PHYSICAL STRUCTURE OF FOUR SYMBIOTIC BINARIES

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Disk accretion powers many astronomical objects, including pre-main sequence stars, interacting binary systems, and active galactic nuclei. Unfortunately, models developed to explain the behavior of disks and their surroundings – boundary layers, jets, and winds – lack much predictive power, because the physical mechanism driving disk evolution – the viscosity – is not understood. Observations of many types of accreting systems are needed to constrain the basic physics of disks and provide input for improved models.

Symbiotic stars are an attractive laboratory for studying physical phenomena associated with disk accretion. These long period binaries ($P_{orb} \sim$ 2-3 yr) contain an evolved red giant star, a hot companion, and an ionized nebula. The secondary star usually is a white dwarf accreting material from the wind of its red giant companion. A good example of this type of symbiotic is BF Cygni: our analysis shows that disk accretion powers the nuclear burning shell of the hot white dwarf and also manages to eject material perpendicular to the orbital plane (Mikołajewska, Kenyon, and Mikołajewski 1989). The hot components in other symbiotic binaries appear powered by tidal overflow from a very evolved red giant companion. We recently completed a study of CI Cygni and demonstrated that the accreting secondary is a solar-type main sequence star, rather than a white dwarf (Kenyon *et al.* 1991).

This project continued our study of symbiotic binary systems. Our general plan was to combine archival ultraviolet and optical spectrophotometry with high quality optical radial velocity observations to determine the variation of line and continuum sources as functions of orbital phase. We were very successful in generating orbital solutions and phasing UV+optical spectra for five systems: AG Dra, V443 Her, RW Hya, AG Peg, and AX Per. Summaries of our main results for these systems appear below.

A second goal of our project was to consider general models for the outbursts of symbiotic stars, with an emphasis on understanding the differences between disk-driven and nuclear-powered eruptions. This portion of the project was also successful, as summarized below.

I. Physical Properties of Several Symbiotic Stars

A. AX Persei

In *On the Nature of the Symbiotic Binary AX Persei*, Kenyon and Mikołajewska pre-

sented optical/ultraviolet photometric and spectroscopic observations for the symbiotic binary AX Persei. This system contains a red giant that fills its tidal lobe and transfers material into an accretion disk surrounding a low mass main sequence star. The stellar masses – $M_g \sim 1\,M_\odot$ for the red giant and $M_h \sim 0.4\,M_\odot$ for the companion – suggest AX Per is poised to enter a common envelope phase of evolution.

The disk luminosity increases from $L_{disk} \sim 100\,L_\odot$ in quiescence to $L_{disk} \sim 5700\,L_\odot$ in outburst for a distance of d = 2.5 kpc. Except for visual maximum, high ionization permitted emission lines – such as He II – imply an EUV luminosity comparable to the disk luminosity. High energy photons emitted by a hot boundary layer between the disk and central star ionize a surrounding nebula to produce this permitted line emission. High ionization forbidden lines – such as [Fe VII] – form in an extended, shock-excited region well out of the binary's orbital plane and may be associated with mass loss from the disk.

B. V443 Herculis

In *Spectroscopic Observations of V443 Herculis: A Symbiotic Binary with a Low Mass White Dwarf*, Kenyon, Dobrzycka, and Mikołajewska completed an analysis of optical/ultraviolet photometric and spectroscopic observations for the symbiotic binary V443 Herculis. This system is a relatively short period system – P $\sim$ 600 days – that contains a red giant and a hot compact star similar to the central star of a planetary nebula. The red giant appears fairly normal: it does not fill its tidal lobe and has a modest amount of circumstellar dust emission. The hot component is more extreme: it appears to lie on the cooling curve of a 0.55 $M_\odot$ white dwarf with a temperature of $\sim 10^5$ K and a luminosity of $\sim 600\,L_\odot$. The lifetime of the source at this position in the HR diagram is very short – less than 10^3 yr – so we conclude that the hot component must be powered by accretion from the low velocity, red giant wind.

