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FINAL REPORT

"A Study of EUV Emission from the 04f Star Zeta Puppis"

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CONTRACT:	**S-14648-F (ARC # 1278)**
TITLE:	**A Study of EUV Emission from the O4f Star Zeta Puppis**
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CI:	**Dr. John Vallerga (Eureka Scientific, Inc.)**
SUBJECT:	**Final Report**
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INTRODUCTION: We were granted a 60 ks EUVE SW Spectrometer observation of Zeta Puppis during the Cycle I phase, which, due to positional constraints, was not observed until November 1993. Unfortunately, the observation suffered a severe UV leak from two B stars (V magnitudes > 6). It was found that only 9 out of 31 night passes were obtained at the roll angle that removed the UV leak resulting in an effective exposure time of only 20 ks. We presented this discrepancy to Dr. Ron Oliversen (Deputy Project Scientist). He informed us that the problem was related to the catalogs used in the EUVE scheduling. Since the EUVE scheduling only checked for B star contamination down to 6th magnitude, the two stars that caused the contamination were not listed (the EUVE staff has determined that the two B stars are SAO 198848, V=6.4 & SAO 198862, V=8.3). We were told that this was an isolated incident and our proposed science was greatly effected because the contaminated high background would make it very difficult to detect the predicted faint line emission. This is shown in Figure 1 where we see that the expected signal is lost in the noise. In order to avoid this problem, the EUVE scheduling procedure has been modified to incorporate additional catalogs when searching for B stars in the field that go down to 10th magnitude. Dr. Oliversen agreed that our effective 20 ks observation did not allow us to carry out our scientific goal, and recommended that we should re-propose the observation at a significantly larger exposure time. The 3 sigma upper limit deduced from our 20 ks observation, along with our expected 60 ks, and our new proposed 140 ks upper limits are compared to the predicted line emission in Figure 1. Our previous 60 ks observation would have been sufficient to detect the strongest line (O V, 135.8A), if present.

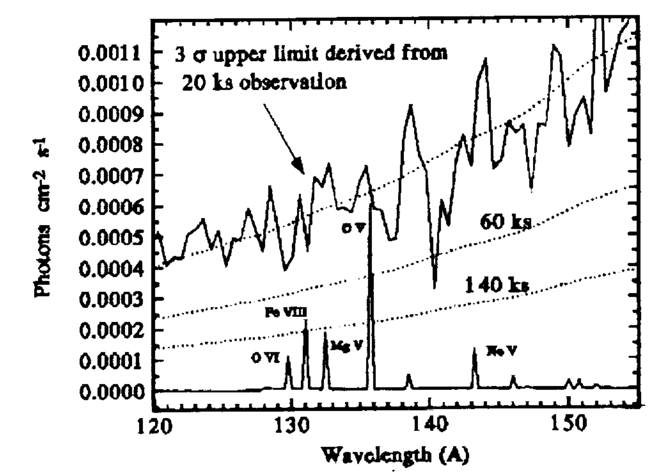

Figure 1. Comparison of the proposed line emission model with 3 σ upper limits. The 5 strongest lines are identified. The dotted lines are the MDF functions provided in the EUVE AO.

Although our primary scientific goal was not achieved under this contract (due to problems beyond our control), the contract funding was used to further our understanding of EUV emission from O stars. Our 20 ks observation did not allow us to carry out our primary objective, i.e., to test the limitations of deeply embedded EUV and X-ray sources. However, it did provide a very useful EUV emission measure upper limit. This upper limit was found to provide a very useful constraint in our analysis of a newly acquired high S/N ROSAT PSPC X-ray spectrum of ξ Pup. In addition, modifications to our stellar wind opacity code have been preformed to investigate the sensitivity of the EUV opacity energy range to different photospheric model flux inputs and different wind structures. These analyses provided the justification for a 140 ks follow up EUVE Cycle III observation of this star. We have recently been informed that our requested observation has been accepted as a Type

1 target for Cycle III.

The remainder of this report focuses on the following: (1) a brief background on the status of X-ray emission from OB stars; (2) a discussion on the importance of EUV observations; (3) a discussion of our scientific objectives, and; (4) a summary of our technical approach for our Cycle III observation (including the predicted EUV counts for various lines).

