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A search for X-ray evidence of a compact companion to the unusual Wolf-Rayet star HD 50896 (EZ CMa)

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Abstract

We analyze results of a ≈ 25 ksec ASCA X-ray observation of the unusual Wolf-Rayet star HD 50896 (= EZ CMa). This WN5 star shows optical and ultraviolet variability at a 3.766 day period, which has been interpreted as a possible signature of a compact companion. Our objective was to search for evidence of hard X-rays (≥ 5 keV) which could be present if the WN5 wind is accreting onto a compact object.

The ASCA spectra are dominated by emission below 5 keV and show no significant emission in the harder 5–10 keV range. Weak emission lines are present, and the X-rays arise in an optically thin plasma which spans a range of temperatures from ≤ 0.4 keV up to at least ≈ 2 keV. Excess X-ray absorption above the interstellar value is present, but the column density is no larger than $N_H \sim 10^{22}$ cm^{-2}. The absorption-corrected X-ray luminosity L_x (0.5–10 keV) $= 10^{32.85}$ erg s^{-1} gives $L_x/L_{bol} \approx 10^{-6}$, a value that is typical of WN stars. No X-ray variability was detected.

Our main conclusion is that the X-ray properties of HD 50896 are inconsistent with the behavior expected for wind accretion onto a neutron star or black hole companion. Alternative models based on wind shocks can explain most aspects of the X-ray behavior, and we argue that the hotter plasma near ~ 2 keV could be due to the WR wind shocking onto a normal (nondegenerate) companion. © 1998 Elsevier Science B.V.

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1. Introduction

The WN5 star HD 50896 (= EZ CMa) ranks as one of the most unusual Wolf-Rayet stars known. It shows optical and ultraviolet variability at a well-established 3.766 d period, but the origin of this periodicity is not well understood. Firmani et al. (1980) concluded that this periodicity could be explained by a companion of mass $1.3(\pm 0.4)\,M_\odot$. In the context of current evolutionary models for mas-

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sive binary systems, such a companion would most likely be a neutron star or perhaps a low-mass black hole. Such WR + c systems could evolve from massive O-type binaries via mass transfer and a supernova explosion (Van den Heuvel, 1976; Moffat, 1992; De Donder et al., 1997). This is an intriguing possibility for HD 50896 since it lies at a distance $z = 315$ pc below the galactic plane, assuming a stellar distance of 1.8 kpc (Howarth & Schmutz, 1995), which could be the result of recoil from a previous supernova explosion.

However, the presence of a compact companion around HD 50896 has been questioned, and in general there is little convincing observational evidence for the existence of WR + c systems. Only a few plausible WR + c candidates have been identified, of which Cyg X-3 is the most compelling (Van Kerkwijk et al., 1996). In the case of HD 50896, other mechanisms besides binarity have been proposed to explain the 3.766 d periodicity. For example, St. Louis et al. (1995) have argued that the periodicity may be linked to the existence of a corotating region where slow and fast wind streams from a single star interact. Such corotating structures, along with precession effects, have also been cited by Duijsens et al. (1996) as possible explanations of the variability. Arguments against binarity based on variations in spectral line shapes have been given by Underhill & Yang (1991) and Georgiev & Ivanov (1995).

Close scrutiny of candidate WR + c systems such as HD 50896 is needed in order to search for evidence of compact companions, thus providing a direct observational test of current models of massive binary evolution. X-ray observations with good high-energy sensitivity provide an excellent search technique since accretion of the WR wind onto a compact companion is generally expected to produce absorbed high-luminosity X-rays at temperatures of at least several keV. HD 50896 is indeed known to be a strong X-ray source, but previous studies give conflicting results for the X-ray temperature (kT) and absorption (N_H)[4]. As a result, several different explanations of the origin of the X-rays have emerged.

Using Einstein data for HD 50896, Moffat et al. (1982) reported absorbed emission with $N_H \sim 10^{22}\,\mathrm{cm}^{-2}$ and $kT \approx 0.5$ keV, as well as a phase-dependent count rate. They concluded that the X-rays originate mainly in the outer regions of the wind as a result of shocks, and hypothesized that the variable component might be induced by a colliding wind shock with the putative companion. In contrast, a subsequent analysis of Einstein data by White & Long (1986) concluded that the X-rays could be due to accretion onto either a low-mass black hole or (less likely) a white dwarf companion, but not onto a neutron star. More recently, ROSAT PSPC observations analyzed by Willis & Stevens (1996) detected only softer X-rays at $kT \approx 0.2$–0.3 keV, with no significant absorption above the interstellar value and no obvious phase dependence. They concluded that this soft emission is wind-related, probably originating in radiative shocks far out in the wind.

The ROSAT and Einstein observations summarized above provide no spectral coverage at energies above 4 keV. As a result, any hard X-ray emission from a compact companion could have escaped detection. Simulations show that most of the X-rays originating from accretion onto a neutron star companion buried deeply in the wind of HD 50896 ($N_H \sim 10^{24}\,\mathrm{cm}^{-2}$) would emerge at energies above ~ 4 keV. In order to search for such hard emission, we have obtained a ≈ 25 ksec pointed observation of HD 50896 using the Advanced Satellite for Cosmology and Astrophysics (ASCA). The ASCA detectors are sensitive in the energy range ≈ 0.5 keV–10 keV, and thus provide a more definitive search for accretion-induced X-rays than was possible with either ROSAT or Einstein.

The ASCA spectra show no significant X-ray emission above ≈ 5 keV. This absence of hard emission, along with estimates of the absorption and X-ray luminosity obtained from spectral fits, argue strongly against accretion onto a compact companion. Alternative models based on wind shocks can explain most aspects of the X-ray behavior. However, such models require radiative shocks in the outer wind to explain the softer emission seen by

[4] X-ray absorption is usually expressed in terms of N_H, the equivalent neutral hydrogen column density toward the source.