C. AG Pegasi

In *The Evolution of the Symbiotic Binary System AG Pegasi: The Slowest Classical Nova Eruption Ever Recorded*, we presented an analysis of new and existing photometric and spectroscopic observations of the ongoing eruption in the symbiotic star AG Pegasi. These observations showed that this binary has evolved considerably since the turn of the century. In particular, recent dramatic changes in both the UV continuum and the wind from the hot component allowed a more detailed analysis than in previous papers.

AG Peg is composed of a normal M3 giant ($M_g \sim 2.5\,M_\odot$) and a hot, compact star ($M_h \sim 0.6\,M_\odot$) embedded in a dense, ionized nebula. The hot component powers the activity observed in this system, including a dense wind ($v_r \sim 1000\,\mathrm{km\,s^{-1}}$; $\dot{M} \sim 10^{-6}\,M_\odot\,\mathrm{yr^{-1}}$) and a photoionized region within the outer atmosphere of the red giant. The hot component contracted in radius at roughly constant luminosity from c. 1850

to c. 1985. Its bolometric luminosity declined by a factor of ~ 4 during the past five years, and it may now be evolving along the constant radius portion of the white dwarf cooling curve. Both the mass loss rate from the hot component and the emission activity decreased in step with the hot component's total luminosity, while photospheric radiation from the red giant companion remained essentially constant.

D. RS Ophiuchi

In *A New Spectroscopic Orbit for RS Ophiuchi,* we derived a spectroscopic orbit for the recurrent nova RS Ophiuchi. We found an orbital period of 460 days for both A-type and M-type absorption features in this system. The mass function and optical light curves suggest RS Oph has a relatively low orbital inclination of $i \approx 30°–45°$.

E. AG Draconis

In *The Evolution of the Symbiotic Binary System AG Draconis,* we analyzed new and archival photometric and spectroscopic observations of the symbiotic star AG Draconis. This binary has undergone several 1–3 mag optical and ultraviolet eruptions during the past 15 years. Our combination of optical and ultraviolet spectroscopic data allow a more complete analysis of this system than in previous papers.

AG Dra is composed of a K-type bright giant ($M_g \sim 1.5\,M_\odot$) and a hot, compact star ($M_h \sim 0.4$–$0.6\,M_\odot$) embedded in a dense, low metallicity nebula. The hot component undergoes occasional thermonuclear runaways that produce 2–3 mag optical/ultraviolet eruptions. During these eruptions, the hot component develops a low velocity wind that quenches X-ray emission from the underlying hot white dwarf. The photoionized nebula changes its volume by a factor of five throughout an eruption cycle. The K bright giant occults low ionization emission lines during superior conjunctions at all outburst phases but does not occult high ionization lines in outburst (and perhaps quiescence). This geometry and the component masses suggest a system inclination of $i \approx 30°–45°$.

F. RW Hydrae

In *Spectroscopic Orbits for Symbiotic Binaries III. Eclipses of the Hot Component in RW Hydrae,* we discussed optical and ultraviolet spectroscopic observations of the symbiotic star RW Hydrae. This system contains an M2 giant and a hot white dwarf, $T_h \approx 80{,}000$ K, in an eclipsing binary system with an orbital period of 370.2 ± 0.9 d. The component masses are $M_g \approx 0.5$–$2\,M_\odot$ for the red giant and $M_h \approx 0.3$–$0.6\,M_\odot$ for the white dwarf. High energy photons from the white dwarf ionize the outer atmosphere of the red giant to produce bright emission lines that vary in phase with the orbital period. Densities within the ionized wind range from $n_e \sim 10^{11}$ cm^{-3} in the inner portion to $n_e \sim 10^8$ cm^{-3} in the outer portion.