1. SCIENTIFIC BACKGROUND: The X-ray production mechanism in OB stars has been a subject of debate for over a decade. The basic discriminator between the proposed models is the spatial location of the X-ray source within the surrounding stellar wind (for a general discussion of these models see Cassinelli 1985). As discussed below, EUV observations have the potential to resolve this issue. To determine this location one must include two sources of X-ray attenuation: (1) the ISM, and; (2) the stellar wind. In these massive stellar winds, the total wind column density (N_w) is much greater than the ISM column density (N_{ISM}). However, since these winds are highly ionized, specific energy ranges can be dominated by either the wind or ISM. For example, in early O stars, the stellar wind component dominates the ISM shortward of ≈ 130 Å, and is essentially transparent longward of 130 Å, where in this range the absorption is controlled by the ISM (see Figure 2).

The importance of determining the X-ray location is fundamental in establishing the intrinsic strength of the X-ray emission with regards to the total stellar energy. If the X-rays are deeply embedded within the wind (total N_w), as suggested by Cassinelli & Olson (1979), the ratio of the intrinsic X-ray flux to stellar flux is of the order of 10^{-3} (Waldron 1984). Whereas, if the X-rays are produced by shocks due to the unstable nature of radiatively driven winds, as proposed by Lucy & White (1980), and since these shocks can only occur in the outer regions of the wind (Owocki, Rybicki, & Castor 1988), where only a small fraction of the total N_w contributes to the wind absorption, the intrinsic X-ray flux will only be slightly larger than the observed value (10^{-7} times the stellar flux).

The astrophysical significance is obvious. First, if the X-rays are proven to be totally due to shocks, then the problem is solved, i.e., we know the mechanism and location. On the other hand, if we find evidence supporting deeply embedded X-ray emission, then, we may ask, what is the mechanism responsible for this large emission, and how do we confine this high density hot plasma; are there magnetic loops on OB stars? At first, since, OB stars do not possess a significant outer convection region, the concept of magnetic loops is questionable. However, over the past several years, studies of magnetic field effects in these stars suggest that these fields may no longer be ignored (see discussion by Cassinelli 1992). For example, the HEAO-2 SSS analysis by Cassinelli & Swank (1983) found evidence for very high temperature gas (> 15 x 10^6K) and they suggested that this gas may be confined in magnetic loops.

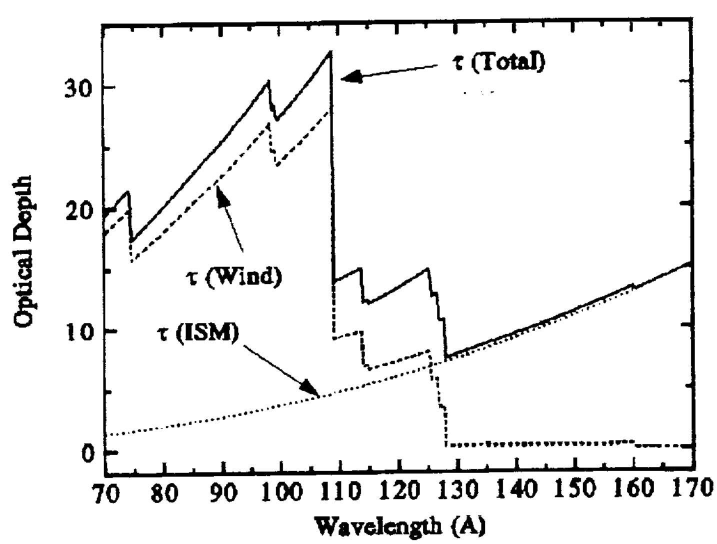

Figure 2. The contributions of the wind and ISM optical depths for the proposed model are compared. The lack of wind absorption longward of 130Å allows a unique opportunity to observe EUV emission from O stars with low ISM column densities.

Our recent ASCA SIS observations of two late O stars (Corcoran et al. 1994) confirm that very high temperature gas is present (10 - 30 x 10^6K), and the emission is thermal as evident by the presence of X-ray lines. Furthermore, since these stars possess various mechanical catalysts (rapid rotation, differential rotation, and non-radial pulsations), along with the strong radiative force, the complex physics involved will require new and innovative approaches to studies of gas dynamics. Clearly, any hint of hot/warm, high density plasma will provide the incentive to continue these studies.