ROSAT as well as a colliding wind shock to explain the hotter plasma revealed by ASCA. We argue that the companion needed to form a colliding wind shock may be a normal (nondegenerate) star, rather than a compact object.

2. ASCA observations and data reduction

The ASCA observation began at 0716 UT on 1995 October 28 (MJD = 50018.303) and ended at 0510 UT on October 29, thus spanning ≈22 h. Assuming binarity and using the ephemeris of Lamontagne et al. (1986), the midpoint of the observation would correspond to orbital phase $\phi = 0.73$, with the entire observation covering phases $\phi = 0.61$–0.86. At $\phi = 0$ the WR star is in front of the putative companion.

All four instruments were operating in parallel, consisting of two solid-state imaging spectrometers (SIS0 and SIS1) and two gas-imaging spectrometers (GIS2 and GIS3). The SIS and GIS passbands are ≈0.5–10 keV and ≈0.8–11 keV respectively. The SIS provide better spatial resolution and energy resolution ($\Delta E/E \approx 3.5\%$ at 6.7 keV), but the GIS are more sensitive at higher energies. Further details on ASCA instrumentation can be found in Tanaka et al. (1994).

Data reduction followed standard procedures using software provided by the High Energy Astrophysics Science Archive Research Center (HEASARC). Data editing removed data taken at low Earth elevation angles and during times of high particle background, as well as hot and flickering SIS CCD pixels. We also excluded data taken during the first 1.1 ksec of the observation to allow for post-maneuver attitude stabilization.

Spectra and light curves were extracted using circular regions of radii 3.4′ (SIS) and 4.2′ (GIS) centered on the source peak. Background was extracted in source-free detector regions well away from the primary source peak. After background subtraction, SIS0 yielded 1180 net source counts in 20 704 s of usable exposure time (average count rate = 0.057 counts s^{-1}), while SIS1 gave 862 counts in 20 510 s. SIS1 provides fewer counts since the source was positioned near the edge of the SIS1 CCD boundary, causing some loss of source photons off of the chip. Each GIS gave ≈500 net source counts in ≈23.9 ksec of usable exposure time.

Spectral analysis was undertaken with the XSPEC (vers. 10.0) modeling package (Arnaud, 1996). During spectral analysis, models were fitted to the SIS0 and SIS1 spectra simultaneously in order to provide tighter constraints on fit parameters, and likewise for the GIS2/GIS3 spectra.

3. Results

3.1. ASCA images

Fig. 1 shows the broad-band (≈0.5–10 keV) and hard-band (4–10 keV) SIS0 images. HD 50896 is clearly seen in both images, although its hard-band emission is faint. About 5% of the SIS0 source counts lie above 4 keV, in good agreement with GIS2 which shows ≈6% of the source counts above 4 keV.

Averaging the positions from the SIS0 and SIS1 broad-band images, the X-ray source peak lies at RA(2000) = 06 h 54 m 14.93 s, DEC(2000) = − 23° 55′ 58.2″ with a 90% confidence error circle of radius 40″ (Gotthelf, 1996). The SIMBAD optical position of HD 50896 lies within the X-ray error circle at an offset of 31.4″ from the X-ray peak, giving assurance that the X-ray source is indeed HD 50896. This is further confirmed by a search of the SIMBAD data base, which shows no other catalogued objects within a 2 arc-minute search radius of the X-ray peak.

3.2. ASCA light curves

Fig. 2 shows the broad-band SIS and GIS light curves, where the SIS0 and SIS1 data have been averaged into a single light curve and similarly for GIS2 and GIS3. The data are binned at 512 s intervals with each SIS contributing an average of 25 counts/bin and each GIS contributing 13 counts/bin. There are no large-amplitude fluctuations above the 3σ level in either light curve.

We have also constructed light curves consisting

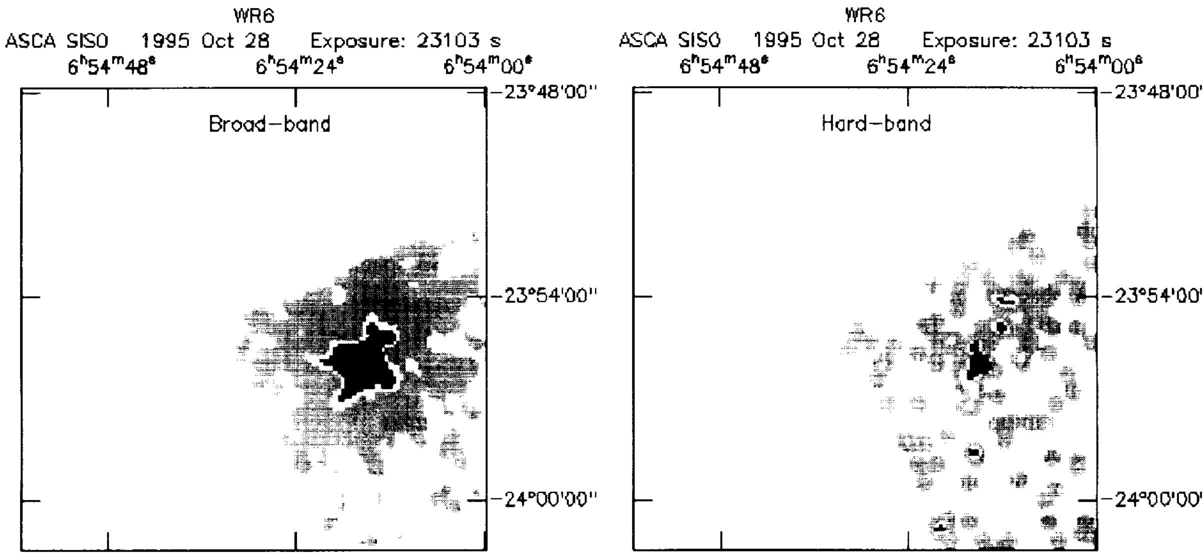

Fig. 1. Smoothed ASCA SIS0 images of HD 50896 acquired on October 28–29 1995. The primary CCD (CCD #1) covers ≈ 11′ × 11′. Left panel is a broad-band image (≈ 0.5–10 keV) and right panel is a hard-band image (4–10 keV). The coordinate overlay (J2000.0) is uncertain by ≈ 30″ in each coordinate.

only of higher energy photons in the 2–10 keV range, using a larger bin size of 1024 s to achieve reliable statistics. These hard-band light curves are similar to the broad-band light curves, showing no large-amplitude variability. The count rate is too low to search for pulsations on timescales of seconds or less.