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G. RS Ophiuchi

In *The Hot Component in RS Ophiuchi,* we analyzed optical and ultraviolet spectrophotometry of the quiescent recurrent nova RS Ophiuchi. Our preferred model for this binary consists of an M-type giant and a B-type shell star with a luminosity of $L_h \sim 100 - 600\ L_\odot$. The ejecta from the recent outburst are slightly enhanced in helium relative to the solar abundance, which agrees with previous estimates from model fits to the optical and ultraviolet light curve. These results indicate that the hot component has a mass close to the Chandrasekhar limit. Although the hot component luminosity is consistent with the high accretion rate needed for recurrent nova eruptions in this system, our effective temperature estimate is not consistent with predicted cooling curves for massive white dwarfs.

H. Z Andromedae

In *The Hot Component in the Symbiotic Binary Z Andromedae: Accretion Disk or Hot Stellar Source?*, we analyzed optical and ultraviolet spectroscopic observations of the symbiotic binary star Z Andromedae. This system consists of an M3-M4 giant and a hot stellar source surrounded by an ionized nebula. The orbital mass function is consistent with $M_g \sim 2\ M_\odot$ and $M_h \sim 0.5\text{–}1\ M_\odot$ as in other symbiotic stars. Our analysis indicates that accretion disk or thermonuclear runaway models reproduce some – but not all – observations of the system in outburst. Distinguishing between different outburst mechanisms requires more elaborate theoretical calculations.

I. Physical Models for Illuminated Red Giant Atmospheres

In *Illumination in symbiotic binary stars: NLTE photoionization models. I. Hydrostatic case,* we developed a non-LTE photoionization code that calculates the atmospheric structure and emergent spectrum of a red giant illuminated by the hot component of a symbiotic binary system. The model assumes hydrostatic, radiative, and statistical equilibrium for the red giant atmosphere and solves the radiative transfer equation with a local escape probability method. We compute non-LTE level populations for a variety of ions and predict the variation of emission line fluxes as functions of the temperature and luminosity of the hot component.

Our models produce strong emission lines only when the hot component has a high effective temperature, $T_h \gtrsim 100{,}000$ K, for hot component luminosities, $L_h \gtrsim 630\ L_\odot$. Predicted electron densities and temperatures for the photoionized atmosphere generally agree with observations. The models also produce reasonably large continuum variations that are consistent with the light curves of some symbiotic stars. However, predictions for most optical and ultraviolet emission line fluxes fall well below those observed in typical symbiotic stars. We conclude that the hot component must illuminate a red giant wind to reproduce observed line fluxes. Hydrostatic red giant atmospheres simply do not have

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enough material beyond the photosphere to account for the emission features observed in most symbiotics.

Illumination can modify the structure of a red giant atmosphere even when the emitted spectrum changes very little. Energetic photons from the hot component cause the atmosphere to expand by several percent for large hot component luminosities. This expansion is insufficient to increase the red giant mass loss rate, except in systems where the giant already fills or nearly fills its Roche lobe.

In *Illumination in symbiotic binary stars: NLTE photoionization models. II. Wind case*, we expanded these models to calculate the wind structure and emergent spectrum of a red giant wind illuminated by the hot component of a symbiotic binary system. We consider spherically symmetric winds with several different velocity and temperature laws and derive predicted line fluxes as a function of the red giant mass loss rate, $\dot{M}$. Our models generally match observations of the symbiotic stars EG And and AG Peg for $\dot{M} \approx 10^{-8}$ $M_\odot\,yr^{-1}$ to 10^{-7} $M_\odot\,yr^{-1}$. The optically thick cross-section of the red giant wind as viewed from the hot component is a crucial parameter in these models. Winds with cross-sections of 2–3 red giant radii reproduce the observed fluxes, because the wind density is then high, $\sim 10^9$ cm^{-3}. Our models favor winds with acceleration regions that lie far from the red giant photosphere or extend for 2–3 red giant radii.

