Light variation in fluorescent binaries

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The essential features of a fluorescent binary light curve model are described. The model applies to a wind and chromosphere irradiated by a hot companion, and is particularly aimed at symbiotic stars. The treatment is in terms of the combined light of all emission lines within a photometric band, rather than individual lines. The model wind is ionization-bounded and the model chromosphere is characterized by a density scale height. Eclipses and shadowing of wind and chromosphere by the stars are included. Photospheric continuum radiation also is included, as in standard binary star light curve models. Solutions are best done both subjectively and objectively, and in time rather than phase so that ephemeris parameters can be found together with light curve parameters. An application to symbiotic nova V1329 Cygni is briefly sketched and the main solution problems are outlined. Surprisingly, a large period change was found at about the 6 σ level, although it needs independent confirmation. Simultaneous fitting in U, B, and V has led to insights regarding periodic variation in this binary. Further specifics and numerical results will follow in a longer paper.

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1 Situation and motivation

Winds from red giant stars feed the interstellar medium and play a major role in advanced stellar evolution, so the study of their structure and kinematics is an important field. A probe of such winds could scarcely be provided better than by a moving point source of ionizing radiation, which indeed is found in symbiotic binaries, where a small ultraviolet (hereafter UV) source orbits through the wind and generates fluorescence. The UV source may be a high temperature region surrounding a hot star (*e.g.* around a white dwarf or neutron star) or may be the star itself. Orbits may be essentially circular or significantly eccentric. Fluorescence may dominate the optical spectrum in the more extreme examples, particularly in symbiotic novae.

Many photometric observations exist for symbiotic stars, with U,B,V data going back at least to the 1960's and photographic magnitudes back to the 1890's. Infra-red data exist, mainly from the 1980's on, but typically not in quantity. A bibliography of data papers has recently been published (Belczynski et al. 2000). However there often are no radial velocities for either star, or perhaps only emission line velocities, so in those cases light curves are the *only* potential sources of information about orbit and ephemeris parameters. Spectra (line strengths, profiles, continuum) are informative about astrophysical conditions and have been appropriately exploited (*e.g.* Nussbaumer and Vogel 1987; Proga et al. 1996; Schwank et al. 1997; Proga et al. 1998), but light curves also can be informative yet have mainly been neglected. Typical *light curve* models for fluorescent binaries are essentially non-quantitative, consisting of discussions, circle and straight line drawings, and calculations based on such drawings. Quantitative physical models could tap the well of information in large backlogs of light curve data. Although it may seem surprising, light curves can even help assess the relative importance of photo excitation vs. ionization-recombination or collisional excitation, averaged over all lines in the optical bands, because that distinction affects the spatial distribution of fluorescence.

2 A strategic model

Strongly fluorescent binaries can have mainly emission line spectra in optical bands, with hundreds or thousands of lines. In extreme cases the photospheric continuum may be minor or even negligible. How is one to model the *light curves*? Begin by recognizing both wind fluorescence and chromospheric fluorescence (fluorescence meaning any non-thermal process that degrades UV light to optical wavelengths). Fluorescence light curves can convey information on spatial distributions of emitting gas, seen in the light of the many emission lines, as there are eclipses and shadowing of UV irradiated winds and chromospheres and there is variation caused by changing distance in eccentric orbits. Individual emission lines might eventually be handled via properly calibrated spectra, but useful at start-up is to treat lines in aggregate, with appropriate parameterization. Let the red giant be star 1 and the UV source be star 2.

The light curve problem is divided into the following logical blocks, among which are a basic physical-geometrical part and a radiative part:

2.1 Ionization boundary

Assume an ionization-bounded fluorescent region in a constant speed red giant wind so that density, ρ, depends on distance, d, as d^{-2}. Consider only hydrogen ionization in regard to the ionization front (as in Seaquist, Taylor, and Button 1984; 1987, hereafter STB) and ionizing UV radiation from a point source (small hot companion). STB show that a quantity f is constant over the front, where (in the form by Wilson, 1999, equivalent to that by STB)

$$f = \frac{1}{2(1-\mu^2)}\left\{\mu - \frac{2\mu^2 r - \mu - r}{2\mu r - r^2 - 1} + \frac{1}{\sqrt{1-\mu^2}}\left(\arctan\left[\frac{r-\mu}{\sqrt{1-\mu^2}}\right] + \arctan\left[\frac{\mu}{\sqrt{1-\mu^2}}\right]\right)\right\}. \quad (1)$$

