The Cooling of the Central Compact Object in Cas A from 2006 to 2020

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Abstract

We report on the study of six Chandra observations (four epochs) of the Central Compact Object (CCO) in the Cassiopeia A supernova remnant with the ACIS instrument in the subarray mode. This mode minimizes spectrum-distorting instrumental effects such as pileup. The data were taken over a time span of \(~14\) yr. If a non-magnetic carbon atmosphere is assumed for this youngest known CCO, then the temperature change is constrained to be \(T = -2900 \pm 600\) K yr\(^{-1}\) or \(T = -4500 \pm 800\) K yr\(^{-1}\) (1\(\sigma\) uncertainties) for constant or varying absorbing hydrogen column density. These values correspond to cooling rates of \(-1.5\% \pm 0.3\%\) per 10 yr and \(-2.3\% \pm 0.4\%\) per 10 yr, respectively. We discuss an apparent increase in the cooling rate in the last five years and the variations of the inferred absorbing hydrogen column densities between epochs. Considered together, these changes could indicate systematic effects such as caused by, e.g., an imperfect calibration of the increasing contamination of the ACIS filter.

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1. Introduction

The Central Compact Object (CCO) in the Cassiopeia A (Cas A) supernova remnant is the youngest known (\(\approx300\) yr) neutron star in our galaxy with an apparently purely thermal X-ray spectrum. The thermal evolution of such a young neutron star is interesting because the cooling rate at this age strongly depends on poorly known properties in the neutron star interior, in particular superfluidity (e.g., Page et al. 2004; Yakovlev & Pethick 2004; Shthernin et al. 2021). Over the course of their evolution, CCOs are discussed to exhibit changes in their atmosphere compositions—e.g., Chang & Bildsten (2004) and Ho et al. (2021, H+21 in the following). According to one model, they have buried, and then re-emerging, magnetic fields that are associated with increasing temperatures (e.g., Ho 2011). As the youngest member of this class, the Cas A CCO is an important reference point for such studies.

The cooling of this CCO has been the topic of continued interest and X-ray monitoring after Heinke & Ho (2010) reported an unexpectedly rapid 4\% (5.4\(\sigma\)) decline of the surface temperature and a 21\% flux decline over a time span of 10 years. These results were based on spectral fits using a non-magnetic carbon atmosphere model that covers the whole neutron star surface and has a uniform effective temperature. The data were obtained from Chandra observations with ACIS-S in the Graded mode,4 which can also affect the spectrum.

These Chandra ACIS-S Graded mode observations of the CCO suffered from several instrumental effects. Since the primary target was the supernova remnant, these observations used the full ACIS-S3 chip which led to relatively slow readout. Since Cas A is bright, the slow readout implies that photon pileup is the most important instrumental effect. Pileup means that two or more photons are detected as a single event.\(^5\) Photon pileup distorts the observed CCO spectrum. The pileup fraction of the Cas A data is gradually decreasing because the sensitivity of the ACIS detector decreases over time. This is mostly due to a contaminant accumulating on the optical-blocking filters of the ACIS detectors. In addition, not all X-ray events are telemetered in the Graded mode,\(^6\) which can also affect the spectrum.

The ACIS-S subarray mode avoids spectral distortion effects due to photon pileup and the Graded telemetry mode. However, it cannot avoid the effect of changing sensitivity of the ACIS detector due to the very specific contamination. Using this more suitable instrument mode, Pavlov & Luna (2009), Posselt et al. (2013, P+13 in the following), and Posselt & Pavlov (2018, PP18 in the following) also carried out monitoring studies of the temperature evolution of the Cas A CCO. PP18 reported conservative 3\(\sigma\) upper limits of \(<3.3\%\) and \(<2.4\%\) for the absolute value of the ten year cooling rate if a non-magnetic carbon atmosphere model is assumed for varying or constant \(N_H\), respectively.

2. Observations and Data Reduction

For this work, we use only Chandra ACIS subarray mode observations. In the subarray mode, only a part of the ACIS chip is read out. The ACIS-S3 chip in the 100 pixel subarray is used for each observation listed in Table 1. This subarray mode reduces the frame time to 0.34 s versus the 3.24 s in full-frame mode, reducing the pileup fraction to less than 1.6\% in all

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\(^5\) For more details, see cxc.harvard.edu/ciao/ahelp/acis_pileup.html.

\(^6\) For more details, see cxc.harvard.edu/ciao/why/cti.html.
epochs (compared to \(\sim 20\%) in the case of the early full-frame mode data; Pavlov & Luna 2009).

Observing epochs P3a and P3b were obtained three days apart in 2015 May, with the subarray placed near the chip readout in P3a, and at the center of the chip for P3b (see PP18 for more details\(^5\)). In observing epochs P1 (2006) and P2 (2013), the subarray was also placed near the chip readout. The two new observations of P4 (2020), which we call P4a and P4b, were obtained three days apart in 2020 May with the subarray placed at the center of the chip.

