A Deep Census of Low-Luminosity X-ray Sources in Globular Cluster ω Cen

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Abstract

We report the results of an analysis of a 291 kilosecond observation of Omega Centauri with the Chandra X-ray Observatory aimed at studying this globular cluster's population of X-ray-emitting binary stars. Combining ACIS-I data from 2000 and 2012, we obtain a deep exposure that reaches a limiting flux of $5 \times 10^{-16}\ erg\ cm^2\ s^{-1}$, or a luminosity of $L_X \sim 2.1 \times 10^{29}\ erg\ s^{-1}$ for sources in the cluster. Given these limits, we expect to be sensitive to most cataclysmic variable stars and many coronally active stars (e.g., BY Draconis and RS CVn stars) in the cluster, as well as large numbers of active galactic nuclei in the background. We find a total of 332 sources in the $17' \times 17'$ field, 138 of which are newly reported here. We assess the fraction of these sources that are likely to be AGN by comparing our results to the Chandra Deep Field. We also present some archival HST images of the brightest X-ray sources in this new sample.

Introduction

Omega Cen was one of the first globular clusters to be observed with the Chandra X-ray Observatory. It has been the subject of many research papers because of its large and diverse population of stars and the cluster is known to be home to many binary systems. A previous study of sources produced a list of 45-70 cluster members including CVs and a quiescent neutron star. Analysing the behaviour and properties of such systems can significantly contribute to the understanding of dynamical cluster evolution. Many of ω Cen's primordial binaries are likely to still exist but the large size of the cluster's core would suggest that a significant number of dynamical interactions have occurred over its lifetime. The population of binary systems is thought to be very high based on ω Cen's large mass of $\sim 4 \times 10^6\ M_\odot$. This research used data with a much deeper exposure time than previous Chandra studies of the cluster and thus was sensitive to much fainter X-ray sources.

X-ray Observations

Four observations of ω Cen were obtained from Chandra ACIS-I; two on 2000 January 24-25 and two on 2012 April 16-17. Different exposure times necessitated reprojecting each observation to a single R.A. and Dec. The software CIAO was used to reproject the datasets to a common pointing. All four exposures were merged into one image using CIAO's *merge_obs* to perform combined photometry on a total exposure time of 291ks. The primary energy range used in the analysis was $0.5 - 4.5\ keV$. No epochs with unusually elevated background levels were found previously in the 2000 data (Haggard et al., 2009) and none were detected in the more recent 2012 observations.

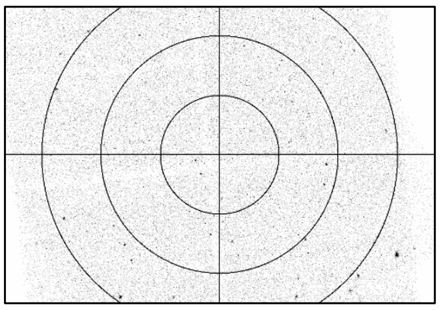

FIGURE 1: The merged 291ks image of ω Cen's core. The circles mark 1, 2, and 3 times the core radius. The centre of the core is marked by the black cross. North is up and east is to the left.

