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THE COMPACT CENTRAL OBJECT IN CASSIOPEIA A: A NEUTRON STAR WITH HOT POLAR CAPS OR A BLACK HOLE?

G. G. Pavlov,[1] V. E. Zavlin,[2] B. Aschenbach,[2] J. Trümper,[2] and D. Sanwal[1]
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ABSTRACT

The central pointlike X-ray source of the Cassiopeia A supernova remnant was discovered in the *Chandra* first light observation and found later in the archival *ROSAT* and *Einstein* images. The analysis of these data does not show statistically significant variability of the source. Because of the small number of photons detected, different spectral models can fit the observed spectrum. The power-law fit yields the photon index $\gamma = 2.6$–4.1, and luminosity $L(0.1$–$5.0\ \mathrm{keV}) = (2$–$60) \times 10^{34}$ ergs s^{-1} for $d = 3.4$ kpc. The power-law index is higher, and the luminosity lower, than those observed from very young pulsars. One can fit the spectrum equally well with a blackbody model with $T = 6$–8 MK, $R = 0.2$–0.5 km, and $L_{\mathrm{bol}} = (1.4$–$1.9) \times 10^{33}$ ergs s^{-1}. The inferred radii are too small, and the temperatures too high, for the radiation to be interpreted as emitted from the whole surface of a uniformly heated neutron star. Fits with the neutron star atmosphere models increase the radius and reduce the temperature, but these parameters are still substantially different from those expected for a young neutron star. One cannot exclude, however, the possibility that the observed emission originates from hot spots on a cooler neutron star surface. An upper limit on the (gravitationally redshifted) surface temperature is $T_s^\infty < 1.9$–2.3 MK, depending on the chemical composition of the surface and the star's radius. Among several possible interpretations, we favor a model of a strongly magnetized neutron star with magnetically confined hydrogen or helium polar caps ($T_{\mathrm{pc}}^\infty \approx 2.8$ MK, $R_{\mathrm{pc}} \approx 1$ km) on a cooler iron surface ($T_s^\infty \approx 1.7$ MK). Such temperatures are consistent with the standard models of neutron star cooling. Alternatively, the observed radiation may be interpreted as emitted by a compact object (more likely, a black hole) accreting from a residual disk or from a late-type dwarf in a close binary.

Subject headings: stars: neutron — supernovae: individual (Cassiopeia A) — X-rays: stars

1. INTRODUCTION

Cassiopeia A is the brightest shell-type galactic supernova remnant (SNR) in X-rays and radio and the youngest SNR observed in our Galaxy. The radius of the approximately spherical shell is $\approx 2'$, which corresponds to ≈ 2 pc for the distance $d = 3.4^{+0.3}_{-0.1}$ kpc (Reed et al. 1995). The supernova that gave rise to Cas A was probably first observed in 1680 (Ashworth 1980). It is thought to be a Type II supernova caused by explosion of a very massive Wolf-Rayet star (Fesen, Becker, & Blair 1987). Optical observations of Cas A show numerous oxygen-rich fast-moving knots (FMKs), with velocities of about 5000 km s^{-1}, and slow-moving quasi-stationary flocculi which emit Hα and strong lines of nitrogen. X-ray observations of Cas A show numerous clumps of hot matter emitting Si, S, Fe, Ar, Ne, Mg, and Ca lines (Holt et al. 1994; Hughes et al. 2000, and references therein). Because this SNR lies at the far side of the Perseus arm, with its patchy distribution of the interstellar gas, the interstellar absorption varies considerably across the Cas A image (e.g., Keohane, Rudnick, & Anderson 1996). Numerous radio, optical, and X-ray measurements of the hydrogen column density (e.g., Schwarz, Goss, & Kalberla 1997; Hufford & Fesen 1996; Jansen et al. 1988; Favata et al. 1997; Hughes et al. 2000) show strong scatter within a range $0.5 \lesssim n_{\mathrm{H,22}} \lesssim 2.3$, where $n_{\mathrm{H,22}} \equiv n_{\mathrm{H}}/(10^{22}\ \mathrm{cm}^{-2})$. Based on recent results, we consider $0.8 \lesssim n_{\mathrm{H,22}} \lesssim 1.6$ as plausible values for the central region of Cas A.

