A soft X-ray observation of ω Centauri with EXOSAT

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Summary. In an observation with the LE1 CMA detector of the EXOSAT observatory we have detected two of the X-ray sources previously discovered in the globular cluster ω Cen with the IPC detector on board of the Einstein satellite. We give improved positions for these two sources. On the basis of comparison of the EXOSAT and Einstein count rates we conclude that these two sources in ω Cen are either very soft (kT ~ 40 eV) or highly variable. If they are very soft, previous estimates of their X-ray luminosities can be too high by an order of magnitude.

Key words: clusters: globular – stars: close binaries – close binaries – X-rays binaries

1. Introduction

Globular clusters contain many X-ray sources per unit mass, as compared to the galactic disc. This is true both for high-luminosity ($L_x \geq 10^{36}$ erg cm$^{-2}$ s$^{-1}$) sources (e.g. Katz, 1975) and for low-luminosity ($L_x \lesssim 10^{34}$ erg cm$^{-2}$ s$^{-1}$) sources (Hertz and Grindlay, 1983). The similarity of the X-ray properties of the high-luminosity sources in globular clusters – their luminosities, their soft spectra, the absence of pulses, the occurrence of bursts – to those of the low-mass X-ray binaries in the galactic disc indicates that they are low-mass X-ray binaries (e.g. Joss and Lewin, 1983). The statistical estimate of the mass of the high-luminosity sources in globular clusters, $\sim 0.9 - 1.9 M_\odot$, is consistent with this interpretation (Grindlay et al., 1984). The high incidence of low-mass X-ray binaries in globular clusters can be explained by the occurrence in dense cluster cores of tidal capture of a neutron star by a main-sequence or giant star (Fabian et al., 1975; Sutantyo, 1975).

Similarly, tidal capture of a white dwarf will lead to the formation of a cataclysmic variable (Hut and Verbunt, 1982). The low-luminosity sources have a lower mass on average than the more luminous sources, as indicated by their occurrence outside the cluster core (Hertz and Grindlay, 1983). These considerations led Hertz and Grindlay to the conclusion that the low-luminosity sources are, in fact, cataclysmic binaries. Verbunt et al. (1984) point out that the X-ray luminosity of some of the low-luminosity sources – those with $L_x \gtrsim 10^{33}$ erg s$^{-1}$ – is rather high for cataclysmic variables, and argue that these sources may be low-mass X-ray binaries in quiescence, i.e. low-mass X-ray binaries in a state of low mass transfer.

As many low-mass X-ray binaries and cataclysmic variables show characteristic X-ray variability, continued observation of globular cluster X-ray sources may provide new clues to their identity. In addition, more accurate positions for the low-luminosity sources can be obtained with EXOSAT, which makes identification of the optical counterparts feasible. Optical spectra of these counterparts can then be obtained to determine the nature of these sources. To pursue these goals we have started a programme of observing globular clusters with the EXOSAT Observatory.

In this paper we report on our EXOSAT observation of ω Centauri (= NGC 5139). This nearby cluster was observed with the Einstein satellite, and five low-luminosity sources, three of whom well outside the cluster core, were detected (Hertz and Grindlay, 1983). The low X-ray luminosities ($< 10^{33}$ erg s$^{-1}$) indicate that they are cataclysmic variables. We will denote these sources HG A, HG B, to HG E.

2. Observation and reduction

We observed ω Cen with the EXOSAT observatory 1984 July 31 from UT 4h56m to 19h03m for a total exposure of 48,783 s. The useful data were obtained with the low energy imaging telescope (LE1) using the channel multiplier array (CMA) with the 3000 Å lexan filter (see Taylor et al., 1981; de Korte et al., 1981). The filter plus telescope response covers the range from roughly 0.1 to 1.5 keV. At the lower end of this energy range the detectability of a source depends principally on the amount of photoelectric absorption by the interstellar medium.

We restricted our attention to the central portion of the field of view, a square of 34'1 x 34'1 centered on $\alpha = 13^h 23^m 48^s$, $\delta = -47^\circ 13' 12''$. Four of the five sources detected by Hertz and Grindlay (1983) were within this region, their source E being excluded.

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We searched for sources in two ways. First we searched the entire central region with use of a sliding-box algorithm. Three sources were detected above a significance threshold where the expected number of accidental sources is less than 0.05 for the entire field searched. Two of these can be identified with early-type stars, HD 116789 and HD 116663, (nos. 2 and 4, respectively, from Woolley, 1966). Their measured fluxes are consistent with the expected ultraviolet contamination from these stars. The third source is located within the \textit{Einstein} error box of HG D.

Subsequently we searched the \textit{Einstein} error boxes of sources HG A, HG B, and HG C, again using the sliding-box algorithm, but now with a detection criterion adapted to the smaller total area searched. Source HG A was detected, sources HG B and HG C were not.

We list the detected sources with their count rates in Table 1, where we also give estimated upper limits to the count rates of sources HG B and HG C.