We employ CIAO version 4.12 and the most recent CALDB version 4.9.5 for the data reduction and extraction of the spectra, and XSPEC (version 12.10.1) for the spectral analysis. The analysis is carried out in the same way as presented for epoch P1 to P3b by PP18 and P+13. In particular, we use similar extraction regions for the source and background. Intervening filaments of the supernova remnant are excluded from the background regions. Spectra are binned with a signal-to-noise ratio of at least 10 per energy bin.

In comparison to the previous CALDB versions used by PP18, version 4.9.5 includes not only updates on the ACIS filter contamination correction, but also on the aspect solution. This resulted in slightly changed off-axis angles (Table 1) for P1–P3b in comparison to PP18. Due to the changed contamination correction, the obtained spectral fit parameters are also slightly different as discussed in Section 3. We note that the measured offsets between the CCO centroid positions in P1–P4 are still too small in comparison to the absolute astrometry uncertainty of Chandra, 0.074.

For the spectral fits, we use the carbon atmosphere models by Suleimanov et al. (2014) with a negligibly low magnetic field (\(B < 10^8\) G), a surface gravitational acceleration of \(\log g = 14.45\), and a gravitational redshift of \(z = 0.375\), which corresponds to a neutron star with \(M_{\text{NS}} = 1.647\, M_\odot\) and \(R_{\text{NS}} = 10.33\) km. Using a distance of 3.4 kpc (\(d = 3.4\, 10^{3.9}\) kpc; Reed et al. 1995), we fix the normalization, \(N = R_{\text{NS}}^2/d^2_{\text{10kpc}} = 923\), where \(R_{\text{NS}}\) is the neutron star radius in kilometers, and \(d_{\text{10kpc}}\) is the distance in 10 kpc. P+13 showed that the significance of the temperature (or flux) difference is very similar to those obtained using tied normalizations (same emission size) or normalizations allowed to vary between observing epochs. The used spectral models are the same as in our previous works (P+13, PP18). Here, we only use the non-magnetic carbon atmosphere model. Hydrogen atmosphere models fit the data equally well, but require an emission area smaller than the total neutron star surface (see P+13 for a detailed discussion).

### 3. Results and Discussion

We verified that the two epochs P3a and P3b, as well as the two epochs P4a and P4b, give similar spectral fit results within uncertainties. This is not surprising because each of this pair of observations is only three days apart and the CCO or its environment is unlikely to change over that time. We therefore tie the spectral fit parameters of P3a with those of P3b (epoch 3 in the following), and similarly P4a with P4b (epoch 4 in the following). As reference time in each epoch, we utilize the exposure-weighted average observing date.

Table 2 lists the reference times and best-fitting parameters for the carbon atmosphere model. We consider two cases: \(N_H\) is tied to the same value for all epochs, or it is allowed to vary. If \(N_H\) is allowed to vary between the epochs, the results for each epoch are independent, and we can compare the results of the first three epochs with our earlier work to identify differences due to a changed calibration database, i.e., CALDB version 4.9.5 in comparison to CALDB 4.7.3 utilized by PP18. The temperature values for each of the three epochs, obtained with the old and new CALDB, agree within 1\(\sigma\). The third epoch has the largest difference, with a lower temperature for CALDB 4.9.5. The absolute value of the temperature difference between epochs 1 and 2 (5.54 yr) slightly decreases to \((0.5 \pm 1.7) \times 10^4\) K (from the previous \((0.8 \pm 1.7) \times 10^4\) K; 90\% confidence levels as in Table 2) while between epochs 2 and 3 (only 2.98 yr), the absolute temperature difference slightly increases to \((2.5 \pm 1.7) \times 10^4\) K (from the previous \(2.1^{+1.9}_{-1.8}\) \times 10^4 K; uncertainties are the 90\% confidence level). The best-fit absorbing hydrogen column densities \(N_H\) also change slightly, with \(N_H\) from epoch 2 and 4 being different by more than 3\(\sigma\). This \(N_H\) difference is also apparent in Figure 1. If taken at face value, two interpretations are possible. One is that the hydrogen column density toward the CasA CCO decreased by 9\% in \(2.5 \pm 0.8\) kpc; Reed et al. 1995, where \(z = 0.375\). An examination of the many contaminant parameters reveals that the same emission size as in our previous works (P+13, PP18). Here, we only use the non-magnetic carbon atmosphere model. Hydrogen atmosphere models fit the data equally well, but require an emission area smaller than the total neutron star surface (see P+13 for a detailed discussion).