In spite of considerable efforts to detect a compact remnant of the supernova explosion, only upper limits on its flux had been established at different wavelengths until a pointlike X-ray source was discovered close to the Cas A center (Tananbaum 1999) in the first light observation with the *Chandra X-Ray Observatory* (see Weisskopf, O'Dell, & Van Speybroeck 1996 for a description). After this discovery, the same source was found in the *ROSAT* High-Resolution Imager (HRI) image of 1995–1996 (Aschenbach 1999) and *Einstein* HRI images of 1979 and 1981 (Pavlov & Zavlin 1999).

In this Letter we present the first analysis on the central source spectrum observed with *Chandra* (§ 2) together with the analysis of the *ROSAT*, *Einstein*, and *ASCA* observations (§ 3). Some interpretations of these observations are briefly discussed in § 4.

2. *CHANDRA* ACIS OBSERVATION AND THE POINT-SOURCE SPECTRUM

The SNR Cas A was observed several times during the *Chandra* orbital activation and calibration phase. For our analysis, we chose four observations of 1999 August 20–23 with the S array of the Advanced CCD Imaging Spectrometer (ACIS; Garmire 1997). In these observations, Cas A was imaged on the back side–illuminated chip S3. The spectral response of this chip is presently known better than those of the front side–illuminated chips used in a few other ACIS observations of Cas A. We used the processed data products available from the public *Chandra* Data Archive. The observations were performed in the timed exposure mode, with a frame integration time of 3.24 s. The durations of the observations were 5.03, 2.04, 1.76, and 1.77 ks. Because of telemetry saturation, the effective exposures were 2.81, 1.22, 1.06, and 1.05 ks, respectively. We selected events with the grades G02346 and discarded events with pulse height amplitudes exceeding 4095 ADU ($\approx 0.7\%$ of the total number) as generated by cosmic rays.

[1] Pennsylvania State University, 525 Davey Lab, University Park, PA 16802; pavlov@astro.psu.edu.
[2] Max-Planck-Institut für Extraterrestrische Physik, D-85740 Garching, Germany; zavlin@xray.mpe.mpg.de.

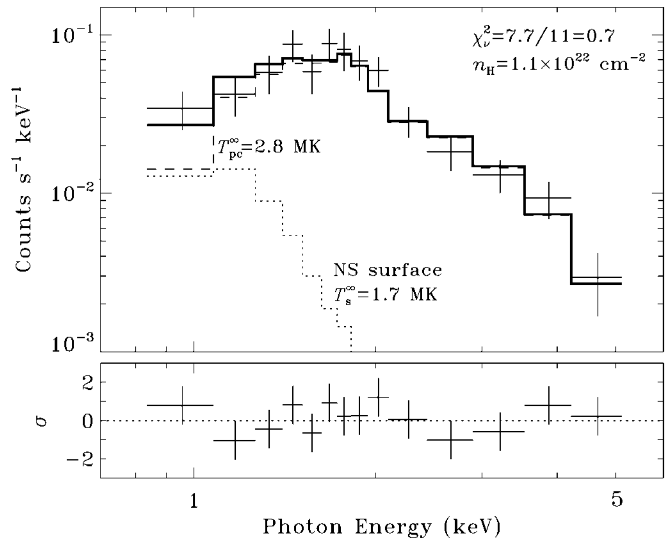

FIG. 1.—*Chandra* ACIS-S3 count rate spectrum from the compact central object of Cas A. The fit for hydrogen polar caps (T^∞_{pc} = 2.8 MK, R_{pc} = 1 km) on a cooler iron NS surface (T^∞_s = 1.7 MK, R = 10 km) is shown.

The images of the pointlike source look slightly elongated, but this elongation is likely caused by errors in the aspect solution, and the overall shapes of the images are consistent with the assumption that this is a point source. Its positions in the four observations are consistent with that reported by Tananbaum et al. (1999): $\alpha_{2000} = 23^h23^m27^s.94$, $\delta_{2000} = +58°48'42''.4$. For each of the images, we extracted the source + background counts from a 3″ radius circle around the point-source center, and the background from an elliptical region around the circle, with an area of about 10 times that of the circle. After subtracting the background, we obtained the source count rates 112 ± 8, 121 ± 13, 112 ± 14, and 127 ± 15 ks^{-1} (counts per kilosecond). The count rate values and the light curves are consistent with the assumption that the source flux remained constant during the four days, with the count rate of 116 ± 6 ks^{-1}. For the analysis of the point-source spectrum, we chose the longest of the ACIS-S3 observations. We grouped the pulse-height spectrum for 306 source counts into 14 bins in the 0.8–5.0 keV range (Fig. 1). The spectral fits were performed with the XSPEC package.