Another question we must address, is there any strong evidence that stellar wind absorption is important? Waldron (1991) found a strong correlation between the X-ray hardness ratios (indicators of X-ray absorption) and the 6 cm radio data (a direct measure of N_w) in O stars, suggesting that the degree of X-ray attenuation is highly influenced by the surrounding stellar wind envelope. He also pointed out that the best fits from the automated HEAO-2 IPC processing (ISM absorption only) for O stars imply that an additional X-ray absorption mechanism must be present. This has also been noted in fitting the limited BBXRT spectra (Corcoran et al. 1993), and in fitting high S/N ROSAT PSPC spectra (Hillier et al. 1993). The presence of wind absorption has been confirmed by our ASCA O star observations (Corcoran et al. 1994), and the ASCA PV phase observation of ς Puppis reported by White (1994).

Unfortunately, the X-ray data (e.g., HEAO-2, ROSAT, and ASCA) alone are not sufficient to determine the spatial location of the X-rays. For example, in a X-ray temperature versus absorption column density plot (so-called "banana plots", see Cassinelli et al. 1981), the range of acceptable fits range a decade in temperature and typically three decades in column density. Although ROSAT (see discussion below) and ASCA have proven to be very useful in improving this wide range of acceptable fits, ***a null or positive detection of EUV emission will provide the fundamental key piece to the puzzle.***

2. IMPORTANCE OF EUVE DATA: Now we ask, how can an EUV observation help to resolve this issue of X-ray location? For O stars, the IPC X-ray data yield a wide range of acceptable fits (assuming Raymond-Smith X-ray spectra); for $N_w \approx 0$, we find acceptable fits require a log T $\approx$ 7.0 and log EM (emission measure) $\approx$ 55, and; for full wind attenuation, we find a log T $\approx$ 6.6 and log EM $\approx$ 57.5 are required (Cassinelli et al. 1981; Waldron 1984). These two limits alone cannot produce enough EUV radiation to be detected by the EUVE, although the full wind case is marginal. However, we propose that in addition to the T and EM stated above, a second low T (or a distribution of low T components), higher EM plasma is also present. This is not unreasonable since in reality any X-ray source more than likely has a continuous distribution of T and EM (e.g., the sun's transition region). For example, in the shock model of Owocki et al. (1988), the density can change by an order of magnitude. The detailed T structure was not determined, but should react in some predictable manner. For a deeply embedded X-ray source, a continuous distribution in T and EM is naturally expected since this is where the density is changing rapidly. This type of structure was used by Wolfire, Waldron, & Cassinelli (1985) to illustrate the compatibility of a thin coronal zone with the IR excess observed (IRAS) in ς Puppis.

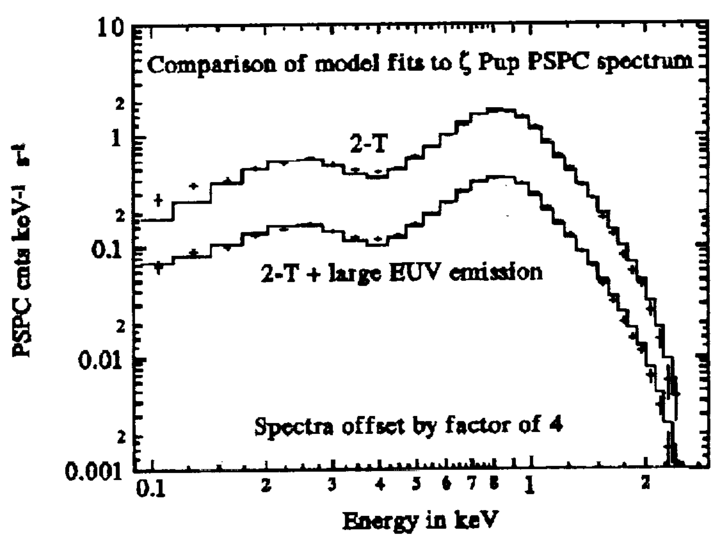

Figure 3. Model fits to PSPC ς Puppis spectrum. Note the discrepancy of the 2-T model in fitting the low bins. This excess can be explained if a large EUV emission source is present. For display purposes, the spectra are offset.