Here $r = d_2/D$ and $\mu = \cos\varphi$ in spherical coordinates $[r, \varphi]$ with origin at (ionizing) star 2, $f = X_{ion} = DL(4\pi\alpha k^2)^{-1}$, where D is instantaneous star separation, L is luminosity in terms of photon counts, $k = \dot{M}(4\pi m_{\rm H} v)^{-1}$, $\dot{M}$ is the wind mass loss rate, $v =$ wind velocity, and α is the hydrogen recombination rate to all excited levels (*cf.* STB). Light curves are not very sensitive to parameter X_{ion}, which specifies a particular f surface, as long as the surface is large enough to allow ionizing radiation to reach the red giant.

2.2 Radiative models

Set up another spherical coordinate system with origin at the wind source star (red giant) and positive polar axis toward the small hot star. Two radiative fluorescence models will be compared for agreement with the observed light curves. Model I has direct local conversion of UV to optical radiation, so geometrical attenuation of UV is important and re-emitted intensity goes as $d_1^{-2} d_2^{-2}$. Incident mean intensity J_{UV} is central to the computation and is computed by numerical integration over the two stars, as they are seen from each wind or chromosphere volume element. Fluorescent optical bandpass radiation is determined by efficiency factors ϵ_U, ϵ_B, and ϵ_V that fix the fraction of intercepted far UV energy dropped into the U, B, and V bands. Model I should be appropriate for photo-excitation. Incident J_{UV} does not enter the computation in Model II, where re-emitted intensity is proportional to ρ^2 (*i.e.* to the product $n_e n_{ion}$ of electron and ion densities), and thus proportional to d_1^{-4}. Bandpass emission is assumed to arise from an integral over the velocity distribution $f(v_e)$ of free electrons, with each velocity having a cross-section σ for interacting with an ion to produce a U, B, or V bandpass photon. That is, one treats integrals $\Phi_w = n_{ion}\int_{v_0}^{\infty} \sigma_w v_e f_w(v_e)\, dv_e$ and $\Phi_c = n_{ion}\int_{v_0}^{\infty} \sigma_c v_e f_c(v_e)\, dv_e$ as parameters of the problem for wind and chromosphere respectively. The integrals represent the numbers of such events per free electron per second, averaged over wind or chromosphere. Model II should essentially apply for collisionally excited or recombination lines. With hydrogen almost fully ionized, the realistic situation would be expected to lie closer to Model II, but should be somewhere between the two models in the general case.

2.3 Orbital eccentricity and shadowing of the wind

Allow the orbit to be eccentric, so there can be variable penetration of the UV source into the red giant wind. Eclipses and shadowing of the wind also are affected by eccentric geometry. Lack of fluorescence from the red star's shadow cone has interesting light curve consequences in the eccentric case, as the shadowed region becomes larger at smaller separations, where the giant star subtends greater solid angles at the UV source (a phenomenon not previously discussed in the symbiotic star literature).

2.4 Chromospheric scale height and eclipses

The red giant chromosphere is irradiated by the UV source, being partly or completely eclipsed by the red giant according to orbital phase (*chromospheric self-eclipse*) and shadowed on the side of the giant away from the UV radiation. The chromosphere has a density scale height, so chromospheric irradiation extends beyond the limits of the giant's photospheric irradiation and its disappearance over the horizon is not discontinuous.

2.5 Photospheric radiation

Stellar photospheric radiation is included, although it may be weak or even negligible in the more extreme fluorescence cases. All the usual binary star effects on the stars are also included, such as tides, thermal reflection, gravity brightening, and limb darkening, as in Wilson (1979; 1990). Red giant photospheric light is more important in infra-red than in optical bands, but most infra-red light curves of symbiotic stars are fragmentary at present and give only sketchy information.

