A neutron star with a carbon atmosphere in the Cassiopeia A supernova remnant

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The surface of hot neutron stars is covered by a thin atmosphere. If there is accretion after neutron star formation, the atmosphere could be composed of light elements (H or He); if no accretion takes place or if the onuclear reactions occur after accretion, heavy elements are expected. Despite detailed searches, observations have been unable to confirm the atmosphere composition of isolated neutron stars. Here we report an analysis of archival observations of the compact X-ray source in the centre of the Cassiopeia A supernova remnant. We show that a carbon atmosphere neutron star (with low magnetic field) produces a good fit to the spectrum. Our emission model, in contrast with others, implies an emission size consistent with theoretical predictions for the radius of neutron stars. This result suggests that there is nuclear burning in the surface layers and also identifies the compact source as a very young (330-year-old) neutron star.

Cassiopeia A is one of the youngest-known supernova remnants in the Milky Way and is at a distance of d = 3.4$^{+0.3}_{-0.4}$ kiloparsecs (kpc) from the Earth. The supernova that gave rise to the remnant may have been observed by John Flamsteed in 1660 (ref. 8); the implied age coincides with the estimated age by studying the expansion of the remnant. Although the supernova remnant is extremely well-studied, the central compact source was only identified in X-ray Chandra X-ray observations. We shall refer to the compact source as Cas A.

We considered archival Chandra X-ray Observatory data from two studies of Cas A, both using the ACIS-S charge-coupled device which provides spatial and spectral information. A series of Chandra observations, totalling 1 megasecond, was performed in 2004 to study the supernova remnant; these are referred to here as the Hwang data. A shorter (70 kiloseconds) observation in 2006 was designed to study the compact source, here referred to as the Pavlov data. Figure 1 shows the Cas A spectra, as well as our carbon model.

We fitted the Hwang and Pavlov data simultaneously with several models: a blackbody, a H atmosphere, and an atmosphere composed of pure He, C, N, or O; these are illustrated in Fig. 2. To identify prominent model parameters, the mass and radius of the atmosphere models were used to the canonical neutron star values of $M_{\text{NS}} = 1.4M_{\odot}$ and $R_{\text{NS}} = 10$ km, where $M_{\odot}$ is the solar mass. The normalization factors, which can be interpreted as the fraction of the black body that is emitting X-ray radiation, was left free. The results are given in Table 1.

The H, He, and C atmosphere provided good fits to the data (somewhat better than the blackbody). However, the derived sizes of the emission region $R$ for H and He (4 km and 5 km, respectively) are much smaller than the theoretical size of a neutron star $R_{\text{NS}}$ (10 km). This would suggest the emission region is a hot spot on the neutron star surface, which would probably result in X-ray pulsations as the hot spot rotated with the star. However, these pulsations have not been detected yet. Fits to the data were performed using an additional (temperature) component, for example, a second blackbody or atmosphere spectrum, which produced inferred $R_{\text{NS}}$ of 0.2 and 2 km for blackbody 0.4 and 11 km for the atmosphere. The high-temperature component has been interpreted as being due to a small hot polar cap, while the low-temperature component is due to emission from the remaining cooler neutron star surface. However, it is difficult to generate, through anisotropic heat conduction, such small regions high-temperature contrast on the neutron star surface. Also, the two temperature regions would again probably produce (undetected) X-ray pulsations. On the other hand, by considering a carbon atmosphere, we derived an emission size $R_{\text{NS}} = 12$ km that closely matches the theoretical prediction for the radius of a neutron star $R_{\text{NS}} = 14$ km. In this case, the X-ray observations are detecting emission from the entire stellar surface, and therefore the emission would not necessarily vary as the star rotates (although local temperature differences could cause small brightness fluctuations on top of the bright background). Thus we conclude that Cassiopeia A is consistent with a low-magnetic field carbon atmosphere neutron star of mass $1.4M_{\odot}$, radius 12 km, and surface temperature $T = 1.8 \times 10^8$ K.