If the source is an active pulsar, we can expect that its X-ray radiation is emitted by relativistic particles and has a power-law spectrum. The power-law fit (Fig. 2, *top*) yields a photon index $\gamma = 3.2^{+0.9}_{-0.6}$ (all uncertainties are given at a 1 σ confidence level) that is considerably larger than γ = 1.4–2.1 observed for X-ray radiation from very young pulsars (Becker & Trümper 1997). The hydrogen column density $n_{H,22} = 1.7^{+0.7}_{-0.5}$ inferred from the power-law fit somewhat exceeds most plausible estimates obtained from independent measurements (see § 1). The (unabsorbed) X-ray luminosity in the 0.1–5.0 keV range, $L_X = 5.8^{+58.3}_{-4.3} \times 10^{34} d^2_{3.4}$ ergs s^{-1}, where $d_{3.4} = d/(3.4$ kpc), is lower than those observed from very young pulsars (e.g., 1.5×10^{36} and 2.3×10^{36} ergs s^{-1} for the Crab pulsar and PSR B0540−69, in the same energy range).

If the source is a neutron star (NS), but not an active pulsar, thermal radiation from the NS surface can be observed. The blackbody fit (Fig. 2, *middle*) yields a temperature $T^\infty_{bb} = 7.1^{+1.1}_{-1.0}$ MK and a sphere radius $R^\infty_{bb} = 0.29^{+0.16}_{-0.09} d_{3.4}$ km, which correspond to a bolometric luminosity $L^\infty_{bb,bol} = 1.6^{+0.3}_{-0.2} \times 10^{33} d^2_{3.4}$ ergs s^{-1}. [We use the superscript ∞ to denote the quantities as measured by a distant observer, distinguishing them from the local values at the NS surface: $T^\infty = g_r T$, $L^\infty = g_r^2 L$, $R^\infty = g_r^{-1} R$, where $g_r = (1 - 2GM/Rc^2)^{1/2} = (1 - 0.41 M_{1.4} R_6^{-1})^{1/2}$ is the gravitational redshift factor and $M = 1.4 M_{1.4}\ M_\odot$ and $R = 10^6 R_6$ cm are the NS mass and radius]. The temperature is too high and the radius is too small to interpret the detected X-rays as emitted from the whole surface