Statistical analysis of the higher signal-to-noise ratio (S/N) SIS data provides no convincing evidence for variability during the ASCA observation. A χ^2 test of a constant count-rate source fitted to the combined SIS0 + SIS1 broad-band light curves gives a probability of constant count rate $P(\mathrm{const}) = 0.65$ when binned at 512 s and $P(\mathrm{const}) = 0.88$ when binned at 256 s.

3.3. ASCA spectra and spectral models

Fig. 3 shows the background-subtracted SIS0 spectrum of HD 50896 as well as the on-chip background spectrum. The spectrum clearly shows that almost all of the photons emerge at energies below ≈ 5 keV.

3.3.1. Emission lines

The SIS0 spectrum shows considerable structure including line-like features at ≈ 1.81 keV and ≈ 2.44 keV. The first feature is seen in all of the detectors and averaging the data from all four spectrometers gives a line energy of $1.83^{+0.05}_{-0.02}$ keV. We classify this feature as a detection of He-like Si XIII (1.84 keV). The second feature is seen in both SIS0 and GIS2 at an average energy of 2.45 (±0.01) keV, but is not clearly seen in SIS1 or GIS3. We thus classify this feature as a possible detection of blended Li-like and He-like SXIV/XV (2.44–2.45 keV). Emission lines at these energies have also been detected in other WR systems such as the WC8 + O binary γ^2 Velorum (Stevens et al., 1996). The presence of Si XIII and SXIV/XV transitions provides model-independent evidence for hot plasma at temperatures near $\sim 10^7$ K, where these lines emit maximum power.

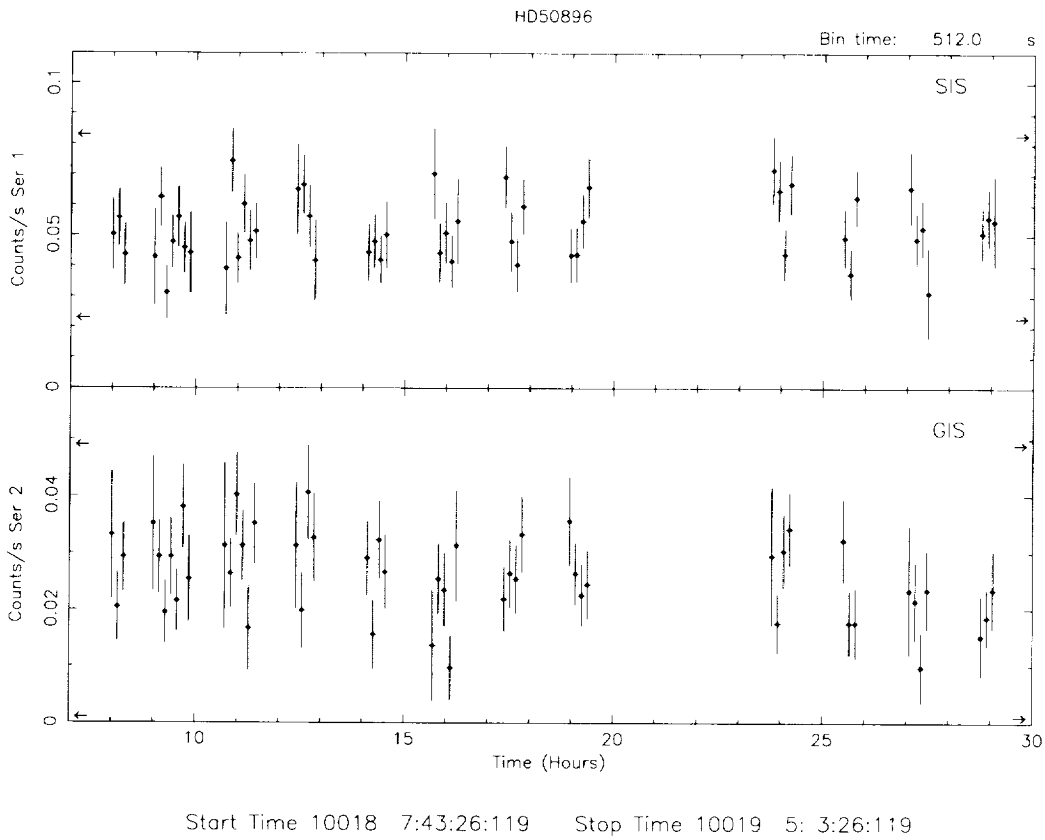

Fig. 2. Broad-band background-subtracted ASCA SIS and GIS X-ray light curves of HD 50896, binned at 512 s intervals. The SIS light curve was constructed by averaging data from the SIS0 and SIS1 detectors ($\approx$0.5–10 keV) and similarly for GIS2 and GIS3 ($\approx$0.8–10 keV). Time is referenced to 0000 UT on 28 October 1995. Error bars are 1σ and arrows mark the level of a $\pm 3\sigma$ fluctuation.

3.3.2. Discrete temperature models

The presence of weak emission lines immediately suggests that the emission is due to an optically thin plasma. Pure continuum models give large fit errors near the line features at 1.84 and 2.44 keV. For example, the absorbed blackbody model with $N_H = 4 \times 10^{20}\,cm^{-2}$ and $kT = 0.28$ keV that gave an acceptable fit to the ROSAT PSPC spectra (Willis & Stevens, 1996) was unacceptable when applied to ASCA SIS (χ^2/dof = 293/136; $\chi^2_{red} = 2.15$). This blackbody model was still unacceptable even if N_H and kT were allowed to deviate from the best-fit ROSAT values.