Interpreting the size of the emission region to be the true neutron star radius $R = R_{\text{NS}}$, we can constrain the neutron star mass $M_{\text{NS}}$ and radius $R_{\text{NS}}$ by using a range...
Luminosities are per bin for the Pavlov data and 140 counts per bin for the Hwang data. X-ray and bolometric luminosities are $L_X$ (0.5-10 keV) = $4.3 \times 10^{33}$ erg s$^{-1}$ and $L_{bol} = 7.0 \times 10^{33}$ erg s$^{-1}$, respectively.

Figure 1. Chandra X-ray spectra of Cas A. Spectra from the Hwang (black) and Pavlov (red) observations and fits with our C spectral model. Error bars are 1 s.d. The lower panel shows the t residuals $S_\chi$ in units of s.d. The Hwang observations place Cas A off-axis (blurring Chandra’s point-spread function), and the high count-rate of Cas A distorts the spectrum through detection of multiple photons during one 3.04-s frame time (known as pile-up). The Pavlov observation is performed in a special instrument configuration to reduce the frame time to 0.34 s (thus reducing pile-up) and places Cas A at the position of best focus.

We used the level 2 event lists provided by the Chandra Data Archive and performed data reduction and analysis with CIAO 4.1 and XSPEC 12.4.0. Owing to the slightly distorted shape of the Cas A point-spread function in the Hwang data, we extracted the source spectra using an elliptical region of dimensions 1.23 by 1.72 arcsec, rotated to match the position angle of the point-spread function ellipticity, and the background from a surrounding annulus of 2.19 to 4.37 arcsec. A tentative extraction method produces similar results. We combine the spectra and responses to make a single, deep spectrum of Cas A. For the Pavlov data, we extract the Cas A spectrum and the nearby background following the procedure of ref. 4. The spectra are binned to achieve at least 1,000 counts per bin for the Hwang data and 140 counts per bin for the Pavlov data. X-ray and bolometric luminosities are $L_X$ (0.5-10 keV) = $4.3 \times 10^{33}$ erg s$^{-1}$ and $L_{bol} = 7.0 \times 10^{33}$ erg s$^{-1}$, respectively.

Figure 2. Model atmosphere spectra. Energy flux for atmosphere models with H, He, C, N, O, and Fe and a blackbody. The energy has been redshifted by $1 + z_g = (1 + 2GM_{NS}/c^2 R_{NS})^{1/2} = 1.3$, where $z_g$ is the gravitational redshift, and the flux has been scaled by $(10 \text{ km} = 3.4 \text{ kpc})^2$. Our models are constructed assuming a plane-parallel atmosphere (because the atmosphere thickness is much smaller than the stellar size) that is in hydrostatic and radiative equilibrium with constant gravitational acceleration $g = (1 + z_g)GM_{NS}/R_{NS}$. The e cient separation of light and heavy elements results in atmosphere cores composed of a single element.$^{25}$ The opacities are obtained from tables computed by theOpacity Project.$^{26}$ (The energy range of the tables covers $E = kT_{eff} = 0.07$–5.0 keV.) When opacities are required beyond this range, we use the $E^{-3}$-dependence of free-free and bound-free absorption; this approximation has a minor effect, except for the Fe model, which is shown for illustrative purposes.) Light-element atmosphere spectra are harder than blackbodies (at the same temperature) because of the energy-dependence of the opacity.$^{27,28}$ So atmosphere spectral results in temperature that are lower and sizes that are larger compared to those obtained using blackbody spectra. Further details of the atmosphere model construction are given in ref. 29. When B is less than $2.35 \times 10^4 \text{ G}$ (8 $10^6$ G for carbon), the magnetic field effects on the radiation transport and atomic sizes in the atmosphere plasma may be negligible.$^{27,28}$ Previous works found poor fits to the data using magnetic ($B = 10^5 \text{ G}$) H atmosphere spectra,$^{14}$ while magnetic mid-Z element models are similar to low-magnetic Fe spectra in that they are blackbody-like in shape and contain many lines.$^{30}$
by the fact that the measured temperature (taken to be from a local hot spot because $R_{\text{NS}}$ could only be used to set an upper limit on the average surface tem-perature). However, with our $T_e$ and $L_{bol}$ (which are surface averages given that $R = R_{\text{NS}}$), detailed com parisons with theoretical models can now be made. 