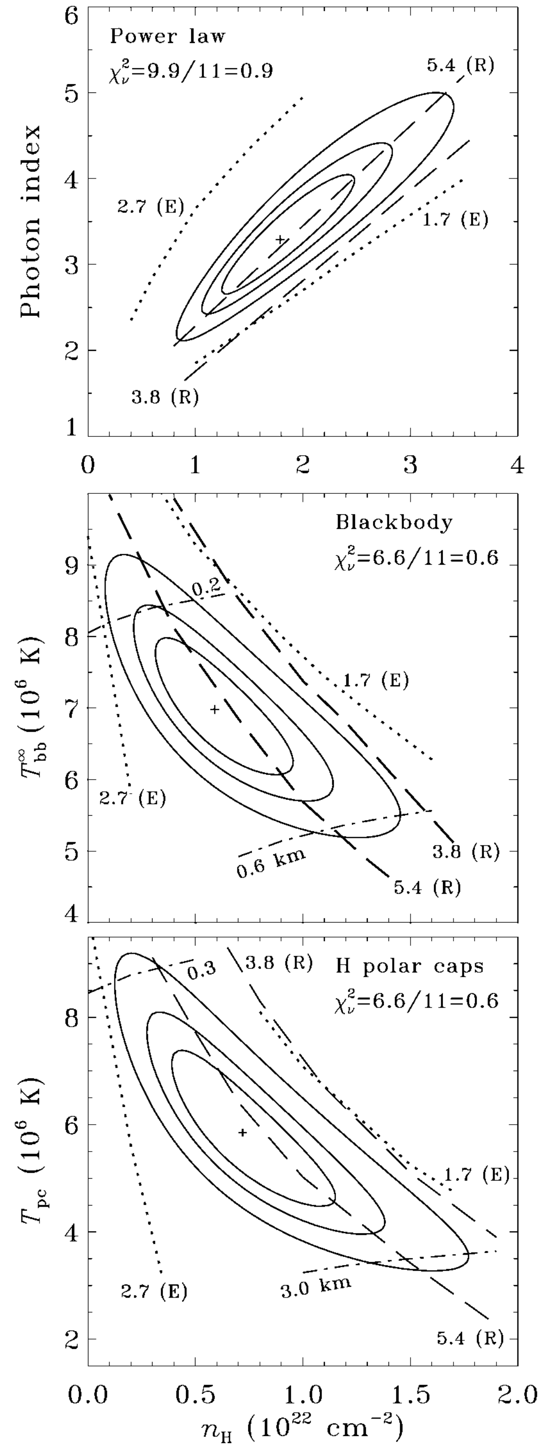

FIG. 2.—The 67%, 90%, and 99% confidence regions obtained from the fits to the spectrum of Figure 1, together with lines of constant *ROSAT* HRI (*long dashed lines*) and *Einstein* HRI (*dotted lines*) count rates, in counts per kilosecond. The dash-dotted curves in the two lower panels are the lines of constant radii of emitting areas (in kilometers).

of a cooling NS with a uniform temperature distribution. The inferred hydrogen column density $n_{\mathrm{H,\,22}} = 0.6^{+0.5}_{-0.3}$ is on a lower side of the plausible n_{H} range.

Since fitting observed X-ray spectra with light-element NS atmosphere models yields lower effective temperatures and larger emitting areas (e.g., Zavlin, Pavlov, & Trümper 1998), we fit the spectrum with a number of hydrogen and helium NS atmosphere models (Pavlov et al. 1995; Zavlin, Pavlov, & Shibanov 1996) for several values of NS magnetic field. These fits show that the assumption that the observed radiation is emitted from the whole surface of a 10 km radius NS with a uniform temperature still leads to unrealistically large distances, ∼20–50 kpc. Thus, both the blackbody fit and H/He atmosphere fits hint that, if the object is a NS, the observed radiation emerges from hot spots on its surface. An example of such a fit, for polar caps covered with a hydrogen atmosphere with $B = 5 \times 10^{12}$ G, is shown in the bottom panel of Figure 2. The model spectra used in this fit were obtained assuming the NS is an orthogonal rotator (with the angles α [between the magnetic and rotation axes] and ζ [between the rotation axis and line of sight] equal to 90°). The inferred effective temperature of the caps is $T_{\mathrm{pc}} = 5.9^{+1.4}_{-1.6}$ MK (which corresponds to $T^{\infty}_{\mathrm{pc}} = 4.5^{+1.1}_{-1.2}$ MK), the polar cap radius $R_{\mathrm{pc}} = 0.8^{+1.1}_{-0.3} d_{3.4}$ km, and $n_{\mathrm{H,\,22}} = 0.7^{+0.4}_{-0.3}$. The bolometric luminosity of two polar caps is $L_{\mathrm{pc,\,bol}} = 2.6^{+1.7}_{-0.5} \times 10^{33} d^2_{3.4}$ ergs s^{-1}. The temperature T_{pc} can be lowered, and the polar cap radius increased, if we see the spot face-on during the most part of the period; extreme values, $T_{\mathrm{pc}} = 3.8^{+1.1}_{-0.8}$ MK and $R_{\mathrm{pc}} = 0.9^{+1.2}_{-0.3} d_{3.4}$ km, correspond to $\alpha = \zeta = 0$.

The fits with the one-component thermal models implicitly assume that the temperature of the rest of the NS surface is so low that its radiation is not seen by ACIS. On the other hand, according to the NS cooling models (e.g., Tsuruta 1998), one should expect that, at the age of 320 yr, the (redshifted) surface temperature can be as high as 2 MK for the so-called standard cooling (and much lower, down to 0.3 MK, for accelerated cooling). To constrain the temperature outside the polar caps, we repeated the polar cap fits with the second thermal component added, at a fixed NS radius and different (fixed) values of surface temperature T_s. With this approach we estimated upper limits on the lower temperature, $T^{\infty}_s < 1.9$–2.3 MK (at a 99% confidence level), depending on the low-temperature model chosen. These fits show that the model parameters are strongly correlated—the increase of T_s shifts the best-fit T_{pc} downward and n_{H} upward. For example, using an iron atmosphere model for the low-temperature component and assuming a hydrogen polar cap, we obtain an acceptable fit (see Fig. 1) for $T^{\infty}_s = 1.7$ MK, $R = 10$ km, $T^{\infty}_{\mathrm{pc}} = 2.8$ MK, $R_{\mathrm{pc}} = 1.0 d_{3.4}$ km, $n_{\mathrm{H,22}} = 1.1$. Note that this T_s is consistent with the predictions of the standard cooling models, and n_{H} is close to most plausible values adopted for the central region of the SNR.