Optically thin plasma models are able to reproduce the overall spectrum and fits are generally improved by using two discrete temperature components (2T) rather than a single temperature component (1T). This suggests that the emitting plasma is distributed over a range of temperatures, and this is substantiated by differential emission measure analysis (Section 3.3.3). Table 1 compares the best-fit parameters for a 2T model using fixed solar element abundances (2T MEKAL) and a similar model in which the Fe abundance was allowed to deviate from solar (2T VMEKAL). Both models are characterized by a "cool component" and a "hot component",

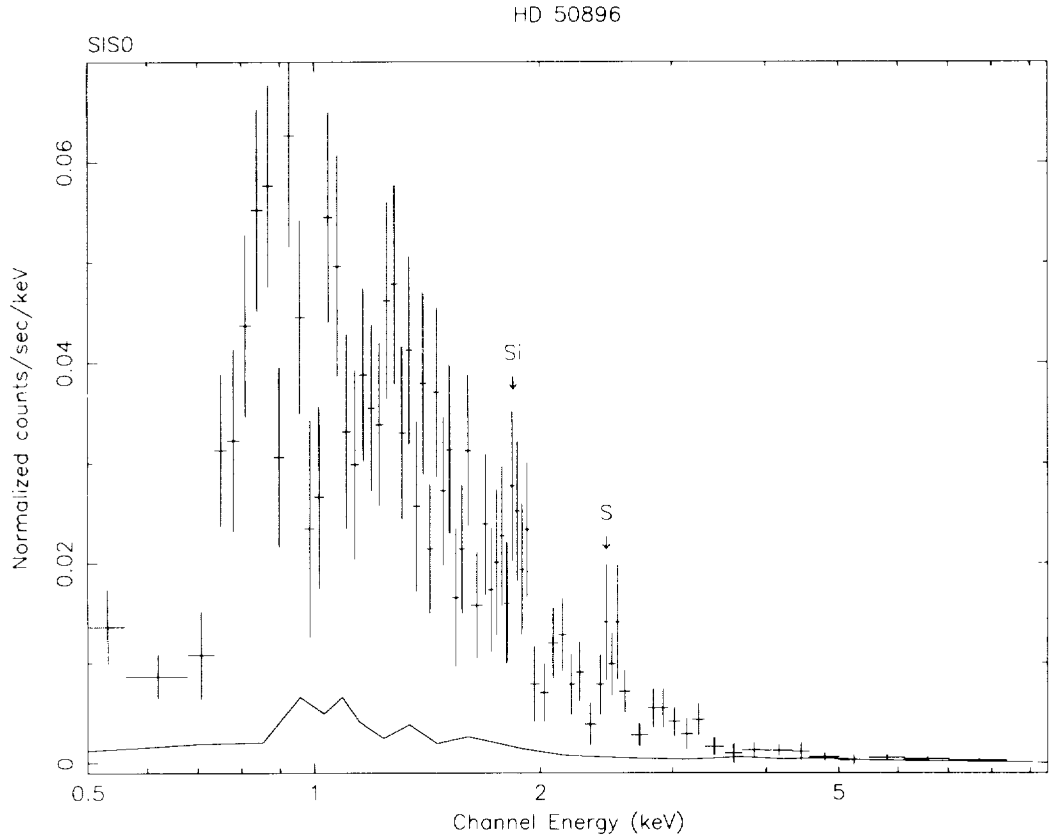

Fig. 3. Background-subtracted ASCA SIS0 spectrum of HD 50896 acquired on October 28–29 1995, binned to a minimum of 10 photons per bin (1180 net counts). Arrows mark probable emission lines from Si XIII and S XIV/XV. The solid line at bottom is the background spectrum extracted from outer regions of the source chip.

with each component allowed to take on different values of temperature (kT), emission measure (EM)[5], and hydrogen column density (N_H). In order to reduce the number of free parameters, the column density of the cool component ($N_{H,1}$) was held fixed at the interstellar absorption value $N_H^{(ism)} = 5 \times 10^{20}\,cm^{-2}$ (Howarth & Phillips, 1986). This strategy was motivated by ROSAT results, which show no significant absorption above the interstellar value for the cool component (Willis & Stevens, 1996). Absorption was modeled using Morrison & McCammon (1983) cross-sections.

[5]EM $= \int n_e n_H dV$, where n_e and n_H are the electron and hydrogen number densities and V is the source volume.

As Table 1 shows, the temperature $kT_1 = 0.6\,(\pm 0.1)$ keV derived for the cool component is not sensitive to abundance assumptions. However, the derived temperature is evidently sensitive to instrumental factors such as bandpass and spectral resolution. The temperature derived for the cool component from ASCA spectra is a factor of two higher than deduced from ROSAT spectra (Willis & Stevens, 1996), but is consistent with the value of 0.5 keV deduced from Einstein data (Moffat et al., 1982). Even though the value of kT_1 is not abundance-sensitive, the fractional contribution of this

Table 1
Spectral fits results for HD 50896

	Solar abundances	Nonsolar abundances
plasma code[a]	MEKAL	VMEKAL
model[b]	($N_{H,1}$ * MEKAL$_1$) + ($N_{H,2}$ * MEKAL$_2$)	($N_{H,1}$ * VMEKAL$_1$) + ($N_{H,2}$ * VMEKAL$_2$)
$N_{H,1}$ (10^{21} cm^{-2})	[0.5]	[0.5]
kT_1 (keV)	0.6 (0.5–0.7)	0.6 (0.5–0.7)
$N_{H,2}$ (10^{21} cm^{-2})	1.4 (0.50–7.5)	4.3 (1.6–7.9)
kT_2 (keV)	3.1 (1.9–3.8)	2.1 (1.6–3.0)
EM$_2$/EM$_{total}$	0.85	0.76
abundances	fixed (solar)	Fe varied[c]
χ^2/dof	165.6 / 132	153.6 / 131
χ^2_{red}	1.25	1.17