### Table 1

| ID  | ObsID | MJD  | \(T_{\text{exp}}\) | C | \(f_{\text{src}}\) | \(S3_X\) | \(S3_Y\) | \(\theta\) |
|-----|-------|------|-----------------|---|--------------|--------|--------|--------|
| P1  | 6690  | 54027| 61.7            | 7443 | 86.5         | 210.7  | 49.0   | 18.4   |
| P2  | 13783 | 56053| 63.4            | 6773 | 87.3         | 215.2  | 50.7   | 17.2   |
| P3a | 16946 | 57140| 68.1            | 6263 | 87.8         | 229.4  | 54.3   | 15.8   |
| P3b | 17639 | 57143| 42.7            | 4556 | 82.5         | 574.6  | 508.1  | 174.2  |
| P4a | 22426 | 58980| 48.2            | 3859 | 86.7         | 334.2  | 506.0  | 57.2   |
| P4b | 23248 | 58983| 28.2            | 2107 | 85.6         | 334.1  | 506.5  | 57.1   |

Note. The ID indicates the abbreviation used for the observing epoch of the Chandra data set with the listed ObsID, \(T_{\text{exp}}\) is the dead-time-corrected exposure time after filtering for high background, (total) counts C and the source count fraction \(f_{\text{src}}\) correspond to the source extraction regions used for the spectral fits in Table 2. \(S3_X\) and \(S3_Y\) are the centroid chip coordinates on ACIS-S3. \(\theta\) is the off-axis angle.

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\(^5\) P3a and P3b were named P3 and P4 in PP18 because they were independent programs with the CCO at different chip positions. Here, we emphasize their close proximity in time in comparison to the next observations.
middle of all subarray observations. If N_H is allowed to vary between epochs, we derive a slope \( \dot{T} = -4500 \pm 800 \) K yr\(^{-1}\) and an intercept \( T_0 = (198.3 \pm 0.4) \times 10^4 \) K (1\(\sigma\) uncertainties, \( \chi^2 = 2.1\) for \( \nu = 2\) dof), shown by the blue points and area in Figure 2. This corresponds to a cooling rate of \(-2.3 \pm 0.4\) (1\(\sigma\))% in 10 yr, and to a characteristic cooling time, \( \tau_{\text{cool}} = T_0 / (\dot{T}) = 440 \pm 80\) yr. If N_H is the same for all epochs, the values are \( T_0 = 2900 \pm 600 \) K yr\(^{-1}\), \( T_0 = (198.4 \pm 0.3) \times 10^4 \) K (1\(\sigma\) uncertainties, \( \chi^2 = 0.9\) for \( \nu = 2\) dof), shown by the red points and area in Figure 2. This corresponds to a cooling rate of \(-1.5 \pm 0.3\) (1\(\sigma\))% in 10 yr, and to a characteristic cooling time, \( \tau_{\text{cool}} = 690 \pm 140\) yr.

The fit for \( T(t) \) is worse for the case where N_H is allowed to vary between epochs, and stronger residuals are apparent in Figure 2 (left panels). This is due to the seemingly faster temperature change between the last two epochs in comparison to the first two epochs as already mentioned above and visible in Figure 1. This can be also illustrated by only considering the last three epochs for a linear temperature fit. For such a fit, the best-fit temperature value in epoch 1 (Table 2) is 4.3\(\sigma\) away from the temperature one would expect according to the linear fit parameters \( \dot{T}_{23} = -7900 \pm 1500\) K yr\(^{-1}\), \( T_{0,23} = (197.2 \pm 0.5) \times 10^4\) K; (1\(\sigma\) uncertainties, \( T_{0,23} = 2015.3\) yr). If the fit results for the varying N_H are taken at face value, it means that either epoch 1 (2006) is an outlier or the cooling of the CCO accelerated after 2012. We regard the latter scenario as unlikely. In 2006, however, the optical thickness of the ACIS blocking filter was still low and the instrument sensitivity was the best of the four epochs. Thus, a deviation of epoch 1 would be also puzzling. The fit where N_H is tied for all epochs is statistically acceptable. For both, N_H free or tied, we note that most of the temperature drop comes from the last epoch; as Figure 1 illustrates, in the last five years the differences are as large (or slightly larger) than the respective ones over the first nine years. If only the first three epochs with the new CALDB are considered, we obtain \( T_{123} = -3400 \pm 1100(1\sigma)\) K yr\(^{-1}\) (free N_H), and \( T_{123} = -3000 \pm 900(1\sigma)\) K yr\(^{-1}\) (tied N_H), lower than the values for all four epochs above.