The presence of a carbon atm osphere on the surface is probably a consequence of the youth of Cas A. The surface of newly-formed neutron stars is uncertain; it is thought to be composed of an element between O and Fe, depending on which layers of the pre-supernova star fall back onto the proto-neutron star; this fallback material could also form light elements through spallation. Over time, the surface accumulates an overlying layer of light elements by accretion from the circumstellar medium (although this can be countered by pulsar wind excavation). Fits to the thermal radiation from other neutron stars do indeed suggest $H_2$ or a atm osphere at $10^4 - 10^5$ years, and $T > 10^6$ K. However, the picture is incoherent for young neutron stars ($t < 10^4$ y). At a depth just below the surface, the temperature (and density) is conducive to nuclear burning ($T > 10^8$ K). Accreted material that surfaces this layer and is rapidly consumed, with depletion of $H$ in $< 1$ y and He in $< 100$ y. This process of dissipative nuclear burning is very tem perature-sensitive; as the neutron star cools, the tem perature drops below the threshold needed for the material to be burned, and a light-element atm osphere can begin to build up after $10^4 - 10^5$ y (ref. 6).

Cas A is the youngest of a c class of neutron stars that are located near the centre of the supernova remnant, possess steady long-term axes and soft therm al spectra, and have no detectable pulsar wind nebulae or radio pulsations. X-ray pulsations have been detected in three members of this class, with periods of tens of seconds. Timing measurements suggest that they have dipole magnetic fields $B = 10^{12}$ G (ref. 21). If the $M_{\text{NS}}$ of Cas A is $(5 \times 10^{15})$ G, then a spectral feature due to the electron cyclotron resonance may appear in the Chandra energy range, but this has yet to be detected. The lack of a visible pulsar wind nebula and no indication of magnetospheric activity (such as radio or gamma-ray emission or a high-energy hard power-law component), like those seen in classical pulsars (with $B > 10^{12}$ G), also suggest the magnetic field is low. The weak surface magnetic field inferred for this class would have important implications for the neutron star population. These objects could be representative of the early life of neutron stars before becoming classical pulsars. In this case, either neutron star magnetic fields develop by a dynamo mechanism, or else a strong field (produced during the collapse of the progenitor star) is buried and has not yet emerged. These objects could also form a distinct group of low magnetic field neutron stars, which never manifest pulsar-like behaviour; this would suggest a large population of cold, unobserved sources. Finally, we note that the detection of

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**Figure 3.** Neutron star mass and radius. 90% confidence contours of around the best-fitting Cas A mass and radius (crosses) for distances of 3.3 kpc (red long-dashed line), 3.4 kpc (thick black solid line), and 3.7 kpc (blue short-dashed line). The upper-left and lower-right regions are excluded by constraints from the requirement of causality and from the fastest-rotating neutron star known. The thin magenta solid lines represent predictions for the mass and radius of neutron stars using different theoretical models (labelled SQM 2, AP4, PAL6, and M50) of the neutron star interior. If we $\times M_{\text{NS}} = 1.4 M_{\odot}$ and the distance to Cas A as = 3.4 kpc (ref. 7), then we nd a surface effective temperat ure $T_e = 1.5_{-0.6}^{+1.4} \times 10^6$ K and emission size $R = 1.5_{-0.7}^{+1.3} \times 10^8$ km. Figure 3 shows 90% confidence contours in mass and radius when both are allowed to vary. The contours for distances between 3.3 and 3.7 kpc constrain $M_{\text{NS}} \approx 1.5 \times 1.4 M_{\odot}$ and $R_{\text{NS}} \approx 8 \times 17$ km. The mass constraint, significantly above the canonical $M_{\odot}$, suggests a moderately stellar explosion of nuclear equation of state.

