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FINAL REPORT
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Report Period - This report covers the period from 2/1/2001 to 8/31/2002 during which the data were reduced, analyzed and submitted for publication.

Research Publications - The final research paper for this project has been accepted for publication in the Astrophysical Journal (Part I) and is scheduled to appear in the 10 Nov. 2002 issue (vol. 579 , no. 2). The paper is entitled *XMM-Newton and VLA Observations of the Variable Wolf-Rayet Star EZ CMa: Evidence for a Close Companion?*, by S.L. Skinner, S.A. Zhekov, M. Güdel, and W. Schmutz.

Synopsis of Research Results - In this research program, we obtained and analyzed X-ray observations of the unusual Wolf-Rayet (WR) star EZ CMa (HD 50896) using the *XMM-Newton* space-based observatory as well as radio observations using *Very Large Array.* These observations yielded the highest quality X-ray spectrum obtained so far of this enigmatic star, as well as the most complete picture of the radio spectral energy distribution at centimeter wavelengths based on *VLA* data acquired at five frequencies. We were able to use these data to place tight constraints on X-ray and radio emission processes, which are in general not well understood in WR stars. The X-ray observations yielded a new discovery - namely the presence of a hard X-ray emission component with an inferred temperature of at least $\sim$3 keV. This emission had escaped detection in a previous X-ray observation with the *ASCA* observatory, and the ability to detect such emission with *XMM-Newton* attests to its much higher sensitivity. We conclude that this hard emission could be produced by shock-heating as the powerful WR wind impacts the surface of a faint lesser companion star. Thus, our results provide indirect support for the idea that the unusual variabililty of EZ CMa is due to a fainter companion that has so far managed to escape detection. The radio data are in very good agreement with expectations for free-free emission from the WR wind and allow us to obtain a reliable estimate of the WR mass loss rate.

Summary of Observations - The *XMM-Newton* observations were obtained on 29 - 30 October 2001 during the AO-1 Guest Observer program. Our X-ray analysis focused on data from the European Photon Imaging Camera (EPIC). The *VLA* observations were obtained during a 3.5 hour interval on 1999 Oct. 19 with the array in hybrid BnA configuration. Radio continuum data were acquired at five different frequencies 1.42 GHz (21 cm), 4.86 GHz (6 cm), 8.44 GHz (3.6 cm), 14.94 GHz (2 cm), and 22.46 GHz (1.3 cm). These radio data are unique since they provide an excellent snapshot picture of the dependence of the radio flux on frequency obtained over a short time interval and are thus immune to the variability effects which can distort results obtained from non-contemporaneous observations at different frequencies.

Summary of Observational Results - The X-ray spectrum shows prominent emission lines from Mg XI, Si XIII, and S XV ions and was modeled as an absorbed multi-temperature optically thin plasma. Our models definitively show that the plasma is not isothermal. We found that most of the X-ray emission comes from relatively cool plasma at $kT_{cool} \approx 0.6$ keV (7 MK). But a hotter plasma component is clearly present in the spectra and is also confirmed by our imaging analysis, which shows a clear detection of hard photons in the 5 - 10 keV bandpass. Assuming that the hard emission is thermal, the inferred temperature is $kT_{hot} = 3.5$ [3.0 - 4.2] keV, where brackets enclose the 90% confidence range. About one-half of the observed (absorbed) X-ray flux is due to this hotter X-ray component.

The *VLA* observations detected EZ CMa at all five frequencies and the emission is point-like (unresolved) down to our best angular resolution of 0.3 arc-seconds. The *VLA* fluxes increase with frequency according to a power law of the form $S_\nu \propto \nu^\alpha$ where $\alpha = +0.69 \pm 0.05$. This value of the spectral index α is in excellent agreement with theoretical predictions for free-free emission from an ionized steallar wind. Using a spherical constant-velocity wind model we derive an ionized mass-loss rate for EZ CMa of 3.8×10^{-5} solar masses per year. This comprises the most reliable estimate of the mass-loss rate of EZ CMa obtained to date, and confirms that WR stars are losing mass at extremely high rates via their powerful winds.

What New and Important Has Been Learned?

Although it has been known for more than two decades that WR stars emit X-rays, the mechanisms by which they are able to heat plasma to the multi-million degree temperatures necessary for thermal X-ray emission are poorly understood. This is partially due to the faintness of the X-ray emission - previous X-ray telescopes have simply lacked the sensitivity to acquire good-quality X-ray spectra of WR stars in reasonable amounts of observing time. Thus, there is a paucity of X-ray spectral data that is of suitable quality to test and constrain X-ray emission models. But, the situation is now beginning to improve. The *XMM-Newton* observatory provides the largest effective area ever achieved in an X-ray telescope and its enhanced sensitivity now makes X-ray spectroscopy of fainter WR stars a feasible endeavour. We have thus initiated a long-term effort to obtain good quality X-ray spectra of WR stars and EZ CMa is the second such star to be observed by us with *XMM-Newton*. In a previous study we reported on similar observations of the WR star WR 110 (Skinner et al. 2002, ApJ, 572, 477).