3. ANALYSIS OF THE *ROSAT*, *EINSTEIN*, AND *ASCA* IMAGES

We reanalyzed the archival data on Cas A obtained during a long *ROSAT* HRI observation between 1995 December 23 and 1996 February 1 (dead-time–corrected exposure 175.6 ks). The image shows a pointlike central source at the position $\alpha_{2000} = 23^{\mathrm{h}}23^{\mathrm{m}}27\overset{\mathrm{s}}{.}57$, $\delta_{2000} = 58°48'44\overset{''}{.}0$ (coordinates of the center of the brightest $0\overset{''}{.}5 \times 0\overset{''}{.}5$ pixel). Its separation from the *Chandra* point-source position, $3\overset{''}{.}3$, is smaller than the *ROSAT* absolute pointing uncertainty (about 6″; Briel et al. 1997[3]). Measuring the source count rate is complicated by the spatially nonuniform background. Another complication is that the 40 day–long exposure actually consists of many single exposures of very different durations. Because of the absolute pointing errors, combining many single images in one leads to additional broadening of the point-source function (PSF). To account for these complications, we used several apertures (with radii from 3″ to 7″) for source + background extraction, measured background in several regions with visually the same intensity as around the source, discarded short single exposures, and used various combinations of long single exposures for count rate calculations. This analysis yields a source count rate of 4.6 ± 0.8 ks^{-1} (corrected for the finite apertures).

We also reinvestigated the archival data on Cas A obtained with the *Einstein* HRI in observations of 1979 February 8 (42.5 ks exposure) and 1981 January 22–23 (25.6 ks exposure). In each of the data sets there is a pointlike source at the positions $\alpha_{2000} = 23^{\mathrm{h}}23^{\mathrm{m}}27\overset{\mathrm{s}}{.}83$, $\delta_{2000} = 58°48'43\overset{''}{.}9$, and $\alpha_{2000} = 23^{\mathrm{h}}23^{\mathrm{m}}27\overset{\mathrm{s}}{.}89$, $\delta_{2000} = 58°48'43\overset{''}{.}7$, respectively. The separations from the *Chandra* position ($1\overset{''}{.}7$ and $1\overset{''}{.}4$) and from the *ROSAT* position ($2\overset{''}{.}0$ and $2\overset{''}{.}5$) are smaller than the nominal absolute position uncertainty (∼4″ for *Einstein*). We extracted the source + background counts from 5″ radius circles and measured the background from annuli of 10″ outer radii surrounding the circles. The source count rates, calculated with account for the HRI PSF (Harris et al. 1984), are 2.2 ± 0.5 (1979 February), 2.7 ± 0.8 ks^{-1} (1981 January), and 2.4 ± 0.6 ks^{-1} (for the combined data). The count rate is consistent with the upper limit of 7.5 ks^{-1}, derived by Murray et al. (1979) from the longer of the two observations.

To check whether the source radiation varied during the two decades, we plotted the lines of constant *ROSAT* and *Einstein* HRI count rates in Figure 2. For all the three one-component models, the domains of model parameters corresponding to the *Einstein* HRI count rates within a $\pm 1\ \sigma$ range are broader than the 99% confidence domains obtained from the *Chandra* spectra. The 1 σ domains corresponding to the *ROSAT* HRI count rate overlap with the 1 σ confidence regions obtained from the spectral data. Thus, the source count rates detected with the three instruments do not show statistically significant variability of the source.

We also examined numerous archival *ASCA* observations of Cas A (1993–1999) and failed to detect the central point source on the high background produced by bright SNR structures smeared by poor angular resolution of the *ASCA* telescopes. In the longest of the *ASCA* SIS observations (1994 July 29; 15.1 ks exposure), the point source would be detected at a 3 σ level if its flux were a factor of 8 higher than that observed with *Chandra*, *ROSAT*, and *Einstein*. The *ASCA* observations show that there were no strong outbursts of the central source.

4. DISCUSSION

The observed X-ray energy flux F_{X} of the compact central object[4] (CCO) is 3.6, 6.5, and 8.2 × 10^{-13} ergs cm^{-2} s^{-1} in 0.3–2.4, 0.3–4.0 and 0.3–6.0 keV ranges, respectively. Upper limits on its optical-IR fluxes ($F_R \lesssim 3 \times 10^{-15}$ ergs cm^{-2} s^{-1} and $F_I \lesssim 1 \times 10^{-14}$ ergs cm^{-2} s^{-1}) can be estimated from the magnitude limits ($R \gtrsim 24.8$ and $I \gtrsim 23.5$) found by van den Bergh & Pritchet (1986). This gives, e.g., $F_{\mathrm{X}}/F_R \gtrsim 100$ for the

[3] Available at http://wave.xray.mpe.mpg.de/rosat/doc/ruh.