Cohen et al. (1994) found that B star models compatible with EUV and X-ray emission require a distribution of temperatures with the corresponding EM scaling as T^{-1}. In addition, our ASCA SIS observations confirm that multiple temperatures are a necessity in fitting O star spectra (unfortunately ASCA data are not very useful for constraining EUV emission since the low energy cutoff is approximately 0.4 keV). ***Therefore, the probability is high that low T, high EM plasma exists in the outer atmospheres of O stars.***

The next step is to determine the maximum size of this second low T, high EM plasma. In our EUVE Cycle I proposal we had to estimate the strength of this component by determining how much low T, high EM plasma can we hide before it begins to effect the IPC X-ray fits. Hillier et al. (1993) obtained a very high S/N PSPC observation of ς Puppis. Since the PSPC is more sensitive to softer X-rays ($\leq$ 0.1 keV), this observation allows us to obtain a much stronger constraint on the soft component as compared to our earlier estimate. Hillier et al. found a best fit to the data required two temperatures (log T = 6.23 and 6.66). From inspection of their model, we find that the PSPC low energy bins suggest that a softer component must be present (this could not be established with IPC data). Our best fit requires at least 3 additional soft line emission sources (the model used log T = 5.2, 5.4, 5.6, 6.4, and 6.65; EM scaling roughly as T^{-1}, and; with the maximum log EM = 58.25). Figure 3 shows a comparison of these two models. Note that the discrepancy is only apparent in the bins below 0.15 keV. An important finding is that this excess emission can be traced to a few EUV emission lines (see Figure 1), i.e., a continuum or power law model will not work. ***Therefore, we argue that this very high S/N PSPC observation provides the first indirect evidence that detectable EUV emission lines from O stars is highly probable.*** This model is also compatible with the IPC data and the EUV emission is about 15% weaker than the IPC based prediction in our initial EUVE Cycle I proposal.

In addition to a distribution in temperatures, the predicted log N_w range from 22.54 to 22.1 suggesting that the EUV and X-ray emission arise from different locations in the stellar wind. The location of the log T $\leq$ 6.4 components are found to be constrained to regions where the wind velocity is < 240 km s^{-1}, and the location of the log T = 6.65 component corresponds to a wind velocity of 1000 km s^{-1} (the terminal velocity for this star is $\approx$ 2400 km s^{-1}). Therefore, the high quality PSPC fit suggests that the EUV and soft X-ray sources have to be deeply embedded in the wind, and the hard X-rays are due to shocks in the outer wind regions. The reason that this soft EUV/X-ray source cannot be located in the outer regions of the wind is that there is just not enough wind absorption to hide this component; the resulting X-ray spectra, for this case, are found to be significantly softer than observed. Since the velocity upper limit of the EUV source decreases rapidly as the EUV detection increases in strength, even the low sensitivity of the PSPC may not be detecting all the EUV emission, i.e., a substantial lower T, higher EM plasma may be hidden in these stars, if the majority of the EUV/X-ray source is deeply embedded in the wind.

3. SCIENTIFIC GOALS: Our primary objective is to use the EUVE SW Spectrometer to search for this low T, (< 500,000K), high EM, ($\approx 10^{58}$) plasma in O stars. As illustrated in Figure 2, a unique EUV window between 128 - 140 Å (a small region of the SW band) exists for certain O stars. This window is a direct consequence of the underlying EUV and X-ray fluxes, as discussed by Waldron (1984) (i.e., the effects of EUV/X-ray emission on opacity structures). The optical depths shown in Figure 2 are the maximum values for the deeply embedded EUV/X-ray source model for ς Puppis (O4f). A simulated net EUVE line emission spectrum for this model is shown in Figure 4 (further discussion is presented in Section 4).