Source Detection

The CIAO tool *wavdetect* detected regions of high photon counts in the merged events file using Ricker wavelet functions with differing scale sizes. The spatial variation of the Chandra PSF was taken into account in the analysis. Information in the outer regions of the Chandra image is not as reliable as in the central region because photons can be scattered off-axis and source images become heavily distorted. For this reason, *wavdetect* was supplied with a psfmap to indicate which data in the events file were most reliable for source detection. The tool *mkpsfmap* created a psfmap at an effective energy of $2.3\ keV$. A source significance threshold of 10^{-6}, which gives ~ 1 false detection per 10^6 pixels, and wavelet scale sizes of $1 - 16$ in intervals of $\sqrt{2}$ were adopted (Freeman et al., 2002). Isolated pixels in groups of $1 - 3$ with count values not less than 2 were denoted by *wavdetect* as sources. To help determine which of these were true sources, the processes above were repeated for additional energy bands: soft ($0.5 - 1.2\ keV$), medium ($1.2 - 2.0\ keV$), $0.5 - 4.5\ keV$, and hard ($2.0 - 7.0\ keV$). This aided in deciding which energy range gave the best signal-to-noise ratio for the sources. Sources were labelled based on their radial distance from the cluster centre and the quadrant in which they lie. The first number in the name denotes the radial distance rounded to the nearest arc minute. The second number (1-4) refers to the quadrant in which the source lies. The third character is a letter denoting the source's azimuthal position within its quadrant in a counter-clockwise direction. 332 sources were detected in the inner 2048 × 2048 pixels (unbinned; 1 pixel = 0.492″). 169 of these sources were reported in recent studies (Cool et al., 2013, Haggard et al., 2009). The total number of newly identified X-ray sources came to 138. 17 detections were found to be spurious upon subsequent examination.

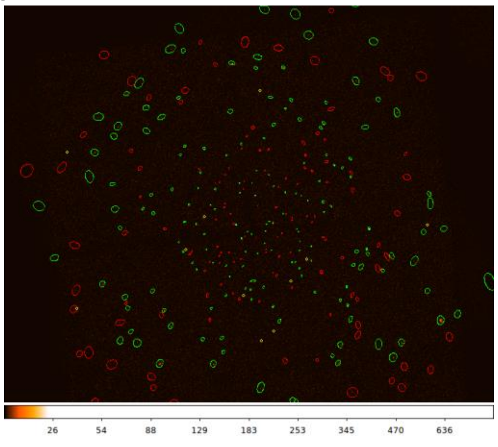

FIGURE 2: The X-ray image of ω Cen's core with redetected sources in green and newly detected sources in red.

AGN Discrimination

Some of these X-ray sources were likely to be Active Galactic Nuclei (AGN). The ratio can be calculated numerically:

$$N = 400 \pm 80\ \left(\frac{f}{2 \times 10^{-15}}\right)^{-0.66 \pm 0.06} \text{sources deg}^{-2}$$

where f is the flux limit in *erg s⁻¹ cm⁻²* and N is number of sources expected at this limit. The field of view is 0.0803 deg². This gives

$$N(f_{upper}) \cong 11^{+3.4}_{-2.9}\ \text{AGN} \quad \text{and} \quad N(f_{lower}) \cong 156^{+6.4}_{-11.7}\ \text{AGN}$$

It is appropriate to estimate ≥ 50% of new sources likely to be AGN.

Optical Counterparts

Images from the Wide Field Channel (WFC) of the Hubble Space Telescope Advanced Camera for Surveys (HST, ACIS) were obtained from the observations dated 2002 June 27-30. 9 images were chosen that cover the central $\sim 10' \times 10'$ region of the *Chandra* images. 3 filters were obtained from each of the 9 images: F435W (B435), F625W (R625), and F658N (Hα). Of the 332 sources detected, 196 sources lie within the optical range. 85 of the 196 are new sources. The 3 brightest sources lie outside the optical range. Two of those sources lie off-axis but were classified as good quality objects. For the next brightest sources, 1.0″ circles were placed at their corresponding positions in the optical images. Candidate stars positioned within the 1.0″ circles for each source were analysed using IRAF's *imexamine*. The tool computed pixel values within appropriate apertures for each visual source. The HST images from the current ACS run present data in the form of counts per second (cps). The magnitudes of the stars were determined by converting the cps into the VEGAMAG system provided by STSCI. The B435−R625 and Hα−R625 magnitudes were determined in order to position the candidate stars on colour-magnitude diagrams (CMDs). The candidate stars were superimposed onto a sample CMD of stars in a 20″ × 20″ square in the central region of ω Cen surrounding a known CV (Cool et al., 2013).