3 Overview of solution problems

Observational papers on symbiotic stars show many cases of regular variation on the orbit periods, but the situation is complicated and at least several mechanisms seem to be at work. The extreme character of V1329 Cyg = HBV 475 was brought to the author's attention by D. Chochol. A detailed and illustrated explanation is in preparation (Chochol and Wilson, 2001, hereafter CW). Here follows a sketch of the V1329 Cyg situation, suitable for this preliminary note.

An overview of the binary was initially built up from spectroscopic considerations and by trial and error light curve experiments. V1329 Cyg spectra show that thermal reflection cannot be the main variation mechanism, as optical light is mostly in emission lines. In fact, thermal reflection cannot even account for a significant part of the variation because reflection should have comparable amplitudes in *IR* and optical bands, yet *J,H,K,L* light curves are nearly flat (CW and contained references). Light curve amplitudes are about $2\overset{m}{.}1$ in U compared to about $1\overset{m}{.}3$ in B and V, which is certainly a large difference. The difference can only be reasonably ascribed to bandpass-dependent relative wind vs. chromosphere luminosity. A large triangular wave in V1329 Cyg's optical light curves led to development of the present model, which synthesizes the wave in terms of superposed wind and chromosphere fluorescence. The B and V waves are nearly the same but U is quite different in both form and amplitude. So not only must the mechanism of V1329 Cyg's triangular wave be identified, but the U vs. B, V changes need to be understood. While the basic mechanism of wind or chromosphere fluorescence or both seems clear, the band to band changes are less obvious. First - what *does not* cause the changes? Density structure, ionization structure, and far-UV opacity do not change with bandpass, whether one thinks of an ionization bounded red giant wind or an illuminated giant chromosphere. The optical stellar continua are unimportant in V1329 Cyg, so what is left to differentiate U from B, V? Only the *relative brightness of wind and chromosphere* remains. Experience shows that a wind-only or chromosphere-only model cannot work simultaneously in U,B,V, so the relative amounts of wind and chromosphere energy dropped into the optical bands must differ significantly between U and the longer wavelength bands. To be specific, wind variation has only small amplitude because it mostly arises from variable penetration of the hot UV source into the red giant wind (eclipses of the wind occur but cause only minor variation). It might be imagined that sufficiently large orbital eccentricity could greatly boost wind fluorescence variation, but there is a compensating loss of wind irradiance at close distances because the giant subtends a larger solid angle at the source, so (*cf.* section 2.3) it shadows more of the wind. Chromospheric variation is therefore needed to gain sufficient variability, especially in U, but it has the wrong waveform for B and V. Briefly, a chromospheric light curve can have a broad minimum, as observed in U, while a wind light curve cannot. The broad minimum is produced by complete or nearly complete disappearance of the irradiated part of the chromosphere around red star inferior conjunction. There is no problem in fitting *U or B, V*, but fitting cannot be successful with the same parameters *unless we change the relative wind and chromosphere brightness between U and B, V.* Neither the wind nor chromosphere light curve waveforms or amplitudes individually change from band to band. What changes is the ratio of wind to chromosphere luminosity, with the chromosphere relatively bright in U and the wind relatively bright in B and V. The luminosities are comparable in the three bands.

The parameters listed in Table 1 can be separated into categories of orbit, aspect, ephemeris, star, wind, chromosphere, radiative (Model I), and radiative (Model II). Light will be declining in a post-outburst symbiotic nova, so time derivatives of one or more parameters need to be introduced for that case. The choice for Model I, in initial work, is dT_2/dt, where T_2 is the effective surface temperature of the ionizing source object (not necessarily a photospheric star temperature). Several other wind and chromosphere parameters surely change with time, but only the variation of T_2 is considered here so as to keep the number of parameters manageable. The choice for Model II is the Φ integral, or actually Φ_w and Φ_c separately in U, B, and V.