Our results are within the \( T \)-bounds reported by PP18. The 10 year cooling rates are consistent with (although slightly slower than) the respective values recently presented by H+21 (-2.2 \pm 0.2 or -2.8 \pm 0.3\% per 10 yr, corresponding to \( \dot{T}_{H+21} = -4090 \pm 360\) K yr\(^{-1}\) and \( \dot{T}_{H+21} = -5070 \pm 480\) K yr\(^{-1}\) for tied or varying N_H, respectively; all with their respective 1\(\sigma\) uncertainties) based on 19 years of Graded mode data of the Cas A supernova remnant. Figure 2 shows the results on the temperature change from our study (left panels) and the H+21 study (right panels) together. Only the relative changes are relevant. The offsets in absolute temperatures are due to different normalizations (reflecting different radius and mass assumptions, spectral model normalization, scattering and pileup considerations for H+21). Interestingly, the last

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### Table 2

| Data | \( t_{\text{model}} \) | \( N_{\text{H}} \) | \( T_{\text{eff}} \) | \( F_{\text{abs}}^{\text{HH}} \) | \( F_{\text{unabs}}^{\text{HH}} \) | \( L_{\text{bol}}^{\text{HH}} \) | \( \chi^2 \) (dof) |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| P1   | 2006.8          | 2.14 \pm 0.02   | 200.0 \pm 0.15  | 7.33 \pm 0.17   | 2.81 \pm 0.08   | 6.4 \pm 0.1     | 1.17 (242)     |
| [0.7x] P2 | 2012.3          | =N_H P1         | 199.1 \pm 1.0   | 7.12 \pm 0.17   | 2.74 \pm 0.08   | 6.3 \pm 0.1     | 1.17 (242)     |
| P3   | 2015.3          | =N_H P1         | 198.3 \pm 0.8   | 7.00 \pm 0.13   | 2.70 \pm 0.07   | 6.2 \pm 0.1     | 1.17 (242)     |
| P4   | 2020.4          | =N_H P1         | 196.1 \pm 0.9   | 6.54 \pm 0.16   | 2.55 \pm 0.08   | 5.9 \pm 0.1     | 1.17 (242)     |

Note. The fits were done simultaneously for P1–P4; the parameters are tied for P3a and P3b, and for the two observations of P4. The normalization is fixed for all epochs in all fits at \( N = 923 \) (see the text). Fluxes are given for the energy range of 0.6–6 keV. \( F_{\text{abs}}^{\text{HH}} \) is the absorbed flux in units of \( 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\), while \( F_{\text{unabs}}^{\text{HH}} \) is the unabsorbed flux in units of \( 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\). All errors indicate the 90% confidence level for one parameter of interest. The bolometric luminosity at infinity is calculated as \( L_{\text{bol}}^{\infty} = 4\pi\sigma T_{\text{eff}}^{4} = 4\pi\sigma 10^{10}N_{\text{H}}^{\text{abs}}T_{\text{eff}}^{4}(1+c)^{-2} \) erg s\(^{-1}\). Its uncertainty only considers the uncertainty of the temperature. \( t_{\text{model}} \) indicates the middle of the observation time of the respective epoch. \( \chi^2 \) is the reduced \( \chi^2 \) and dof are the degrees of freedom of the X-ray spectral fits.
four H+21 epochs seem to indicate a slowing of the temperature decrease—the opposite behavior to what our best-fit values seem to imply. In addition, the H+21 residuals closest in time to the time of our residuals show nearly mirrored behavior. For instance, our residuals in 2012 are positive, while the closest in time to the time of our residuals show nearly mirrored behavior. For instance, our residuals in 2012 are positive, while the H+21 residuals of 2012 are negative. Although somewhat surprising, not much can be learned from this since statistical fluctuations can explain both of these (insignificant) trends.

As a final note, we emphasize that the non-magnetic carbon atmosphere model is not the only one that fits the CCO spectrum. For instance, hydrogen atmosphere models with low magnetic fields ($B < 10^{10}$ G) fit the CCO spectra equally well. Such a fit does not show a temperature decrease over time (P +13). The fit with the hydrogen atmosphere models implies small emission areas, i.e., hot spot emission, and the apparent flux decrease is due to decreasing hot spot area. In contrast, a fit with a carbon atmosphere model produces an emission size consistent with expectations for the entire surface of a neutron star. Since no X-ray pulsations of the CCO (as one might expect for hot spots) have been detected, and the hypothesis of residual nuclear burning for very young and hot neutron stars can be applied to this CCO, it is argued that a carbon atmosphere that covers the entire neutron star surface, i.e., there are no hot spots, is the CCO’s carbon atmosphere. Such a model is not the only one that can explain the data; for instance, our residuals in 2012 are positive, while the closest in time to the time of our residuals show nearly mirrored behavior. For instance, our residuals in 2012 are positive, while the H+21 residuals of 2012 are negative. Although somewhat surprising, not much can be learned from this since statistical fluctuations can explain both of these (insignificant) trends.

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