

Final Performance Report for NAG5-13696

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I. SUMMARY OF PROJECT ACTIVITIES:

1. Brief description of the primary objectives and scope of the project:

A major question for symbiotic stars concerns the nature and cause of their outbursts. A small subset of symbiotics, the "slow novae" are fairly well established as thermonuclear events that last on the order of decades. The several symbiotic "recurrent novae", which are much shorter and last on the order of months, are also thought to be thermonuclear runaways. Yet the majority of symbiotics are neither slow novae nor recurrent novae. These are the so-called "classical symbiotics," many of which show outbursts whose cause is not well understood. In some cases, jets are produced in association with an outburst, therefore an investigation into the causes of outbursts will yield important insights into the production of collimated outflows.

To investigate the cause and nature of classical symbiotic outbursts, we initiated a program of multi-wavelength observations of these events. First of all in FUSE Cycle 2, we obtained six observational epochs of the 2000-2002 classic symbiotic outburst in the first target of our campaign - class prototype, Z Andromedae. That program was part of a coordinated multi-wavelength Target-of-Opportunity (TOO) campaign with FUSE, XMM, Chandra, MERLIN, the VLA, and ground-based spectroscopic and high time-resolution photometric observations. Our campaign proved the concept, utility, and need for coordinated multi-wavelength observations in order to make progress in understanding the nature of the outburst mechanisms in symbiotic stars. Indeed, the FUSE data were the cornerstone of this project.

The present program is a continuation of that cycle 2 effort. Indeed, the observations acquired in this program are vital to the proper interpretation of the material acquired in cycle 2 as the new data cover the critical time period when the star continues to decline from outburst and actually returns to quiescence. The utilization of these data have allowed us to refine and complete description of our new model for classical symbiotic system outbursts.

2. Brief description of the findings:

Our multi-wavelength observations motivated consideration of a new model which we term the Disk-Instability Trigger. Observations in our campaign on Z And (see Sokoloski et al. 2002), led us to hypothesize that a disk instability caused the initial brightening of Z And in 2000, but that the outburst emission later became dominated by a response from the nuclear burning shell. The typical time between outbursts in Z And and the theoretical expectation that symbiotic disks may be unstable suggest that a sudden increase in accretion through the disk triggered the outburst. However, the rise to optical maximum occurred in several spurts, implying that multiple processes were responsible for the overall optical brightening. After the initial optical rise, radio and FUV observations indicated that radiation from the hot WD was blocked by a thick shell of material. Combining estimates of the column density of material required to produce this blockage and the shell size allows us to estimate the amount of material that was ejected. In addition to evidence for roughly spherical outflow in the form of shell ejection, we have also detected collimated outflow in the form of a radio jet. Finally, both the FUV and X-ray flux rose with the optical flux during the outburst, and the increase in total luminosity appears to be too large to be produced by accretion alone. Therefore, we may have evidence that the shell-burning rate increased within approximately 100 days of the outburst trigger.

Emission line strengths of the FUSE-band species, especially when combined with lines of the same species from the other spectral regions, provide diagnostics of the colliding wind/shock region. The high-resolution of FUSE-band absorption features provide a unique opportunity to probe several aspects of the outburst material. Note especially that FUSE provides important information for the analysis of the x-ray data as FUSE observations of H I absorption are at sufficiently high resolution to allow the separation of the interstellar component from the systemic component of the absorption. The contribution of the ISM column can then be accurately determined and constrained in fits to the x-ray data, enabling the intrinsic absorption column to be determined separately, and the absolute metallicity of the gas in the binary to be determined. FUSE sees various stages of ionization, and hence can determine the ionization level of the gas. Together with the x-ray

measurements, which are sensitive to the overall metallicity, the abundances are much better constrained than with either individual piece of data.

In the case of our outburst Z And observations, P-Cygni profiles are apparent in many lines in the FUV spectra and, as in the case C III 1176 or P V 1117, they evolve on a time scale of weeks (see Figure). Our first FUSE epochs showed a large amount of gas (e.g., singly and doubly ionized C, Fe, and Si), which only partially covers the source of FUV emission. Multiple line features evolve from absorption to emission as the outburst progresses, and there is evidence for hot gas moving at hundreds of km-s⁻¹, as well as for significant collisional excitation. At initial observations shortly after maximum, few emissions were seen, but by January 2001 some 4 months following peak brightness, emission lines of quite high ionization (such as P V, S V) are appearing in the spectra. See attached spectrum plot.

The outburst of Z And, studied with 6 epochs of observation in that initial program, has been the largest-scale (and longest duration) outburst in more than 30 years for this prototype classical symbiotic. We had originally expected return-to-quietness during cycle 2. In the course of our analysis it became obvious that observations at or near quietness were vital for understanding the outburst mechanism critically and for our new model analysis. Due to the lengthy outburst duration, we proposed and were granted additional time in cycle 3 to cover the outburst decline and highly important return-to-quietness phases. The quietness observations for this program were finally obtained in late summer and fall, 2003 after some substantial delay.