The stringent conditions are that we can only observe early O stars (highly ionized winds) with $N_{ISM} \leq 10^{20}$, and to overcome the still rather large optical depth ($\approx$8), the EUV EM must be quite large, EM $\approx 10^{58}$. This EM is not unreasonable for deeply embedded X-ray sources (as discussed above). Unfortunately, because O stars typically have $N_{ISM} >> 10^{20}$, our choice of targets is highly restricted. However, the unredden O4f star, ς Puppis, is unique not only because of its low ISM column density, $N_{ISM} = 10^{20}$, but also because it is hot enough such that its stellar wind opacity is essentially transparent longward of 128 Å. Historically, this star has served as the benchmark for testing various stellar wind models. Except for the EUV, it has been observed extensively in the radio through X-ray spectral bands. ***This opportunity should not be overlooked.***

In our EUVE Cycle I proposal we had hoped to obtain evidence of EUV emission from this star, where upon, we could have requested a follow-up deeper exposure. As discussed above, our original plan could not be accomplished due to an unforeseen UV leak problem. Therefore, since it is not clear about the future of another EUVE Cycle, we are requesting a 140 ks observation. This will provide a strong S/N (> 7) for the strongest line (O V), and it will allow us to fulfill our secondary objective. ASCA observations of O stars (Corcoran et al. 1994) suggest that in order to get acceptable fits to the data, the abundances of Fe and Mg had to be changed. In particular, Fe had to be reduced by more than 50%, and Mg had to be increased by about 15%. Since our model predicts Fe VIII and Mg V emission lines (using standard abundances), our EUVE observation has the potential to test whether this X-ray prediction is real or related to an unknown SIS instrumental effect. In addition, at 140 ks we may pick up the weaker O VI line which would be very useful for studies of radiation transfer effects in the EUV emitting region. The expected S/N values for all predicted lines is discussed in Section 4.

Our EUV observations of ς Puppis, whether we obtain a detection or not, will provide a definitive answer to the problem we are addressing. First, a null detection will rule out the possibility that the X-ray emission is deeply embedded. Second, a detection will allow us to determine very strong constraints on the depth of this emission. For this case, various models will be run to determine the necessary conditions to fit the EUV and X-ray emission. Because of the expected sensitivity of the EUV radiation to stellar wind absorption, using EUV data along with X-ray data will provide a definite outer limit to the X-ray source location in the wind. This would not rule out the possibility that shocks in the outer regions may still be present (as demonstrated by our PSPC fit), but it would clearly indicate that in terms of the total stellar energy balance, a substantial contribution is present in the lower regions of the wind. Also, Krolik and Raymond (1985) discussed that these winds may possess both strong and weak shocks, with the weak shocks being responsible for the observed X-rays. The strong shocks occur deeper in the wind and produce mainly EUV radiation. Lacking EUV observations, these strong shocks have not received much attention.

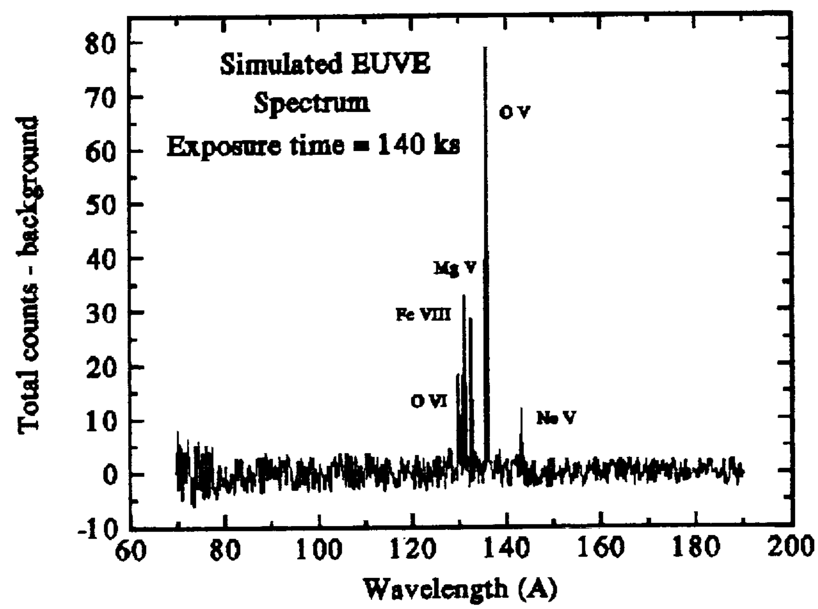

Figure 4. A simulated EUVE net counts spectrum with noise for the proposed model. The six lines are labeled. The O V line should clearly be detected which is the major scientific objective.

