Novae and Accretion Disc Evolution

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Abstract

At outburst the classical nova generates an extended optically-thick wind driven by radiation pressure in the continuum. At maximum light the optical luminosity is close to the Eddington-limit. The subsequent decline illustrates the interaction between radiation and matter in a wind which gradually thins as the mass loss rate falls at an approximately constant Eddington-limit luminosity. As the wind thins so the effective photosphere shrinks back into the underlying binary, and an increasing fraction of the radiation is emitted at ultraviolet wavelengths. Model atmosphere computations show how the increasing flux of ultraviolet photons is associated with the shell becoming more and more ionized through radiative ionization. Attempts to study the internal structure of the wind confirm that the luminosity must be close to the Eddington limit and must be expelled from close to the white dwarf surface. It is generally agreed that the outbursts are caused by runaway nuclear burning of accreted material at the white dwarf surface, but it is possible that some events of the classical nova type may be caused by runaway accretion at a super-critical rate.

In dwarf novae very different behaviour is evident. The outbursts are located within the accretion disc and are generated either by mass-transfer bursts due to dynamical instability of the Roche-lobe filling star, or by an instability within the disc itself. In either case the eruption behaviour is due to an enhanced accretion flux through the accretion disc. One important aspect of the radiation hydrodynamics is the luminosity generated by impact of the mass-transfer stream with the accretion disc and penetration by the stream within the disc. Attempts at examining this penetration region are described and results compared with observed behaviour of disc evolution through the course of an outburst. The possibility that disc instabilities will not propogate in realistic discs which deviate from axial symmetry is considered.

1 Photospheric Boundary Conditions and Optically Thick Winds

The concept of a nova envelope as an expanding optically thick wind dates back at least to 1929 when PIKE (1) pointed out that the initial brightness increase required an "outrush of gas taking place with a velocity not less than 200 km s^{-1}." He then describes the subsequent evolution in the following manner. "The expansion cannot, of course, continue indefinitely, for presently the star begins to fade; but at the same time the gas which is actually moving outwards at the time of maximum must continue to do so, as its velocity exceeds the parabolic value for the star. An inward contraction of the photosphere is, however, quite possible, even though the gases themselves are moving outwards; we have only to suppose that the velocity and density of the shells that are being shot off from the inner core begin ultimately to diminish. There will then be a sort of "clearing" of the atmosphere; we shall be able to see further and further into the gas as time goes on, and the photosphere will actually appear to be contracting."

Although a "clearing" atmosphere is associated with increasing velocity at a constant mass loss rate, the description is otherwise an accurate statement of the basis of the continuous-ejection, optically-thick model of classical novae. Later work which adopted those ideas includes GERASIMOVIC (2), COWLING (3), WHIPPLE and

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PAYNE-GAPOSHKIN (4) and GROTRIAN (5). More recent work has been FRIEDJUNG (6) and BATH and SHAVIV (7). Here we adopt the scheme of the latter authors with a general description of the envelope in terms of a sequence of steady-state winds.

Assuming that the gas outflow is approximately steady and spherically symmetric then from continuity the density at radius r is,

$$\rho = \frac{\dot{m}}{4\pi r^2 v} \qquad (1)$$

where $\dot{m}$ is the steady mass loss rate. The position of the photospheric surface will depend on the run of opacity, K, and velocity, v, in the optically thin region extending from the photosphere to the observer. As a first approximation we take these as constant. The observed expansion velocity greatly exceeds the local escape velocity and gravitational deceleration is therefore unimportant. The opacity may be shown to be dominated by electron scattering and therefore opacity variations are spread over an extended spatial region. As we will show the position of the photosphere is strongly wavelength dependent but at this stage, to illustrate some of the properties of optically thick winds we assume a scattering opacity throughout the optically thin region. The position of the photosphere is then determined by the line-of-sight optical depth given by $\tau = 2/3$ and

$$\frac{2}{3} = \int_{r_s}^{\infty} K\rho dr = \frac{K\dot{m}}{4\pi r_s v_s}$$

where subscripts s denote the photospheric surface. We obtain

$$r_s = \frac{3K\dot{m}}{8\pi v_s} \qquad (2)$$

Thus the photosphere shrinks as either the mass loss rate falls or the outflow velocity increases. Clearly, as the mass loss rate falls the photosphere moves inward and we have a "clearing" atmosphere. Changes in $\dot{m}$ or v can be considered within the steady-state assumption so long as the variations in $\dot{m}$ and v are sufficiently slow that the changes are spread, by expansion of the flow, over a large enough volume. In practice this quasi-steady assumption is valid for slow novae and increasingly breaks down for fast and very fast novae. In these later cases the structure must change towards prompt ejection of a shell.