Figure 1 compares model line fluxes with observations of EG And. The H I and He II lines are now Hα and He II $\lambda1640$. We adopt Vogel's velocity law for $\dot{M} = 10^{-8}$, 10^{-7}, and 10^{-6} $M_\odot\,yr^{-1}$. We also adopt $L_h \sim 16$ $L_\odot$, $T_h \sim 7.5 \times 10^4$ K, $L_g \sim 950$ $L_\odot$, $T_g \sim 3700$ K, $R_g \sim 75$ $R_\odot$, $A = 1.5$ AU, a 400 pc distance, and $E_{B-V} = 0.05$ (Vogel *et al.* 1992). Open triangles show predictions for $r_{cs} = R_g$; filled triangles show predictions for $r_{cs} = 2.5R_g$. As in AG Peg, the model fluxes reach a minimum level at the lowest mass loss rates due to the emission measure set by the hydrostatic atmosphere. This limit is most noticeable in lower ionization lines that form throughout the ionized wind at higher mass loss rates, such as H I and He I. The observations include *IUE* data at orbital phase 0.465 re-reduced for this study and ground-based optical data from KPNO. We adopt I(He I$\lambda5876$)/I(Hα) $\sim 0.01 - 0.1$ as typical for S-type symbiotics in the absence of a real detection of this line.

Our models bracket observations for $r_{cs} > R_g$. For the best estimate of the mass loss rate, $\dot{M} \approx 10^{-8}$ $M_\odot\,yr^{-1}$, we can match observed fluxes only for C IV and N V if $r_{cs} \approx R_g$. Observations of other lines exceed predictions by factors of 3–10. The model predictions exceed all of the observed fluxes for $r_{cs} \sim 3R_g$ when $\dot{M} \approx 10^{-8}$ $M_\odot\,yr^{-1}$. Model and observed fluxes agree if we reduce both r_{cs} and the abundances of CNO elements. For such low mass loss rates, illumination greatly modifies the wind velocity and density through thermal expansion, and probably reduces r_{cs} as outlined in §2.5. A modest reduction in the cross-section to $r_{cs} \approx 2R_g$ would bring the predicted H I, He I, and He II fluxes into reasonable agreement with the observations. Predicted fluxes for the

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CNO elements then exceed observed fluxes by factors of 3–5, which we interpret as a low metal abundance. The high negative radial velocity, ~ -100 km s^{-1}, and high galactic latitude, $b \approx -22°$, indicate that EG And is a member of the halo population and likely to have lower metal abundances than adopted in our models. Other symbiotics, such as AG Dra, have similarly low metal abundances.

Figure 1 – Comparison of model line fluxes from the wind models for Vogel's law, and two cross sections with observations for EG And. Open and filled triangles show the line fluxes of the wind model for the cross section R_g^2 (open triangles) and $2.5^2 R_g^2$ (triangles) for $T_h = 10^5$ K, a distance of 1 kpc, $\log \beta = -3$, and $\dot{M} = 10^{-6}, 10^{-7}$, and $10^{-8} M_\odot$ yr^{-1}. At each ion, $\dot{M}$ increases with increasing line flux. The crosses connected by the dashed line indicate observations at d = 1 kpc corrected for reddening, $E(B - V) = 0.05$ mag. Except for the He I line, where crosses show possible range of the fluxes, i.e., 0.1 - $0.01 \times F(H\alpha)$.
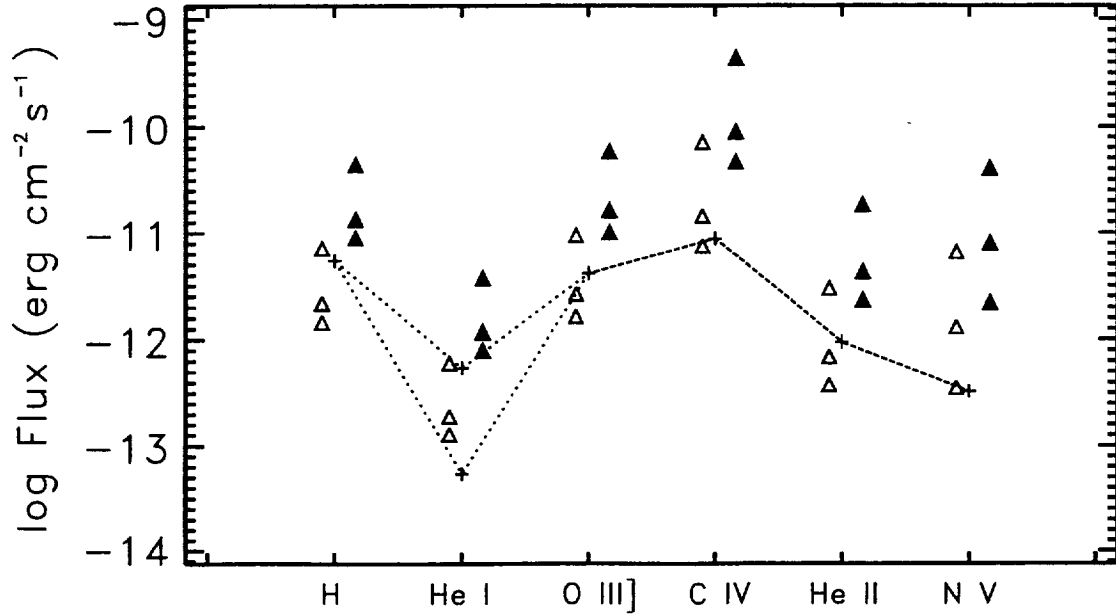
J. The Old Nova GK Persei