Results are from simultaneous fits of SIS0 and SIS1 spectra using XSPEC (vers. 10). Parentheses enclose 90% confidence ranges. Square brackets enclose parameters that were held fixed. [a] MEKAL = Mewe et al. (1995) optically thin plasma code. VMEKAL = variable abundance version of MEKAL. [b] Two-component model, with each component specified by its equivalent hydrogen column density (N_H), plasma temperature (kT), and emission measure (EM). In addition, Fe abundance was varied in the VMEKAL model. [c] Fe abundance converged to a best-fit value Fe = 0.40 (0.27–0.60) × solar, with all other elements fixed at solar abundances. Abundances are referenced to Anders and Grevesse (1989).

cooler plasma to the total emission measure depends strongly on abundances, with nonsolar abundance fits placing a larger fraction of the EM at cooler temperatures.

In contrast, the derived temperature (kT_2) and absorption column ($N_{H,2}$) of the hot component are abundance-sensitive. By examining different models that allow a wider range of abundance variations than shown in Table 1, we obtain a range of values $kT_2 = 1.6$–4.3 keV and $N_{H,2} = (1.4$–$7.0) \times 10^{21}$ cm^{-2}. Thus, our models do not provide precise values for the temperature or absorption column of the hotter plasma, but they do indicate that plasma at temperatures above ~ 1 keV is present and that some of this hotter plasma is absorbed at values well above interstellar. The most likely source of this excess absorption is the strong WR wind.

Finally, Table 1 shows that some improvement in fit accuracy of the discrete 2T models can be achieved by allowing the iron abundance to deviate from solar, with best-fit values converging to Fe = $0.4^{+0.2}_{-0.1} \times$ solar. In addition, the ASCA spectra are consistent with an overabundance of nitrogen, as recently reported on the basis of HST spectra by Boroson et al. (1997). Even so, we do not regard ASCA abundance measurements as definitive due to the deficiencies in existing plasma codes (Mewe et al., 1995) and the inherent difficulties in extracting reliable abundances from low S/N moderate resolution X-ray spectra. Reliable abundance measurements from X-ray spectra for sources as faint as HD 50896 will very likely need to await the improved sensitivity of next-generation X-ray telescopes.

3.3.3. *Differential emission measure models*

The differential emission measure (DEM) function $D(T) = n_e n_H dV/d(\log T)$ measures the relative contribution of plasma at a temperature T to the total spectrum. We have attempted to construct the DEM function of HD 50896 from the SIS spectra using the XSPEC model C6PMEKL, which is an iterative algorithm based on Chebyshev polynomials (Lemen et al., 1989). The shape of the DEM profile is sensitive to abundance assumptions and to the method used to model absorption, but some general conclusions can be drawn, as summarized below.

All DEM models show a local maximum in the DEM function peaking at ≈ 0.7–1.0 keV, with significant emission occurring on either side of this maximum from the ASCA low-energy cutoff at ≈ 0.4 keV up to nearly 2 keV. This confirms that the emission is in fact due to plasma forming over a broad range of temperatures, as already suspected from discrete temperature models. In addition, some (but not all) DEM models show a second peak at ≈ 4–5 keV. This suggests that some plasma up to temperatures as high as ≈ 4–5 keV could be present. However, this higher energy peak may be an unphysical result that arises from our application of the DEM algorithm to low S/N spectra. There is some reason to believe that this is the case since the ≈ 4–5 keV peak is *not* present in DEM reconstructions which allow a significant fraction of the emission to arise at higher absorption levels of $N_H \approx 10^{22}$ cm^{-2}.

3.3.4. Fluxes and X-ray luminosity

The 2T VMEKAL model summarized in Table 1 gives a broad-band flux F_x(0.5–10 keV) = 1.26(1.81) $\times 10^{-12}$ erg cm^{-2} s^{-1}, where the value in parentheses is absorption-corrected. At a distance of 1.8 kpc, the absorption-corrected luminosity is then L_x(0.5–10 keV) = 7×10^{32} erg s^{-1}. Using $L_{bol} = 10^{5.1} L_\odot$ (Howarth & Schmutz, 1995), one obtains $L_x/L_{bol} = 1.4 \times 10^{-6}$. This ratio is quite typical of that found for other WN stars (Fig. 1 of Wessolowski, 1996), and suggests that the X-ray emission of HD 50896 is not atypical for its class.

If the ASCA flux measurement is restricted to the lower energy 0.3–2.5 keV ROSAT bandpass, the observed (absorbed) flux is F_x(0.3–2.5 keV) = 8.9×10^{-13} erg cm^{-2} s^{-1}. This value differs by only $\approx 3\%$ from that measured with the ROSAT PSPC at comparable phase $\phi = 0.70$ on 1992 September 23 (Willis & Stevens, 1996). Thus, there is no evidence that the *soft* X-ray luminosity of HD 50896 changed significantly during the ≈ 3 yr between the ROSAT and ASCA observations. However, our measurements show that $\approx 30\%$ of the observed flux emerges at energies above 2.5 keV, and the temporal behavior of this harder emission is not yet known.

4. Discussion: origin of the X-ray emission

In this section, we reexamine the origin of the X-ray emission from HD 50896 in light of the new ASCA results. We consider both compact companion models and wind shock models.

4.1. X-rays from accretion onto a compact companion

If the 3.766 day periodicity is due to a companion, then the mass function derived by Firmani et al. (1980) gives a companion mass $M_{comp} = 1.3(\pm 0.4) M_\odot$. In the framework of the current evolutionary picture for massive binaries (cf. Van den Heuvel, 1976), a companion of this mass would most likely be a neutron star. However, the companion mass is more uncertain than implied by the formal error bars (Section 4.1.2), and a mass greater than $1.3 M_\odot$ is possible. Thus, a low-mass black hole companion will also be considered. A white dwarf companion is a third possibility, but is very difficult to justify on evolutionary grounds (White & Long, 1986) and will not be considered here.