It is important to do both subjective and objective fitting in most parameter adjustment problems, and especially so where intuition needs to be developed and correlations are serious. Trial and error fitting of V1329 Cyg light curves was difficult but informative. Actually there was no success in fitting the U,

Table 1: Identification of parameters

Category	Symbol	Parameter
Orbit	$a = a_1 + a_2$	Relative orbital semi-major axis
”	e	Orbital eccentricity
Aspect	ω_1	Argument of periastron (red star)
”	i	Orbit inclination to plane of sky
Ephemeris	T_0	Initial epoch
”	P	Orbit period
”	dP/dt	Time derivative of orbit period
Stars	$r_1 = R_1/a$	Mean red giant relative radius
”	$r_2 = R_2/a$	UV source relative radius
”	q	Mass ratio, m_2/m_1
”	T_1	Red giant temperature
”	T_2	UV source temperature
” (Model I)	dT_2/dt	Time derivative of UV source temperature
”	misc. minor parameters	Gravity brigtening, reflection, etc.
Wind	$\rho_w\,(d_1 = a)$	Wind density at distance a
”	X_{ion}	STB ionization parameter
” (Model I)	$\kappa_{w,uv}$	Effective far UV wind opacity
” (Model I)	$\epsilon_w\,(U, B, V)$	Energy fraction deposited in given band
” (Model II)	$\Phi_w = n_{ion} \int_{v_0}^{\infty} \sigma_w v_e f_w\,(v_e)\,dv_e$	Emitted photons per second per free electron at wind reference location
” (Model II)	$d\Phi_w/dt$	Time derivative of Φ_w
Chromosphere	$\rho_c\,(h = 0)$	Density at base of chromosphere
” (Model I)	$\kappa_{c,uv}$	Effective far UV chromospheric opacity
” (Model I)	$\epsilon_c\,(U, B, V)$	Energy fraction deposited in given band
” (Model II)	$\Phi_c = n_{ion} \int_{v_0}^{\infty} \sigma_c v_e f_c\,(v_e)\,dv_e$	Emitted photons per second per free electron at base of chromosphere
” (Model II)	$d\Phi_c/dt$	Time derivative of Φ_c

B, and V curves *as a set* by trial and error, although the separate curves could be represented satisfactorily. However they were subsequently solved by Least Squares via the Differential Corrections process, and those solutions were successful for both Model I and Model II. With l_O, l_C respectively meaning observed and computed light, $r = l_O - l_C$ a residual, p_k a parameter, and Δp_k a correction to an input p, the equation of condition is

$$r = \frac{\partial r}{\partial p_1}\Delta p_1 + \frac{\partial r}{\partial p_2}\Delta p_2 + ... + \frac{\partial r}{\partial p_n}\Delta p_n. \quad (2)$$

Solutions were done with time as the independent variable (rather than phase) so that the slow decline in system brightness could be modeled and ephemeris parameters T_0, P, and dP/dt could be extracted.

For the model to reproduce V1329 Cyg's observed light curve symmetry, we must be viewing the orbit nearly along its major axis, which means that the argument of periastron, ω_1, is close to $\pi/2$. Thus the amplitudes of wind and chromosphere fluorescence add almost directly and their summed waveform is nearly symmetrical about the conjunctions. The mass ratio, m_2/m_1 cannot reasonably be found from light curves in this case and was assumed to be 0.15. Proper discussion of the Differential Corrections results would exceed a reasonable space for this overview note, but will be included in CW. Briefly, the Least Squares solutions found that e ranges between 0.10 and 0.20 and i between $\approx 75^\circ$ and 90° under various assumptions. The argument of periastron indeed comes out close to $\pi/2$ under both Model I and Model II. The red giant nearly fills its lobe under Model I, but is well detached under Model II. Parameters have reasonable values under both models. Potentially the most interesting is that there appears to be an enormous dP/dt of about -0.00200 ± 0.00035 *s.d.* which, if real, means that the period has been dropping by about 2 days per cycle over the past 30 years. Could the large dP/dt be due to a tradeoff against $d\omega/dt$? Attempts to solve for apsidal motion found $d\omega/dt$ not significantly different from zero (about $+1.7 \pm 1.7 \times 10^{-5}$ radians per day), and the correlation matrix shows that $d\omega/dt$ is only slightly correlated with dP/dt. Results for dP/dt were nearly the same whether $d\omega/dt$ was adjusted or not. Note that dP/dt was found from the light curves in their entirety, not merely from minima or maxima used as tick marks. The utilization of whole light curves can allow one to uncover period changes in noisy or astrophysically unclean data. However V1329 Cyg's dP/dt needs confirmation.

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