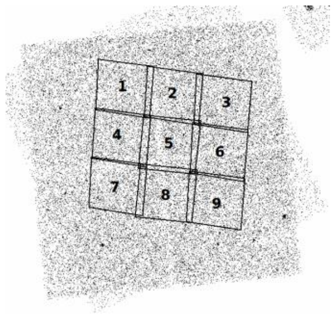

FIGURE 3: HST coverage (black rhombi) over the 17′ × 17′ Chandra FOV. North is up and east is to the left.

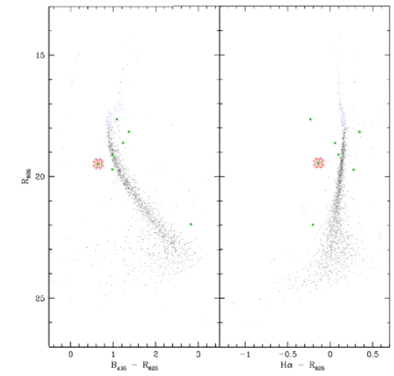

FIGURE 4: Candidate stars (green points) for a source superimposed on a sample CMD for ω Cen. The suspect star is denoted by a red asterisk symbol.

Discussion

Using the deepest Chandra exposure of Cen to date, this research has almost doubled the number of known X-ray sources in the cluster to a new limiting flux of $L_X \sim 2.1 \times 10^{29}\ ergs\ s^{-1}$. Out of the total 332 sources, it is expected that a large fraction $N \simeq 50\%$ are background AGN. The number of AGN in the region is inversely proportional to the flux and many sources positioned in the central region of the cluster are well-defined and have relatively bright flux values. It is expected that most of the central core sources are cluster members and that fainter sources off-axis are contributory AGN. The density of the core compared to the outer edges of ω Cen is much higher and it is more likely to find sources here that are binary star systems. The radial distribution of X-ray sources is consistent with expectations from other observations of globular clusters.

Two of the optical candidate sources (one shown in FIGURE 4) are both blue and Hα-bright. These two properties are highly suggestive of a compact accreting binary. The bright Hα emission indicates an emission line from excitation of hydrogen in an accretion disc. $42b_2$ is possibly faintly blue but is also quite bright in the Hα band. Source 14k is highly likely to be a cataclysmic variable with 24c being the only other source deemed a possible CV. 41h does not lie far enough from the main sequence to be considered a likely CV and could perhaps simply be a very faint blue star. Given the position of the supposed counterpart to source 24c, it is possible that it might be part of the MS and still quite bright in the Hα band. A CV with a weak disc could present these properties as was observed in NGC 6397 (Cool 1998).

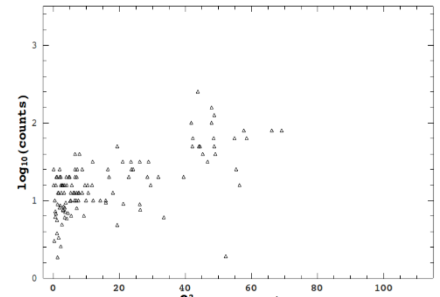

FIGURE 5: New Chandra source fluxes as a function of the angular distance from the centre of the cluster.

Future Work

Future goals in this research include new analysis of the 168 redetected sources and inspection of their X-ray luminosities to determine any significant change from the 2001 data. Candidate counterparts for the remaining new sources must be analysed and classified. Their X-ray luminosities in the soft and hard energy bands will also be calculated to further aid in distinguishing source types. The software program DAOPHOT will be used to conduct much more accurate aperture photometry than that carried out by IRAF's *imexamine*.

Acknowledgements

This research had made use of data obtained from the *Chandra Data Archive* and the *Chandra Source Catalog*, and software provided by the *Chandra X-ray Center (CXC)* in the application packages CIAO, ChIPS, and Sherpa.

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