4.1.1. Accretion onto a neutron star companion

Wind accretion onto a neutron star companion of mass $M_{ns} = 1.3 M_\odot$ could explain the temperature of the hotter emission detected by ASCA, but encounters problems explaining the X-ray luminosity and absorption. Using the results of Davidson & Ostriker (1973), the accretion shock temperature is $kT_{shock} = 0.1 m_H v_{rel}^2 \approx 3.8$ keV, where $v_{rel} \approx 1920$ km s^{-1} is the velocity of the neutron star relative to the WR wind. Here, we have assumed a terminal wind speed $v_\infty \approx 1900$ km s^{-1} (St. Louis et al., 1995) and have adopted $M_{wr} = 10 M_\odot$, which gives a semi-major axis $a = 1.6 \times 10^{12}$ cm ≈ 10 AU. This predicted shock temperature is within the range of values inferred for kT_2 from our discrete temperature models (Section 3.3.2).

Adopting a mass loss rate $\dot{M}_{wr} \approx 8 \times 10^{-5}$ $M_\odot$ yr^{-1} (Leitherer & Robert, 1991) and assuming a steady spherically-symmetric wind, the accretion rate onto the neutron star is $\dot{M}_{acc} = 7 \times 10^{-10} M_\odot$ yr^{-1} (Eqs. (5)–(7) of Davidson & Ostriker, 1973). The predicted intrinsic X-ray luminosity is then $L_x^{(acc)} =$

5×10^{36} erg s^{-1}, as derived from the well-known relation

$$L_x^{(acc)} = \frac{G M_{ns} \dot{M}_{acc}}{R_{ns}}. \quad (1)$$

The predicted accretion luminosity exceeds that measured with ASCA by more than three orders of magnitude. Also, the numerical simulations of Stevens & Willis (1988) predict values of $L_x^{(acc)} \sim 10^{35}$–10^{36} erg s^{-1}, again much larger than observed.

The above simplified calculation of $L_x^{(acc)}$ (Eq. (1)) ignores several effects such as gravitational focusing of the wind by the compact object, X-ray radiation pressure on the wind, and X-ray heating and ionization of the WR wind by the compact object. The refined numerical calculations of Blondin et al. (1990) indicate that these effects, when considered collectively, tend to increase the predicted accretion rate by about a factor of two over the Davidson & Ostriker results. Thus, a more detailed treatment of the accretion process only worsens the discrepancy between theory and the observed X-ray luminosity.

The predicted absorption column for accretion X-rays originating near the surface of a neutron star orbiting at $a \approx 10$ AU is $N_H \sim 10^{24}$ cm^{-2} (cf. Moffat & Seggewiss, 1979). This value is about two orders of magnitude larger than that derived for the hot component from ASCA spectral fits (Table 1), presenting an additional problem for the accretion interpretation.

Because of the above discrepancies, it seems very unlikely that the X-ray emission of HD 50896 arises from accretion onto a neutron star companion. However, the presence of a neutron star cannot be conclusively ruled out using X-ray data alone. If the neutron star were rotating near break-up, accretion could be inhibited by centrifugal effects (Davidson & Ostriker, 1973). Also, some models predict small neutron star radii which would give rise to very hot X-ray emission at $kT \sim 100$ keV (cf. the review of King, 1995). Such high-temperature emission, if present, would not be detected by ASCA.

4.1.2. Accretion onto a black hole companion

The formal error bars associated with the companion mass $M_{comp} = 1.3\,(\pm 0.4)\,M_\odot$ derived by Firmani et al. (1980) reflect only the uncertainty in the mass of the WR star, which they assumed to be $M_{wr} = 10 \pm 5\,M_\odot$. An additional source of uncertainty is the orbital inclination, which is not well known (McLean, 1980). The polarization model used to derive i invokes several assumptions, including a circular orbit. The derived orbit is in fact noncircular, ($e = 0.34$; Firmani et al., 1980) and this can lead to spurious inclination estimates (Brown et al., 1982). If the value of i inferred from polarization models is incorrect, then the companion may be more massive than $1.3\,M_\odot$, leaving open the possibility that it is a low-mass black hole or perhaps even a normal intermediate mass star.

Two general possibilities exist for producing X-ray emission from accretion onto a black hole, namely (i) spherical accretion onto a diskless black hole, and (ii) disk accretion. The radiation from spherical diskless accretion should emerge either in the optical or as very high energy (≥ 50 keV) X-rays and γ rays (Shapiro & Lightman, 1976), and is thus not compatible with ASCA results. In a binary system it is more likely that an accretion disk will form around the black hole, and in that case the efficiency η for converting rest mass energy into radiation will be high. The total radiative luminosity is $L_{rad} \sim \eta \dot{M}_{acc} c^2$, where $\eta \approx 0.06$–0.42 (Eq. (14.5.1) of Shapiro & Teukolsky, 1983). This efficiency is comparable to or greater than that for neutron star accretion ($\eta \approx 0.1$). The predicted accretion rate for a $\sim 2\,M_\odot$ black hole is only a few times larger than for a neutron star, and is of order $\dot{M}_{acc} \sim 10^{-9}\,M_\odot$ yr^{-1}. The total radiative luminosity from a black hole is then $L_{rad} \sim 10^{36}$–10^{37} erg s^{-1}. For the accretion rates considered here, most of this luminosity should emerge as X-rays (Eq. (14.5.38) of Shapiro & Teukolsky, 1983), but the observed L_x is several orders of magnitude below this prediction.