In *A Laboratory for Magnetized Accretion Disk Model: Ultraviolet and X-ray Emission from Cataclysmic Variable GK Persei,* we analyzed the ultraviolet spectrum of the cataclysmic variable GK Per at maximum light. The flat ultraviolet spectrum in this system requires a truncated inner accretion disk and an unusually flat radial temperature profile. This requirement is not satisfied by any non-magnetic steady or non-steady disk model.

We considered a magnetized accretion disk model to explain the ultraviolet spectrum. The available data on the white dwarf spin and possible quasi-periodic oscillations constrain the magnetic field, B_*, and the disk accretion rate, $\dot{M}$, to lie along a well-defined spin-equilibrium condition $(\dot{M}/10^{17} \text{ g s}^{-1}) \sim 100(B_*/10^7 G)^2$. Our self-consistent treatment of the magnetic torque on the disk flattens the disk temperature distribution outside the disk truncation radius. This modified temperature distribution is too steep to explain the UV spectrum for reasonable field strengths.

X-ray heating is a plausible alternative to magnetic heating in GK Per. We estimated that the disk intercepts $\sim 5\%$ of the accretion energy in outburst, which results in an extra disk luminosity of ~ 5–$10 \; L_\odot$. Model spectra of optically thick disks are too blue to match observations. The UV spectrum of an optically thick disk with an optically thin, X-ray heated corona resembles the observed spectrum. The X-ray luminosity observed during the outburst indicates $\dot{M} < 10^{18}$ g s^{-1}, which is a factor of 10 lower than that required to explain the ultraviolet luminosity. Radiation drag on material flowing inward along the accretion column lowers the shock temperature and reduces the X-ray luminosity. Most of the accretion energy is then radiated at extreme ultraviolet wavelengths.

II. The Eruptions of Symbiotic Binary Stars

In *On the Nova-like Eruptions of Symbiotic Binaries,* Kenyon and Mikołajewska discussed three popular explanations for the nova-like eruptions observed in symbiotic binary stars and compared model predictions with recent observations. Most outbursts occur when unstable hydrogen shell burning causes a hot white dwarf to expand to a radius of 1-100 $R_\odot$. This model predicts a long duration constant luminosity phase following visual maximum, and observations of the symbiotic novae and several steady burning sources confirms this feature of thermonuclear runaway calculations. At least two symbiotics erupt when the accretion rate from a circumstellar disk onto a solar-type central star increases by 1-2 orders of magnitude. Simple accretion models emit $\sim 50\%$ of the gravitational energy in the disk and the remainder in a hot boundary layer between the disk and central star. Observations of CI Cyg and AX Per support this picture for accretion rates below $\sim 10^{-4} \, M_\odot \, yr^{-1}$, but boundary layer emission vanishes for higher accretion rates. Finally, we associated observations of extra reddening and the

appearance of high ionization emission lines in R Aqr with an increase in the Mira mass loss rate initiated, perhaps, by a helium shell flash above the Mira's degenerate core.