Wolf-Rayet stars are massive hot stars with radiative atmospheres. Unlike cool stars, they are not believed to have convection zones which could sustain internally-generated magnetic fields. As such, their X-ray emission is thought to be fundamentally different from cooler convective stars like the Sun whose X-ray emission arises in hot plasma that is magnetically confined in coronal loops. In *single* hot WR and O-type stars that are not members of binary systems, the X-ray emission has traditionally been attributed to shocks that are distributed throughout their powerful winds, which have characteristic outflow velocities of ~2000 - 3000 km/s. Theoretical models predict that such X-ray emission should be rather soft, with characteristic temperatures $kT \leq 1$ keV. Thus, the dominant cool emission component in EZ CMa at $kT_{cool} \approx 0.6$ keV could be due to such wind shocks. However, the hotter plasma at $kT_{hot} \approx 3.5$ keV cannot be explained by the traditional radiative wind shock picture. Such high plasma temperatures are not predicted by the standard wind-shock model. Thus, a different mechanism is needed to explain the hotter plasma.

The unambiguous detection of hot X-ray emitting plasma in EZ CMa (and in our previous study of WR 110) presents a challenge to current theories of X-ray emission in hot stars. There are at least two possible solutions to this dilemma. Either a new theory of X-ray emission in hot stars is needed, or EZ CMa is not a single star but instead a close binary system. Mechanisms that can produce hot plasma are capable of operating in close binaries, such as shock heating that occurs as the wind of the WR star collides with either the wind of the companion or with the companion's surface. If EZ CMa is indeed a close binary, then the cooler emission detected by XMM-Newton could arise via the traditional radiative shock mechanism operating in the WR wind, while the hotter plasma could be explained by the WR wind shocking onto a fainter companion.

Although there is no *direct* evidence at this time for a companion, previous studies have invoked a putative companion to explain the coherent 3.765 day optical/UV variability. Given that no large radial velocity variations have been detected, one expects that a companion, if present, is less massive than the WR star. Some authors have speculated on the basis of evolutionary models for massive binaries that such a low mass companion could be a neutron star (NS). But this now seems quite unlikely since the observed X-ray luminosity is about three orders of magnitude lower than expected for the WR wind accreting onto a NS companion. This deficit could be explained if accretion were inhibited by a NS rotating near breakup, but we believe a more plausible scenario is that the companion is a normal (nondegenerate) star.

We thus proceed on the assumption that the companion is a normal star that is fainter (and less massive) than EZ CMa and that the 3.765 day optical/UV periodicity is due to orbital motion. Kepler's third law then gives a companion separation of 0.12 AU. We then further assume that the luminosity of the hot X-ray component is due to the WR wind shocking onto the companion. Since the companion is presumed to be less massive, its wind would be overwhelmed by the stronger WR wind and a shock would be set up at or near the companion surface. Using a simple hard-sphere shock models, the radius of the companion needed to explain the X-ray luminosity is $R_{comp} \approx 0.2 - 0.5\ R_{\odot}$. The lower value uses a shock model in which radiative cooling is important while the higher value assumes an adiabatic shock.

We also obtain a prediction of the maximum temperature of the X-ray emitting shock near the companion surface. Using two different wind velocity laws, both of which are plausible, we find that the shock temperature could be as low as $kT_{shock} \approx 2.5$ keV and as high as 7.5 keV. Although there are several uncertainties involved in this calculation (such as the question of whether the WR wind has reached its terminal speed before shocking at the companion surface), the range of inferred shock temperatures encompasses the value $kT_{hot} = 3.5$ keV measured from the X-ray spectra. We thus conclude that both the luminosity and temperature of the hot X-ray component could be accounted for by the WR wind shocking onto a lesser companion at a separation of $\approx$0.12 AU with a radius in the range $R_{comp} \approx 0.2 - 0.5\ R_{\odot}$.

The above range of R_{comp} suggests a late-type companion, and such a companion would not have had time to reach the main sequence if it formed contemporaneously with the massive star EZ CMa. Thus, the companion could be a pre-main-sequence (PMS) object. This possibility is of interest since at least one other WR star, γ^2 Velorum, is now thought to be associated with a population of low-mass PMS stars and a PMS companion was detected at close separation by *Chandra* (Skinner et al. 2001, ApJ, 558, L113; and Pozzo et al. 2000, MNRAS, 313, L23).

In summary, we have found that the WR star EZ CMa emits higher-temperature X-ray emission than is predicted using traditional radiative wind shock X-ray emission models for single stars. We have shown that this hot plasma could be explained by the WR wind shocking onto the surface of a less-massive (fainter) companion star at close separation. Although there is so far no direct detection of such a companion, the presence of hot X-ray plasma and the well-documented 3.765 d optical/UV period of EZ CMa provide a strong argument for binarity.