4.2. Wind shocks

Wind shock models predict X-ray luminosities that are in general agreement with the observed value, and thus provide an attractive alternative to compact companion models. Two possibilities must be considered here, namely (i) radiative wind shocks that are set up by line-driven instabilities in the powerful WR wind, and (ii) a colliding wind shock that forms when the WR wind impacts either the surface or wind of the putative companion. A third possibility, that the X-ray emission is due to a collision between the WR wind and the surrounding ring nebula S 308 seems to be ruled out by ROSAT observations (Willis & Stevens, 1996).

4.2.1. Radiative wind shocks

Theoretical models indicate that X-ray emitting shocks can form in the winds of single massive OB stars as a result of line-driven instabilities (Lucy & White, 1980; Lucy, 1982). This mechanism might also operate in WR stars, and Willis & Stevens (1996) concluded that radiative wind shocks are the most likely explanation of the soft X-ray emission ($kT \approx 0.2$–0.3 keV) that was detected by ROSAT.

In the formulation of Lucy (1982), the post-shock temperature of the X-ray emitting plasma is given by

$$T_{\rm shock} = \frac{3}{16} \frac{\mu \, m_{\rm H}}{k} U^2, \tag{2}$$

where U is the shock speed, μ is the mean molecular weight in the wind, $m_{\rm H}$ is the mass of atomic hydrogen, and k is Boltzmann's constant. Under simplifying assumptions, the shock speed can be written as

$$U^2 = 2 \nu v_s v_{\rm wind}, \tag{3}$$

where v_s is the isothermal sound speed in the wind and ν is a dimensionless free parameter of the theory. For WR stars, typical shock speeds are $U \approx (280\text{–}340)\sqrt{\nu}$ km s^{-1}, with corresponding shock temperatures of $kT_{\rm shock} \approx (0.1\text{–}0.3)\nu$ keV. Here, we have considered values of μ in the range $0.67 \leq \mu \leq 1.33$, where the lower limit corresponds to Population I stars and the upper limit corresponds to a fully-ionized helium wind (Lang, 1980). A comparison with observations suggests $\nu \leq 1$ (Table 1 of Lucy, 1982), in which case the X-ray emission should be soft with $kT_{\rm shock} \leq 0.3$ keV.

Although the above temperatures are compatible with ROSAT results, they are too low to explain the range of temperatures deduced from ASCA data. The radiative shock model could at best explain only the softer emission that is present in the ASCA DEM function at energies below the peak at ≈ 0.7–1.0 keV. Detailed arguments in favor of the radiative wind shock interpretation for the softer emission can be found in Willis & Stevens (1996).

Although the softest X-rays detected by ASCA and ROSAT might be due to radiative wind shocks, this interpretation has not yet received broad observational support for WN-type stars in general. We call attention to the study of Wessolowski (1996), who analyzed ROSAT observations of a sample of 61 putatively single WN-type stars and found no correlation between L_x and either wind momentum or kinetic wind luminosity. If the softer X-rays from WN stars do indeed arise in radiative wind shocks, then the absence of such correlations is puzzling. A summary of these issues and of current approaches to wind shock modeling can be found in Feldmeier et al. (1997).

4.2.2. WR wind shocking onto a nondegenerate companion

We assume now that HD 50896 has a companion, but that the companion is a normal (nondegenerate) star. Since the inferred mass of the companion is low, the strong WR wind would overwhelm any wind from the companion and a shock would form at or near the companion surface. This is the case of a colliding wind shock with one dominant wind discussed by Luo et al. (1990) and Stevens et al. (1992), and can be thought of in simplest terms as a hypersonic WR wind impacting a hard sphere. This model has been applied to another candidate WR + c system, the runaway WN7 star HD 197406 (Marchenko et al., 1996).

By conservation of energy the predicted X-ray luminosity for a WR wind shocking onto a nondegenerate companion is

$$L_x = (f/2)\dot{M}_{\rm acc} v_{\rm wind}^2, \tag{4}$$

where f is the efficiency for converting wind kinetic energy into X-rays and the accretion rate depends on the geometrical cross-section of the companion as $\dot{M}_{acc} = \dot{M}_{WR} R^2_{comp}/4a^2$ (White & Long, 1986). If the binary system is coeval then the companion would be on or approaching the main-sequence and a mass of $1.3\,M_\odot$ would correspond to spectral type F and a radius $R_{comp} \approx 1.2\,R_\odot$. This radius, along with the mass loss parameters given in Section 4.1.2, yields $L_x \approx f(6 \times 10^{34})\,\mathrm{erg\,s^{-1}}$. Thus, this mechanism could account for the X-ray luminosity of HD 50896 if the conversion efficiency were about one percent ($f \approx 0.01$). In fact, lower efficiencies would be allowed since this mechanism only needs to account for the X-ray luminosity of the hotter component if the softer emission arises via a different process such as radiative wind shocks. An efficiency of one percent is consistent with numerical shock models which give values of f ranging from less than 0.01 up to 0.16 (Luo et al., 1990).

In the strong shock limit discussed by Stevens et al. (1992), the predicted shock temperature is (analogous to Eq. (2))

$$T_{shock} = \frac{3}{16}\frac{\bar{m}}{k} v^2_{wind}, \tag{5}$$

where $\bar{m}$ is the average mass per particle in the wind. Taking $v_{wind} = v_\infty = 1900\,\mathrm{km\,s^{-1}}$, one obtains $kT_{shock} = 4.2\bar{m}$ keV, where $\bar{m}$ is expressed in units of the solar abundance value 0.6×10^{-24} g. Thus, for solar wind abundances one expects a shock temperature $kT_{shock} \approx 4.2$ keV, but if the WR wind is hydrogen-depleted then values of $\bar{m}$ could be twice solar (Stevens et al., 1992), and the shock temperature would be proportionately higher. ASCA fits give temperatures that are slightly below these estimates (Table 1), but this difference could easily be accounted for by uncertainties in methods used to determine the terminal wind velocity (Prinja et al., 1990) and by the possibility that for a companion at ≈ 10 AU the wind may have only reached $\approx 90\%$ of its terminal speed. Given these uncertainties, a predicted shock temperature as low as $kT_{shock} \approx 2\bar{m}$ keV is not unreasonable.