### 3. Results

To compare the \textit{EXOSAT} and \textit{Einstein} results we transform all count rates into flux received at earth, \( f_E \), and X-ray luminosity at the source, \( L_x \), both integrated over the 0.5–4.5 keV interval. The \textit{EXOSAT} CMA detector is sensitive to photons of lower energies as the \textit{Einstein} IPC detector. Hence the expected count rate in the \textit{EXOSAT} CMA for a source of given count rate in the \textit{Einstein} IPC depends on the spectrum of the arriving flux. This in turn depends on the spectrum at the source and on the amount of interstellar absorption. For the reddening to \( \omega \) Cen we use \( E(B-V) = 0.11 \) (Harris and Racine, 1979), which corresponds to an effective column density of \( N_H = 0.73 \times 10^{21} \text{ cm}^{-2} \), where we use the relation given by Gorenstein (1975). We use the abundances and cross sections given in Morrison and McCammon (1983) to calculate the effects of absorption on the X-ray spectra.

Many cataclysmic variables show hard X-ray spectra (Cordova and Mason, 1983). Hertz and Grindlay (1983) assumed that all sources in \( \omega \) Cen have a thermal bremsstrahlung spectrum of 5 keV. (There were too few IPC counts to measure the source temperatures.) If we assume the same spectrum, we find that the X-ray fluxes of HG A and HG D are about ten times higher in our observation than they were during the \textit{Einstein} IPC observation (Table 2). This conclusion is not dependent on the exact value of the column density to \( \omega \) Cen: a change of column density of 10\% with respect to the value used in Table 2 would lead to a change in

### Table 1. X-ray sources in \( \omega \) Cen. The estimated uncertainty in the \textit{EXOSAT} positions is 10\".

<table>
<thead>
<tr>
<th>Source</th>
<th>\textit{Einstein} IPC count rate (counts s(^{-1}))</th>
<th>\textit{EXOSAT} CMA count rate (counts s(^{-1}))</th>
<th>\textit{EXOSAT} Position ( \alpha (1950) ), ( \delta (1950) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG A</td>
<td>0.0070</td>
<td>0.0021 ± 0.0005</td>
<td>13(^h)22(^m)50(^s)00(^'') 04(^m)21(^s)00(^'')</td>
</tr>
<tr>
<td>HG B</td>
<td>0.0050</td>
<td>&lt;0.00020(^b)</td>
<td>13(^h)24(^m)28(^s)3 03(^m)51(^s)</td>
</tr>
<tr>
<td>HG C</td>
<td>0.0061</td>
<td>&lt;0.00020(^b)</td>
<td></td>
</tr>
<tr>
<td>HG D</td>
<td>0.0048</td>
<td>0.0020 ± 0.0003</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) From Hertz and Grindlay (1983)
\(^b\) 3\(\sigma\) upper limit

### Table 2. 0.5–4.5 keV fluxes and de-reddened luminosities for two assumed source spectra

<table>
<thead>
<tr>
<th>5 keV thin thermal</th>
<th>40 eV black body</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_E ) (^a)</td>
<td>( L_x ) (^a)</td>
</tr>
<tr>
<td>erg cm(^{-2}) s(^{-1})</td>
<td>erg s(^{-1})</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>( 2.8 \times 10^{-13} )</td>
<td>( 9.5 \times 10^{32} )</td>
</tr>
<tr>
<td>( 2.0 \times 10^{-13} )</td>
<td>( 6.8 \times 10^{32} )</td>
</tr>
<tr>
<td>( 2.4 \times 10^{-13} )</td>
<td>( 8.3 \times 10^{32} )</td>
</tr>
<tr>
<td>( 1.9 \times 10^{-13} )</td>
<td>( 6.5 \times 10^{32} )</td>
</tr>
</tbody>
</table>

\( EXOSAT \)CMA observation

| HG A | \( <2.2 \times 10^{-13} \) | \( <75. \times 10^{32} \) | \( <0.10 \times 10^{-13} \) | \( <0.55 \times 10^{32} \) | \( <380. \times 10^{32} \) |
| HG B | \( <2.2 \times 10^{-13} \) | \( <75. \times 10^{32} \) | \( <0.10 \times 10^{-13} \) | \( <0.55 \times 10^{32} \) | \( <380. \times 10^{32} \) |
| HG C | \( <2.2 \times 10^{-13} \) | \( <75. \times 10^{32} \) | \( <0.10 \times 10^{-13} \) | \( <0.55 \times 10^{32} \) | \( <380. \times 10^{32} \) |
| HG D | \( 23. \times 10^{-13} \) | \( 78. \times 10^{32} \) | \( 0.10 \times 10^{-13} \) | \( 0.57 \times 10^{32} \) | \( 400. \times 10^{32} \) |

\(^a\) \( N_H = 7.3 \times 10^{20} \text{ cm}^{-2} \)
\(^b\) Distance = 5.1 kpc
the X-ray luminosities for the assumed 5 keV spectra of less than 2\%.