[4] According to the convention recommended by the *Chandra* Science Center, this source should be named CXO J232327.9+584842. We use the abbreviation CCO for brevity.

ROSAT energy range and $F_X/F_R \gtrsim 200$ for the *Chandra* and *Einstein* ranges. The flux ratios are high enough to exclude coronal emission from a noncompact star as the source of the observed X-ray radiation. A hypothesis that CCO is a background active galactic nucleus or a cataclysmic variable cannot be completely rejected, but its probability looks extremely low, given the high X-ray–to–optical flux ratio, the softness of the spectrum, and the lack of indications on variability.

The strong argument for CCO to be a compact remnant of the Cas A explosion is its proximity to the Cas A center. The source separation (1″–5″) from the SNR expansion center, found by van den Bergh & Kamper (1983) from the analysis of proper motions of FMKs, corresponds to a transverse velocity of 50–250 km s^{-1} (for $d = 3.4$ kpc, $\tau = 320$ yr). Much higher transverse velocities, 800–1000 km s^{-1}, correspond to the separation (16″–20″) from the position of the apparent center of expanding SNR shell derived by Reed et al. (1995) from the radial velocities of FMKs. Thus, if CCO is the compact remnant of the SN explosion, it is moving south (or SSE) from the Cas A center with a transverse velocity of a few hundred kilometers per second, which is common for radio pulsars.

A lack of radio pulsations (Woan & Duffett-Smith 1993) and a resolved synchrotron nebula, together with the steep X-ray spectrum and low luminosity, suggest that the CCO is not an active pulsar. However, the observed X-rays could be emitted from the NS surface with a nonuniform surface temperature distribution. Various possibilities to explain the small size and high temperature of the emission region at the NS surface, as well as other possible interpretations of the observed radiation, will be described elsewhere (see also details given in Pavlov et al. 1999). Here we only briefly mention that hot spots on a cooler NS surface could form if $\gtrsim 10^{-12}\, M_\odot$ of hydrogen or helium have accreted on the NS magnetic poles (e.g., just after the SN explosion). Since the thermal conductivity of the liquid portion of degenerate NS envelopes is proportional to Z^{-1} (Yakovlev & Urpin 1980), the low-Z polar caps are hotter than the rest of the (presumably iron) surface. Using the relations between the temperature T_b of the outer boundary of the internal isothermal region and the effective surface temperature for different chemical compositions of envelopes (Chabrier, Potekhin, & Yakovlev 1997), we found that, for instance, the effective temperatures of the H cap and Fe surface are $T_{\rm pc}^\infty = 2.8$ MK and $T_s^\infty = 1.7$ MK, for $T_b = 400$ MK, $M = 1.4\, M_\odot$, and $R = 10$ km. As we have shown in § 2, a two-component model spectrum with such temperatures is consistent with the observed CCO spectrum for $R_{\rm pc} \simeq 1$ km. Such an explanation of the CCO radiation is compatible only with the standard cooling scenario—the difference of chemical compositions could not account for a large ratio (∼10) of the cap and surface temperatures required by the accelerated cooling.

Alternatively, the observed radiation could be due to accretion onto a NS or a black hole (BH). Accretion from the circumstellar matter (CSM) does not look plausible because it would require too high CSM densities and/or low object velocities. However, we cannot exclude the possibility that CCO is an X-ray transient in a long-lasting quiescent state slowly accreting from a dwarf secondary component in a close binary (e.g., an M5 V dwarf with $M_{\rm bol} = +9.8$ would have $I \simeq 24.7$, consistent with the upper limit on the I flux) or from a residual disk which remained after the SN explosion. The CCO luminosity and spectrum resemble those of low-mass X-ray binaries (LMXBs) in quiescence, although we have not seen variability inherent to such objects. The criterion suggested by Rutledge et al. (2000) to distinguish between the NS and BH LMXBs in quiescence, based on fitting the quiescent spectra with the light-element NS atmosphere models, favors the BH interpretation. Critical observations to elucidate the nature of CCO include searching for periodic and aperiodic variabilities, deep IR imaging, and longer *Chandra* ACIS observations which would provide more source quanta for the spectral analysis.

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