In *The Secondary Outburst Maximum of T Coronae Borealis: Implications for Accretion Disk Physics*, John Cannizzo and Kenyon examined Webbink's hypothesis that the accretion of a torus of matter onto a main sequence star caused secondary maxima during the 1866 and 1946 eruptions of the recurrent nova T CrB. Our simple 1-D hydrodynamical calculations showed that the accretion disk viscosity must increase with time to produce light curves resembling observations. We adopted a model in which the viscosity parameter α increases from a seed value α_i to a final value α_f via the relation $\alpha(t) = \alpha_f/[1 + (\alpha_f/\alpha_i)\exp(-t/\tau)]$. The observed light curve requires $\alpha_i = 10^{-3}$ and $\alpha_f = 3$ if the initial torus mass is $10^{-4} M_\odot$ and the viscous growth time, τ, is the orbital time at the initial radius of the torus. Our model implied that the physical mechanism responsible for producing the viscous dissipation in the accretion disk has a fast growth rate and saturates to an α of order unity. Balbus & Hawley identify an MHD instability with the same growth rate and saturation viscosity required by our phenomenological model. The good agreement between parameters estimated from observations and those derived from a physical viscosity mechanism suggested that this instability is a promising source for the accretion disk viscosity.

In *On Symbiotic Stars and Type Ia Supernovae*, Kenyon and collaborators examined the possibility that wide binaries containing a red giant and a white dwarf produce a significant fraction of type Ia supernovae (SN Ia). These binaries probably cannot account for SN Ia events if the white dwarf mass must evolve to the Chandrasekhar limit during the expected lifetime of the red giant primary star. However, symbiotic binaries are good candidates for helium detonation supernovae in low mass white dwarfs. If helium detonations can produce the majority of SN Ia events, then symbiotic stars might account for a large fraction of type Ia supernovae.

In *The Secondary Outburst Maximum of T Coronae Borealis: Hydrodynamic Simulations of the Blob and Accretion Disk*, J. Cannizzo, M. Ruffert, and Kenyon completed an SPH calculation of an accretion disk around a main sequence star. The goal is to try to understand the evolution of the outburst of T CrB, a symbiotic with a lobe-filling red giant primary. We found that a blob ejected by the giant gets smeared out into a disk within several dynamical time scales. Once a disk is formed, it evolves as a normal viscous disk. We were able to account for the secondary maximum in T CrB if the viscosity within the disk grows from $\alpha \sim 10^{-5}$ to $\alpha \sim 3$ with a local growth rate of $2/\Omega$, where Ω is the orbital frequency.

In *He I Emission Lines in Symbiotic Stars*, D. Proga, J. Mikołajewska, and Kenyon analyzed the He I spectrum of symbiotic binaries. As in earlier studies, we found significant deviations from case B predictions for every system considered. In most cases, the $\lambda\lambda5876, 6678$ lines serve to distinguish between *S–type* and *D–type* symbiotics

in that $I(\lambda 6678)/I(\lambda 5876) \gtrsim 0.50$ for *S–types* and $I(\lambda 6678)/I(\lambda 5876) \sim 0.25$ for *D–types*. We followed Almog & Netzer (1989) and derive predicted intensity ratios for comparison with the observations. Our models indicate densities of $n_e \sim 10^{10}$ cm^{-3} for most *S–type* systems and $n_e \lesssim 10^{10}$ cm^{-3} for all *D–type* systems. The He I intensity ratios require large optical depths, $\tau_{3889} \sim 100\text{--}1000$, for most sources; the nebular sizes are then roughly 1 AU for *S–types* and 10 AU for *D–types*. These results agree with previous density and size estimates for symbiotics; thus, our He I model provides a useful diagnostic for the physical conditions within dense photoionized nebulae.

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