Although the WR wind shocking onto a close nondegenerate companion could very likely explain the hotter plasma seen in ASCA spectra as well as the X-ray luminosity, this model is not without problems. Specifically, (i) the probability of finding a low-mass normal stellar companion in orbit around HD 50896 is low if the WR progenitor was an O-type star, and (ii) modulation of the observed X-ray flux with orbital phase should be present, but was not detected in a series of previous ROSAT observations (Willis & Stevens, 1996).

The probability that HD 50896 has a low-mass normal stellar companion is low since that would seem to require a progenitor binary system with a high mass ratio, consisting of a massive O-type primary and a low-mass secondary. The study of Garmany et al. (1980) shows that binaries containing an O-type component rarely have mass ratios $q = M_1/M_2 \geq 3$. Even so, some high mass ratio systems such as 16 Sgr ($6 \leq q \leq 11$) do exist and systems with even higher mass ratios should occur (Abt & Levy, 1978) but would be difficult to detect. It is also important to recall that the mass of the putative companion to HD 50896 is not well-known as a result of uncertainties in the mass of the WN star and the orbital inclination (Section 4.1.2). A companion mass $M_{comp} \approx 2$–$3\,M_\odot$ may not be out of the question, which would correspond to an early A-type star if on the main sequence.

The failure to detect X-ray modulation tied to the 3.766 d orbital period in a sequence of eight previous ROSAT observations of HD 50896 (Willis & Stevens, 1996) may also pose problems for the shocked companion model. If the hotter plasma detected by ASCA does originate at or near the companion surface, then one would expect to see a change in the overlying absorption and in the observed (absorbed) X-ray flux as the companion moves in front of and then behind the WR star. Such changes in attenuation and spectral hardness have been seen in other candidate colliding wind shock systems such as γ^2 Velorum (Willis et al., 1995; Stevens et al., 1996).

If such orbital X-ray modulation is indeed present in HD 50896, we can only offer a few possible reasons as to why it might have escaped detection with ROSAT. These include, (i) lack of ROSAT sensitivity to the harder emission above ≈ 2.5 keV (softer emission formed by radiative wind shocks far out in the WN5 wind is not expected to undergo strong modulation, but harder emission from a colliding wind shock along the line-of-centers should be modulated), (ii) incomplete ROSAT phase coverage (orbital phases $0.71 \leq \phi \leq 1.0$ have not yet been sampled), (iii) an orbital geometry that is not conducive to X-ray modulation (e.g. low orbital inclination). The first two possibilities could be tested in follow-up observations using instruments with good high energy coverage (e.g. ASCA or AXAF) and tighter orbital phase sampling. Such observations might be worthwhile given that phase-dependent X-ray variability was reported on the basis of Einstein observations (Moffat et al., 1982), and that the X-ray variability shown by other candidate colliding wind systems such as γ^2 Velorum is sharply-peaked in orbital phase.

5. Conclusions

We have presented new ASCA observations of the unusual WR star HD 50896 (= EZ CMa) which help clarify the nature of its X-ray emission. The main conclusions of this study are the following:

1. The ASCA spectra reveal weak emission lines and spectral fits show that the X-ray emission arises in a multi-temperature optically thin plasma. Plasma is present over a broad range of temperatures from ≤ 0.4 keV up to at least ≈ 2 keV, but there is no significant emission above 5 keV. Some absorption above the interstellar value is present, which is most likely due to the WR wind, but spectral fits constrain the column density to values $N_H \lesssim 10^{22}$ cm^{-2}.
2. No significant X-ray variability ($\geq 3\sigma$) was seen during the ≈ 22 h spanning the ASCA observation, down to a sensitivity-limited time resolution of 512 s. A comparison with a previous ROSAT observation shows no significant change in the soft-band flux (0.3–2.5 keV) over a timespan of ~ 3 yr. However, $\approx 30\%$ of the X-ray flux emerges at energies above 2.5 keV and the temporal properties of this harder emission are not yet known.
3. The absorption-corrected X-ray luminosity of HD 50896 is L_x (0.5–10 keV) = 7×10^{32} erg s^{-1} at an assumed distance of 1.8 kpc. This gives $L_x/L_{bol} = 1.4 \times 10^{-6}$, which is typical of other WN stars.
4. Models which assume the X-ray emission arises from accretion onto a neutron star or low-mass black hole companion are not consistent with ASCA results. Such models either overestimate L_x, fail to reproduce the observed temperature structure, or predict much higher column densities than deduced from the ASCA spectra.
5. Radiative wind shock models based on the formulation of Lucy (1982) provide a possible means of explaining the softer X-ray emission detected by ASCA and ROSAT (Willis & Stevens, 1996), but such models cannot explain the hotter plasma above ~ 1 keV that is clearly present.
6. The temperatures of the hotter plasma and the observed X-ray luminosity are compatible with estimates derived from a model in which the WR wind shocks onto the surface of a normal (non-degenerate) companion. However, the probability of finding such a companion around HD 50896 is low and some variability of the X-ray flux with orbital phase is anticipated, but has not yet been detected.

In summary, we find no compelling evidence that the X-ray emission of HD 50896 is due to wind accretion onto a neutron star or black hole companion. The X-ray spectrum, X-ray luminosity, and L_x/L_{bol} ratio are quite similar to those of other WN stars, giving no reason to believe that the X-ray emission of HD 50896 is anomalous. Wind shock models can account for most aspects of the X-ray behavior, but require both a radiatively-driven wind shock component to account for the soft emission seen in ROSAT observations and a colliding wind component to reproduce the hotter emission revealed by ASCA. Additional X-ray observations with tight phase coverage and good high-energy sensitivity are needed to search for variability in the flux at energies above ≈ 2.5 keV, which should occur if the WR wind is in fact impacting a companion in a noncircular orbit.

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