Although it was possible to produce interim results from only the outburst-state observations, a more thorough and logical presentation of our work should include analysis of the quietness state observations and publication of our proposed new model for symbiotic star outburst would be less well-received without the full perspective provided by analysis of the complete outburst and return-to-quietness. Therefore, the results from the cycle 2 component of our studies were to be combined with the cycle 3 epochs to announce our new outburst model for classical symbiotic systems, the Disk-Instability Trigger model, and to document the entire outburst period.

Unfortunately, due to a variety of complications including functional work requirements for the PI (Keyes) and medical issues for the primary co-I (Sokoloski), we were unable to complete the important summary paper within the grant period. We were denied an extension due to an oversight on my part, and as a result, publication of our summary paper has been delayed to beyond the ending period of this grant. As we write this in early summer 2005, the summary paper has been submitted, is under review, however its final construction has occurred after the ending of this funding. We had planned, under the auspices of this grant, to complete an important second paper detailing the entire set of FUV observations of the Z And outburst sequence, however due to the unfortunate curtailment of funding we are not able to do so.

3. Name and date (or anticipated date) of the publication of results:

We announced our multi-wavelength campaign and presented first results, including initial description of our Disk-Instability Trigger model, at the Grönigen CV meeting.

Sokoloski, J.L., Kenyon, S.J., Kong, A.K.H., Charles, P.A., Kaiser, C.R., Seymour, N., Espey, B.R., Keyes, C.D., McCandliss, S.R., Filippenko, A.V., Li, W., Pooley, G.G., Brocksopp, C., & Stone, R.P.S. 2002 in *The Outbursts of Cataclysmic Variables and Related Objects*, B.T., Gansicke, K. Beuermann, & K. Reinsch eds., ASP Conference Proceedings, 261, p. 667

Important results from this investigation are included in our summary paper which has been submitted to the *Astrophysical Journal*.

A "Combination Nova" Outburst in Z Andromedae: Nuclear Shell Burning Triggered by a Disk Instability, by J. L. Sokoloski, S. J. Kenyon, B. R. Espey, C. D. Keyes, S. R. McCandliss, A. K. H. Kong, J. Aufdenberg, A. V. Filippenko, W. Li, C. Brocksopp, C. R. Kaiser, P. A. Charles, M. Rupen, R. P. S. Stone

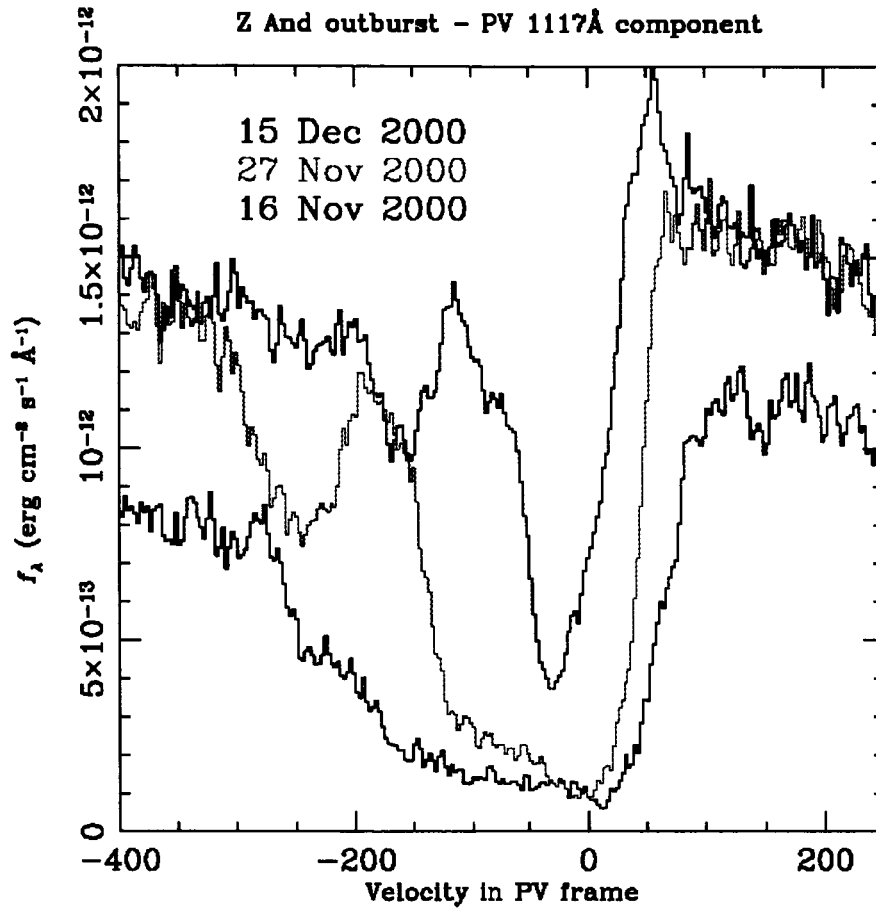


Figure 1: 16 Nov 2000 (lower); 27 Nov 2000 (middle); 15 Dec 2000 (upper). P V FUSE line profile variations on a time-scale of weeks near the peak of the 2000-02 outburst of Z Andromedae reveal the velocity structure of ejected material as it becomes optically thick.