### A New Kind of Nova

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Abstract. We performed extensive, multi-wavelength observations of the prototypical symbiotic star Z Andromedae between 2000 and 2003, during a large eruption. The rise to optical maximum occurred in three distinct stages. During the first stage, the rise was very similar to an earlier, small outburst which we determined was due to an accretion-disk instability. In the second stage, an optically thick shell of material was ejected, and in the third stage, the shell cleared to reveal a white dwarf whose luminosity was roughly  $10^4 L_{\odot}$ . We suggest that the outburst was powered by an increase in the rate of nuclear burning on the white-dwarf surface, triggered by a sudden burst of accretion. This outburst thus combined elements of both dwarf novae and classical novae.

### 1. Introduction

Determining the cause of classical symbiotic-star outbursts has been a long-standing challenge. These eruptions recur too frequently for nova-like thermonuclear runaways, and their peak luminosities appear to be too large for dwarf-nova-like disk instabilities. Although quasi-steady nuclear burning is probably present on the surface of the white dwarfs (WDs) in most symbiotics, classical symbiotic outbursts are also distinctly different from the long-term variability seen in supersoft X-ray sources.

Symbiotic stars are interacting binaries in which material is transferred from an evolved red-giant star to a more compact, hot star, usually a WD (see, e.g., Kenyon 1986; Corradi, Mikołajewska, & Mahoney 2003). In most symbiotics, the red giant under-fills its Roche lobe, and the mass transfer proceeds via gravitational capture of the red giant's wind. An accretion disk may or may not form (Livio 1988). Radiation from the accreting WD partially ionizes the nebula formed by the red-giant wind. This ionized nebula gives rise to intense emission lines. Because typical quiescent-state WD luminosities in symbiotic stars are roughly  $10^3 L_{\odot}$  (e.g., Mürset et al. 1991), quasi-steady nuclear shell burning is thought to be taking place on the WD surface in the majority of systems (see also van den Heuvel et al. 1992; Sokoloski et al. 2001).

There are at least three types of symbiotic-star outbursts. Slow novae and recurrent novae appear to be due to thermonuclear runaways on the WD surface. The nature of the more common classical symbiotic outbursts, however, is not yet known. These eruptions can recur as frequently as every few years, and can brighten in the optical by one to a few magnitudes. Kenyon (1986) found that dwarf-nova-like accretion-disk instabilities in a symbiotic star can only produce outbursts of up to about one magnitude, so outburst modeling efforts have generally focused on expansion of the WD photosphere at constant bolometric luminosity (due to the accretion rate rising above the maximum value for steady-burning), or hydrogen shell flashes. The amount of mass lost during classical symbiotic outbursts has implications for whether symbiotic WDs can accrete enough material to explode as Type Ia supernovae. Since the mass loss can take the form of a collimated jet, the nature of classical symbiotic outbursts is also linked to the issue of jet formation.

# 2. Multi-wavelength Monitoring of Z Andromedae

The hot components (e.g., white-dwarf plus accretion disk) in symbiotic stars emit the bulk of their energy in the FUV. However, they also radiate significantly at radio through X-ray wavelengths, and important diagnostics are found in each of these observational regimes. To investigate the nature and cause of classical symbiotic-star outbursts, we performed multi-wavelength observations, including observations with the FUSE (9 spectra from 2000 Nov 16 to 2003 Aug 4), Chandra (1 observation on 2000 Nov 13), and XMM (2 observations on 2001 Jan 29 and Jun 11) satellites, the VLA (9 observations between 2000 Oct 13 and 2003 Jul 24) and MERLIN (6 observations between 2001 Jan 28 and 2002 May 6) radio interferometers, and extensive ground based optical spectroscopy and photometry, during the recent 2000-2003 activity phase of Z And.

Additional optical spectroscopic coverage extended back to 1994. The full set of observations is described in detail in Sokoloski et al. (2005).