4. TECHNICAL SUMMARY: The EUV/X-ray model used to fit the PSPC data for ς Puppis incorporates the currently available Raymond-Smith emissivities, the ISM cross sections of Morrisson & McCammon (1983), and the stellar wind cross sections of Waldron (1984), which have been updated to include Ca, Ar, Fe, and Ni photoionization edges. We adopt a distance of 440 pc and a log N_{ISM} = 20.00±0.05 (Shull & Van Steenberg 1985). The He I column density is expected to be roughly a factor of 10 lower and is not important for the wavelength region of interest. Since the adopted ISM cross sections are found to be about 7% lower than those listed in the EUVE Appendix H for the wavelength region of interest, to compensate, we use a value for log N_{ISM} = 20.07 (a 17% increase). Hence, the observed S/N values may actually be larger than the predictions (see Table 1). At first, one may question how an EUV detection could be achieved at a log N_{ISM} > 20, but as shown in Figure 2, a unique EUV window between 128 - 140 Å exists where the combined ISM and stellar wind optical depths are < 9. Since O stars are strong X-ray sources and possibility stronger EUV sources (the goal of this study), detection of EUV emission lines is expected in this narrow wavelength window. ***Again we stress that ς Puppis, because of its highly ionized stellar wind, and due to its relatively low N_{ISM} (unusual for an O star), represents the ONLY O star that has a chance of being detected by EUVE.***

To determine the required EUVE SW Spectrometer exposure time needed to fulfill the science objectives, we obtained the electronic SW distributed background count rate and SW area function data files from the CEA/EUVE ftp site. The model predicts that 5 relatively strong lines are present in this narrow wavelength window. In order to satisfy our primary (a EUVE detection of the strongest line, O V), and secondary (strengths of Fe and Mg lines) scientific goals, we have based our exposure time calculation on obtaining a S/N > 3 for the Mg line. Using the procedures outlined in the EUVE GO Program Handbook, we found that an exposure time of 140 ks satisfies these requirements. For the background counts we used a $\Delta\lambda$ = 0.5 and a source to background height ratio = 0.1 appropriate for a point source. The predicted S/N, EUVE SW source counts, and various other relevant quantities are listed in Table 1 for the 5 strongest lines predicted by the model (see Figs. 1 & 4 -- NOTE: Fig. 4 shows a simulated EUVE SW total - background counts spectrum as a function of wavelength). As discussed above, the observed S/N may be larger, in which case, we may also pick up the weak O VI and Ne V lines, and other lines may also be present. Due to the high S/N PSPC observation, our fitted EUV emission measure is highly constrained to a deviation of < 10%. Therefore, at a minimum, the O V line should easily be detected which would satisfy our primary goal.

TABLE 1. Predicted EUVE Counts and S/N

Ion	λ Å	predicted line flux/10^{-4} photons cm^{-2} s^{-1}	bkgd/10^{-4} cnts s^{-1}	area cm^2	source cnts	bkgd cnts	S/N
O VI	129.8	1.09	6.00	1.20	18.31	46.20	2.28
Fe VIII	131.0	2.26	6.09	1.15	36.39	46.89	3.99
Mg V	132.5	1.87	5.92	1.09	28.54	45.58	3.32
O V	135.8	6.01	5.65	1.00	84.14	43.51	7.45
Ne V	143.3	1.31	5.19	0.77	14.12	39.96	1.92

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15. Supplementary Notes

16. Abstract

We were granted a 60 Ksec EUVE observation of Zeta Puppis. Unfortunately, due to a severe UV leak, the effective exposure time was only 20 Ksec, which did not allow us to carry out our scientific goals. As recommended by the EUVE Deputy Project Scientist, we have re-proposed this observation. Although our primary scientific objective was not achieved, the contract funding was used to further our understanding of EUV emission from O stars.

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