The approximate photospheric conditions in the nova photosphere can be established once the bolometric luminosity is known. For 30 novae in M31 ARP (8) showed that the maximum magnitude was in the range -6.2 to -8.5. ROSINO (9) has confirmed this narrow magnitude range. We conclude that the luminosities at maximum light lie in the range 6×10^{37} to 6×10^{38} erg s^{-1}. During the decline estimates of the photospheric temperature, using a variety of methods of determination, indicate increasing temperatures and hence increasing bolometric corrections. However, only with direct ultraviolet observations by GALLAGHER and CODE (10) did it become clear that these were sufficiently large to require that the total bolometric luminosity was constant throughout the main stages of the optical decline. It was pointed out independently by BATH and SHAVIV (7) and by GALLAGHER and STARRFIELD (11) that this was most probably a general property of classical novae as a whole. According to this work the optical decline of a classical nova is primarily caused by flux redistribution to shorter wavelengths as the photosphere contracts, while the energy loss rate remains approximately constant. Thus the luminosity is close to 10^{38} erg s^{-1} throughout the optical evolution of the nova outburst, and close to the Eddington limit for a solar mass object.

Radiation pressure in the continuum may be the driving term in wind ejection -not only at maximum light but continuing through the subsequent optical decline. This concept of a radiation pressure driven wind that slowly evolves through stages of decreasing rates of mass loss is the main feature of recent studies of the structure of the ejecta.

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The effective temperature of the photosphere assuming a luminosity $L = \alpha L_{ed}$, where α is of order unity, is then

$$T_e = \left(\frac{\alpha L_{ed}}{4\pi\sigma r_s^2}\right)^{\frac{1}{4}} = \left(\frac{256\pi^2\alpha GM}{9a}\right)^{\frac{1}{4}} \frac{1}{K^{3/4}} \left(\frac{v_s}{\dot{m}}\right)^{\frac{1}{2}} \qquad (3)$$

At constant α, the temperature is a function of v_s and $\dot{m}$ only. This is also true of the photospheric density, which from the equation of continuity (Equation 1) and Equation 2 is,

$$\rho_s = \frac{16\pi v_s}{9K^2\dot{m}} \qquad (4)$$

The equation of state provides similar relations for the gas and radiation pressure,

$$Pg_s = 3^{\frac{1}{2}}\left(\frac{4}{3}\right)^3\left(\frac{R}{\mu}\right)\left(\frac{\alpha\pi GM}{K^{11}a}\right)^{\frac{1}{4}}\left(\frac{v_s}{\dot{m}}\right)^{3/2} \qquad (5)$$

$$Pr_s = 4\left(\frac{4}{3}\right)^3\left(\frac{\alpha\pi GM}{K^3}\right)\left(\frac{v_s}{\dot{m}}\right)^2 \qquad (6)$$

The physical state of the photosphere is determined by the ratio $v_s/\dot{m}$. Through equation (3) we may express the physical variables as functions of T_e only. For a scattering opacity and hydrogen abundance X = 0.7 the relations are,

$$\begin{aligned}
\rho_s &= 4.43 \times 10^{-13}\left(\frac{T_e}{10^4}\right)^2 \alpha^{-\frac{1}{2}}\left(\frac{M}{M_\odot}\right)^{-\frac{1}{2}} \text{ g cm}^{-3} \\
Pg_s &= 5.97 \times 10^{-1}\left(\frac{T_e}{10^4}\right)^3 \alpha^{-\frac{1}{2}}\left(\frac{M}{M_\odot}\right)^{-\frac{1}{2}} \text{ dyne cm}^{-2} \\
Pr_s &= 2.52 \times 10\left(\frac{T_e}{10^4}\right)^4 \text{ dyne cm}^{-2} \\
r_s &= 4.66 \times 10^{12}\left(\frac{T_e}{10^4}\right)^{-2} \alpha^{\frac{1}{2}}\left(\frac{M}{M_\odot}\right)^{\frac{1}{2}} \text{ cm}
\end{aligned} \qquad (7)$$

At maximum light the effective temperature of the nova envelope is $T_e \approx 10^4$ °K. We conclude that the photospheric densities are low by stellar standards, the pressure is indeed dominated by radiation pressure and the size of the optically thick envelope at 5×10^{12} cm is very much larger than the underlying binary separation which is typically $\approx 10^{11}$ cm. At outburst the entire binary system is surrounded by an opaque optically-thick wind almost two orders of magnitude larger than the binary system itself.

