Pavlov et al. (2002a). The Kes 79 source appears to be of this type. All have luminosities, $L_{\rm X}$, between 10^{33} and 10^{34} ergs s^{-1}. There is only one convincing case for pulsed emission; the central source in PKS 1209−51/52 has a period of 0.424 s, a sinusoidal pulse shape, and a pulsed fraction of ≈10% (Zavlin et al. 2000; Pavlov et al. 2002b).

We note that Kes 79 was searched for radio pulsations by Gorham et al. (1996) at 430 and 1420 MHz. No pulsations were observed above a level of 0.7 mJy at 1420 MHz. (This is rather weak support for the "radio-quiet" classification since a large fraction of pulsars discovered in modern surveys, e.g., Manchester et al. 2001, have lower fluxes than this limit.)

The X-ray spectra of all these objects are close to blackbody spectra. The classical blackbody model, however, predicts a temperature that is too high and a surface area that is too small when compared with generally accepted models of neutron stars. For example, Chakrabarty et al. (2001) have fitted the spectrum of the Cas A object and find a temperature of 0.49 keV and a star radius of 0.52 km; compared with the 8–16 km radius expected. The radiation source could be a single hot spot on the star surface, but this is hard to reconcile with the observed lack of pulsations (≤25% pulsed) determined by Murray et al. (2002).

A light-element atmosphere will reduce the derived temperature and increase the derived radius. D. A. Lloyd, L. Hernquist, & J. S. Heyl (2002, in preparation) have calculated emergent spectra and find that the actual temperature, $T_{\rm eff}$, is always less than the temperature, $T_{\rm bb}$, derived by fitting a blackbody spectrum to the observed data. Chakrabarty et al. (2000) find that a H atmosphere model applied to the Cas A source yields a temperature of 0.26 keV and a radius of 2.2 km. They conclude that existing surface-radiation models do not explain the Cas A object and that accretion models also fail to account for the lack of an optical counterpart. The more luminous Kes 79 object, if a classical blackbody, would require a radius of only 1.0 km to achieve the observed luminosity at the measured temperature of $T_{\rm bb} = 0.48$ keV. Application of the light atmosphere model of D. A. Lloyd et al. (2002, in preparation) predicts that $T_{\rm eff}$ is a factor of 1.8 lower than $T_{\rm bb}$, or 0.27 keV. This lower temperature would increase the required radius to 3.2 km, still short of the 8–16 km expected. Since the theoretical models used so far have been simple, perhaps adjustments might be made in the model atmosphere to achieve a fit with a standard radius. Obviously better models are needed.

Among the five central compact objects (CCOs) mentioned, the most luminous is in the largest remnant, G347.3−0.5. The source in Kes 79 is the second most luminous. Kes 79 is about the same size as PKS 1209−51/52 but in a denser environment, so it is probably older. Thus, the central source in Kes 79 may also be the second oldest specimen of the "radio-quiet" isolated pulsar group. This agrees exactly with the conclusion of Pavlov et al. (2002a) that the older CCOs are more luminous. If these central objects are similar, they are certainly not cooling rapidly and the apparent increase in emitting area with age is a mystery.

Certainly, the source in Kes 79 is worthy of more study. It happens to be in a remnant that has a well-defined outer shell and, interpreting this as a shock, one can derive information about the SN explosion that produced it. Future work should include sensitive searches for radio and/or X-ray pulsations and, although none is expected, a sensitive search for an optical counterpart.

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