Cataclysmic variables do not always have hard spectra. Very soft spectra, with characteristic black-body temperatures $kT \sim 25$–30 eV have been observed during outbursts of the dwarf novae SS Cyg (Cordova et al., 1980), U Gem (Cordova et al., 1984) and VW Hya (Van der Woerd et al., 1985). The spectrum of AM Her shows a soft component, with $kT \sim 46$ eV, with a luminosity comparable to that of its hard spectral component (Heise, 1982). For a known count rate in the Einstein IPC detector the predicted count rate in the EXOSAT CMA detector will be much higher for a soft source than for a hard source. If we assume a black body spectrum of temperature $kT = 40$ eV for the sources HG A and HG D, the X-ray luminosities in the 0.5–4.5 keV band are the same within the errors for the Einstein and EXOSAT observations and substantially lower than the luminosities found with an assumed hard spectrum. This is also shown in Table 2.

The upper limits that we can set to the fluxes of HG B and HG C depend strongly on the source temperature (Table 2). For the softest spectra some decrease in luminosity since the Einstein observation is required to explain our nondetection. However, the non-detection of HG B and HG C with EXOSAT is compatible with constant fluxes if the spectra of these sources are hard.

The estimated X-ray luminosities for assumed 40 eV spectra depend strongly on the exact value of the column to $\omega$ Cen: a change in the column density of 10\% leads to a change in the X-ray luminosities for assumed soft spectra of $\sim 15\%$. As the values derived from the Einstein and EXOSAT count rates change in a similar way, the uncertainty in the column density does not affect our conclusions.

4. Discussion

If sources HG A and HG D have hard ($kT \sim 5$ keV) spectra, both sources have increased their X-ray luminosities between the Einstein and EXOSAT observations by a factor of $\sim 10$. Their X-ray luminosities during the EXOSAT observation would be higher than those of cataclysmic variables observed in the galactic plane.

Therefore we prefer to interpret the observations as indicating that the spectra of sources HG A and HG D are very soft, of the order of 40 eV. We have taken a look at the Einstein data base, and confirmed that the IPC pulse height analysis is consistent with such an interpretation. This means that the X-ray luminosities of HG A and HG D need not have changed significantly between the Einstein and EXOSAT observations, and are comparable to those of other cataclysmic variables. The bulk of the luminosity would reside in the ultraviolet spectral region. HG A and HG D could be AM Her systems. If their X-ray spectra are composite, with both a hard and a soft component – like the spectrum of AM Her itself – the Einstein count rate is due to the hard component, and the EXOSAT count rate mainly to the soft component.

They could also be dwarf novae in outburst. We consider this unlikely, as the probability is small that both systems would be undergoing an outburst during both the Einstein and the EXOSAT observation.

An interesting possibility is that HG A and HG D are nova-like variables. It has been noted that the optical and ultraviolet properties of nova-like variables are similar to those of dwarf novae in outburst (e.g. Warner, 1976). If this similarity also holds for the X-ray properties, one would expect several nova-like variables to have very soft X-ray spectra. The fact that nova-like variables such as T Aur, DQ Her and UX UMa, although bright in the optical, are not seen with hard X-ray detectors (Cordova and Mason, 1983), could be explained this way.

The derived X-ray luminosities of the low-luminosity sources in globular clusters depend critically on the characteristic temperatures assumed. Hertz and Wood (1985) derive the luminosity distribution of low-luminosity globular cluster X-ray sources under the assumption that all sources have hard spectra. Their results will have to be revised if a significant fraction of the sources in fact has a very soft spectrum. In the extreme case that all sources have the same very soft spectrum, the revision will only shift the distribution to lower X-ray luminosities. In the more likely case that there is a spread in temperatures, some sources being soft and others hard, both form and position of the X-ray luminosity distribution will change.

To derive a theoretical luminosity distribution Hertz and Wood assume that the ratio between X-ray and bolometric luminosity is $\sim 0.1$ for all sources. This assumption may also have to be revised: for a 40 eV black body the ratio is $\sim 1.4 \times 10^{-3}$, for a 25 eV black body $\sim 3 \times 10^{-6}$. Hence the bolometric luminosity distribution will be even more affected by the presence of soft X-ray sources than the X-ray luminosity distribution.

If the sources listed by Hertz and Grindlay with X-ray luminosities in excess of $10^{33}$ erg s$^{-1}$ have soft X-ray spectra, their X-ray luminosities can be lower by an appreciable factor. This would weaken the argument by Verbunt et al. (1984) that the brightest of the low-luminosity sources in globular clusters are too bright to be cataclysmic variables.

5. Epilogue

In principle a source-finding algorithm that uses the point spread function is more accurate and sensitive than the sliding-box algorithm used for this paper. In a preliminary analysis of our observation using such an improved algorithm we detect several additional sources. We intend to proceed with the investigation of these sources once the exact nature of the point spread function and background variations have been clarified (see EXOSAT Express no. 12, p. 67).

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References


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