The emission of neutrinos determines the therm evolution of a neutron star at ages $< 10^5$ y. The particle reactions that contribute to this emission are determined by the state of the matter, which is strongly dependent on the total mass of the star. Owing to the small uncertainties in the temperature and age of Cas A, as well as our measured mass, Cas A can be used to constrain matter properties in the stellar interior. More importantly, because the next youngest neutron stars for which surface helium emission has been measured have ages exceeding a few thousand years, Cas A (with an age of about 330 years) serves as a valuable window into the early life of a passively-cooling neutron star. Previously, the utility of Cas A in studying the therm evolution was hindered...
hydrogen-like C edge at about 0.45 keV (unredshifted), in similar sources with less intervening gas and dust than Cas A has, would not only provide further evidence for carbon atom atmospheres but also give a measurement of the gravitational redshift.

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| Atm osphere m ode l         | \( N_H \) \( (10^{22} \text{ cm}^{-2}) \) | \( kT \) (eV) | Nor m ali zati on | \( \chi^2/\text{d.o.f.} \) | Null hypothesis probability (%) |
|----------------------------|------------------------------------------|--------------|------------------|-------------------------------|--------------------------------|
| Hydrogen                   | 1.65\(^{+0.04}_{-0.03}\)               | 241\(^{+7}_{-6}\) | 0.18\(^{+0.03}_{-0.03}\) | 106.2/99                      | 29                             |
| Helium                     | 1.62\(^{+0.06}_{-0.04}\)               | 228\(^{+8}_{-9}\) | 0.22\(^{+0.05}_{-0.05}\) | 112.4/99                      | 17                             |
| Carbon                     | 1.73\(^{+0.04}_{-0.04}\)               | 155\(^{+7}_{-6}\) | 1.84\(^{+0.56}_{-0.56}\) | 105.3/99                      | 31                             |
| Nitrogen                   | 1.37                                    | 172           | 1.18             | 388/99                        | 0                              |
| Oxygen                     | 1.03                                    | 234           | 0.20             | 2439/99                       | 0                              |

| Blackbody m ode l          | \( kT = 387\,\text{eV} \) \( R = 1.05^{+0.08}_{-0.06}\,\text{km} \) | 134.2/98     | 11                             |

Table 1. X-ray spectral fitting of Cas A. Joint t results to the Hwang and Pavlov data with neutron star atm osphere and blackbody m ode ls that are modi ed by photoelectric absorption \( N_H \) (using the Tubingen-Boulter absorption routine TBABS with w im s model abundances in the X-ray spectral tting package XSPEC; see http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html), dust scattering\(^{23}\), and corrections for pile-up\(^{24}\) (the grade migration parameter of the pile-up algorithm is allowed to oat freely and is 0.36 for the best- m ode l). Chand ra data with such high statistics reveals system atic uncertainties in the Chand ra calibration\(^{13}\), so we added a system atic uncertainty of 3% in quadrature. All param eter errors are given at 90% con dence. Errors are not reported when the reduced \( \chi^2 > 2 \). The normalization refers to the fraction of the neutron star surface emitting radiation (for a 10 km stellar radius and 3.4 kpc distance). The null hypothesis probability is the probability that one realization of the m ode l to the data would have a reduced \( \chi^2 \) greater than that obtained; less than 5% indicates a poor t. \( T = T/(1 + z_g) \) and \( R = R/(1 + z_g) \) are the temperature and radius measured by an observer at infinity, and d.o.f. is the number of degrees of freedom.