### 3. Results

## 3.1. I. Hot-Component Effective Temperature

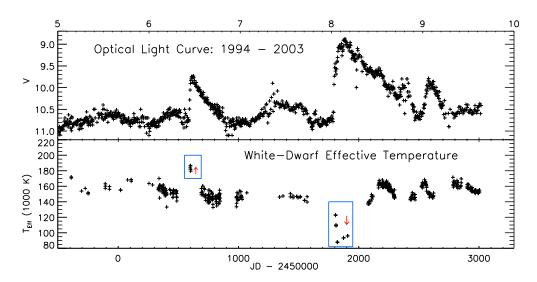


Figure 1. Top: Long-term optical light curve of Z And, from the American Association of Variable Star Observers (AAVSO). The light curve shows the small outburst in 1997 and the larger 2000-2002 event (and subsequent rebrightening). Bottom: Estimates of the hot-component effective temperature from the ratio of He II 4686 and H $\beta$  nebular emission lines. Orbital phase from the ephemeris of Mikołajewska & Kenyon (1996) is shown on the top.

In the top panel of Fig. 1, we show the optical light curve of Z And from 1994 to 2003, from the American Association of Variable Star Observers (AAVSO). In the bottom panel, we plot estimates of the hot-component effective temperature,  $T_{hot}$ , that we derived from 274 nights of optical spectroscopy. It is clear from the disparate behavior of  $T_{hot}$  during the small outburst in 1997 and the larger eruption in 2000-2002 that these two events were quite different. Therefore, our first conclusion is that not all classical symbiotic star outbursts are due to the same physical mechanism.

We estimated the effective temperature of the source of ionizing photons (the hot component) from 1994 to 2003 using a method based on that of Iijima (1981) plus examination of the highest ionization-potential species present in the optical and contemporaneous FUV spectra (for details, see Sokoloski et al. 2005). The behavior of the first outburst covered by our optical spectral monitoring is consistent with an accretion-disk instability, or dwarf nova. The evidence for this interpretation includes: the shape and size of the optical outburst (fast rise plus exponential decay, and  $\Delta V \leq 1$ ); the evolution of the hot-component effective temperature; the roughly constant fractional amplitude of the photometric oscillation at the WD spin period due to magnetic accretion (after

subtraction of the contribution from the red giant) throughout the outburst (Sokoloski & Bildsten 1999); and the expectation that the potentially large disks in symbiotic stars should in fact be unstable.

In the 2000-2002 event, the rise to optical maximum proceeded in three distinct stages, the optical brightness increased by well over the one magnitude that can be produced by a disk instability in a symbiotic (Kenyon 1986), and the hot-component effective temperature evolved in a rather complex way. The 2000-2002 eruption was therefore not a simple dwarf nova.

## 3.2. II. Three-Stage Rise

The 2000-2002 eruption of Z And began like the smaller event in 1997. Fig. 2, in which the 1997 and 2000 light curves are overlayed, shows the similarity between the first stage of the 2000-2002 event and the rise to maximum in 1997. This initial correspondence suggests that the physical trigger mechanism was the same for both the large 2000-2002 outburst and the small 1997 eruption. At the very beginning of the 2000-2002 event, the U-band flux rose quickly and the U-B color became more blue (see Skopal et al. 2002, for more complete coverage of this blue spike). Since the U brightness tends to be dominated by reprocessed ionizing radiation from the hot component, the 2000-2002 outburst probably began with a process that rapidly increased the luminosity of the hot component. The blue flare early in the 2000-2002 event provides a glimpse of an initial  $T_{hot}$  increase in 2000 (like the  $T_{hot}$  increase seen in 1997) before the main effective-temperature dip later in the 2000-2002 eruption. We therefore conclude that the 2000-2002 outburst began with a disk instability, as in 1997.

During the second stage of the 2000-2002 outburst,  $T_{hot}$  dropped (see Fig. 1) and the U-B color reddened, first sharply, and then more gently. The first FUSE spectrum, taken near the end of the second stage of the outburst, was dominated by blue-shifted absorption profiles indicating significant outflow (see Sokoloski et al. 2002), and the ratio of P V line components was as expected for an optically thick plasma. The uncharacteristically low 5 GHz radio flux density of 0.42 mJy measured during the second stage of the outburst (on 2000 Oct 13) suggests that the ionized, bremsstrahlung-emitting nebula was smaller than usual due to a reduced flux of ionizing photons from the WD. In addition, on 2000 Nov 23 (at the beginning of the third stage of the outburst), the optical oscillation at the WD spin period was not detected. Thus, the magnetic hot spots on the surface of the WD appear to have been hidden. All of these phenomena can be explained by an ejection from the surface of the WD of an optically thick shell of material, or possibly the presence of an optically thick wind.

During the third stage of the rise to optical maximum in 2000,  $T_{hot}$  slowly began to increase again and the U-B color became more blue, the FUV spectrum moved from absorption to emission, the radio flux rose, and the final increase in optical flux became dominated by U-band emission. These changes are consistent with the clearing of material that had shrouded the FUV continuum in the second stage of the outburst, to reveal a hot, luminous white dwarf.

### 3.3. III. White-Dwarf Luminosity

We find that the increase in WD luminosity during the 2000-2002 outburst of Z And was too large to have been produced by accretion alone. The most likely

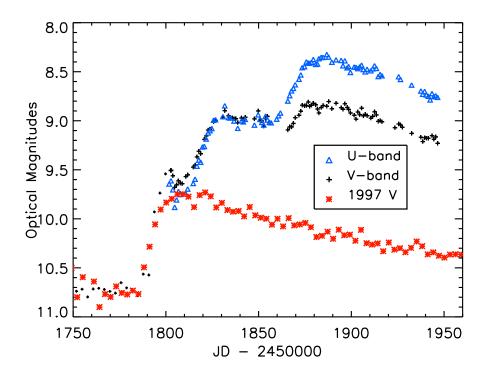


Figure 2. U and V-band light curves from the early part of the 2000-2002 outburst of Z And, with the 1997 V-band light curve shifted in time and over-plotted. The optical rise initially follows the same course for the two events. In 2000, however, the first-stage rise proceeds beyond the maximum level reached in the 1997 event, and the outburst evolution subsequently takes a different path. The triangles and crosses are our data from the Katzman Automatic Imaging Telescope (KAIT; Li et al. 2000; Filippenko et al. 2001), and the dots and \* symbols are data from the AAVSO.

explanation is that the rate of nuclear shell burning on the surface of the WD increased, probably as the result of the sudden influx of fresh fuel.

To determine the bolometric luminosity of the WD throughout the 2000-2003 activity period, we estimated the WD radius,  $R_{WD}$ , at the time of each of the 9 FUSE observations by scaling the WD photosphere models of Barman et al. (2000) to the extinction-corrected FUSE fluxes, using the effective temperatures described above, and assuming a distance of 1 kpc and mass of 0.65  $M_{\odot}$  (Schmid & Schild 1997). We then obtained the WD luminosities using the standard relation  $L_{hot} = 4\pi R_{WD}^2 \sigma T^4$ . The derived hot-component luminosities are close to  $10^4 L_{\odot}$  from the end of 2000 to late 2001. For comparison, the Eddington luminosity for a  $0.65 M_{\odot}$  white dwarf is  $L_{Edd} = 3 \times 10^4 L_{\odot}$  ( $M/0.65 M_{\odot}$ ).

If the 2000-2002 outburst was entirely accretion powered, the required accretion rate to produce  $10^4 L_{\odot}$  would be  $\dot{M} \approx 5 \times 10^{-5} M_{\odot} \, \mathrm{yr}^{-1}$ , where we adopt  $R_{WD} = 0.1 \, R_{\odot}$  as indicated by scaling the FUV fluxes to photospheric models, and  $M_{WD} = 0.65 \, M_{\odot}$ . Such a high accretion rate would be difficult to sustain in Z And for a full year. If the outburst was nuclear powered, on the other hand,

only a few times  $10^{-7} M_{\odot}$  of fuel would be required to produce  $L_{hot} \sim 10^4 L_{\odot}$  for one year, which is more reasonable. If we take into account the kinetic energy of the ejected mass (Tomov et al. 2003; Brocksopp et al. 2004), thermonuclear involvement in the outburst is even more strongly indicated<sup>1</sup>.

#### 4. Combination Nova

We see evidence for phenomena that usually occur in two distinct types of cataclysmic variable star outbursts in the same symbiotic star event. The 2000-2002 outburst of Z And appears to have been triggered by a disk instability, as in dwarf novae, and then powered by an increase in nuclear shell burning on the WD, in a milder version of the phenomenon that powers classical novae. The outburst in Z And therefore combines elements of dwarf novae and classical novae, and we refer to this new type of event as a combination nova.

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<sup>&</sup>lt;sup>1</sup>Kilpio et al. (2005) also suggest that nuclear shell burning played a role in the 2000-2002 outburst of Z And, although their trigger mechanism is a collapse of the accretion disk when the red-giant wind speed drops below a critical level.