In conditions in which the bolometric luminosity is constant through the decline, the optical luminosity will be determined by the bolometric correction at each decline stage. Since the bolometric correction is fundamentally determined by the effective temperature we conclude that as the nova declines so the physical state described by Equations (7) will be approximately the same in the photosphere at the same magnitude below the optical maximum in all novae. For an illustrative example BATH and SHAVIV (7) showed that with a Plank spectrum radiating predominantly at optical wavelengths in the Rayleigh-Jeans region of the Planck curve, the correlation with decline stage in magnitudes, ΔM, is given by

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$$
\begin{aligned}
T_e &= 15{,}280 \times 10^{(\Delta M/7.5)}\ {}^{\circ}K \\
r_s &= 1.99 \times 10^{12} \times 10^{(-\Delta M/3.75)}\ \alpha^{\frac{1}{2}} \left(\frac{M}{M_{\odot}}\right)^{\frac{1}{2}}\ \mathrm{cm} \\
\rho_s &= 1.03 \times 10^{-12} \times 10^{(\Delta M/3.75)}\ \alpha^{-\frac{1}{2}} \left(\frac{M}{M_{\odot}}\right)^{-\frac{1}{2}}\ \mathrm{g\ cm^{-2}} \qquad (8) \\
Pg_s &= 2.13 \times 10^{(\Delta M/2.5)}\ \alpha^{-\frac{1}{2}} \left(\frac{M}{M_{\odot}}\right)^{-\frac{1}{2}}\ \mathrm{dyne\ cm^{-2}} \\
Pr_s &= 1.37 \times 10^{2} \times 10^{(\Delta M/1.875)}\ \mathrm{dyne\ cm^{-2}}
\end{aligned}
$$

The non-analytic equivalent of these relations for the complete Planck spectrum is straightforward to obtain (BATH (12)). In the case of the general model atmosphere problem the same principal applies.

This explicit dependence of the physical conditions on the decline stage leads to the expectation that the spectral appearance of classical novae should be the same at the same stage of decline of all novae. As a general property this is the case. As MCLAUGHLIN (13) emphasises, the spectral appearance at any stage of the decline is closely related to the amount that the optical light has declined from maximum. Thus, for example, the Orion stage begins between 1 and 2 magnitudes below maximum light. There then follows in sequence the HeI flash, the [OIII] flash, disappearance of the principal absorption lines and the appearance of emission lines of oxygen and nitrogen in a time sequence of increasing ionization level. The ionization fractions in the photospheric region due to photoionization have been estimated by BATH (12) to be 50% at the decline stages shown in Table 1.

Table 1 Ionization level as a function of decline stage

ΔM	Ionization level
1.45	OII
1.55	NII
2.85	NIII
3.15	OIII
3.75	NIV
4.10	OIV
4.85	OV, NV

From observed estimates of the effective temperature and the associated outflow velocity the mass loss rates required to generate the necessary optically-thick conditions can be estimated using Equation (3). The deduced mass loss rates are $10^{21} - 10^{22}$ g s^{-1} at maximum light and then decrease over the decline as the wind "clears" and the photospheric temperatures increase. For typical outburst durations of 10-100 days at average mass loss rates of 10^{21} g s^{-1} the total mass lost in the outflowing envelope is 10^{-5} $M_{\odot}$. This agrees with estimates based on direct measurements of the nova shell mass in the nebular stage. At the same time these values for the mass loss rate imply an energy input rate at the base of the envelope of $GM\dot{m}/R$. Substituting values for the white dwarf surface we obtain 10^{38} erg s^{-1}. Thus there is approximate equipartition between the energy flux in the wind and the radiative energy flux.

2 Optically-thick Wind Models

The structure of optically -thick winds generated by nova eruptions has been investigated by RUGGLES and BATH (14) and KATO (15). Assuming that at any stage the variations in $\dot{m}$ are small within the optically thick region, the envelope is described

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in terms of a quasi-stationary sequence of spherically symmetric winds. The photosphere is assumed to be a well defined surface below which LTE conditions apply. Integration of the equations of momentum and energy conservation in these conditions give the required envelope solutions for a range of values of $\dot{m}$. In non-static conditions two contributions to the luminosity are present. Firstly, the luminosity as measured in the fluid reference frame, which in optically-thick conditions is the diffusive fraction of the total radiative luminosity. Secondly, there is the advective luminosity, which is the fraction of the luminosity that is carried out by material motion of the fluid. The surface photospheric conditions (Equations (2) and (3)) provide the outer boundary conditions which must be simultaneously satisfied. The presence of a critical point further constrains the solutions to be specified by two free parameters. These are the mass loss rate, $\dot{m}$, and the critical point radius. KATO (15) employs an additional constraint through balance of energy loss in the wind by energy generation through nuclear burning.

The resulting winds have the following main features. At highest mass loss rates $\gtrsim 10^{21}$ g s^{-1} there exists a trapping radius below which matter is sufficiently optically thick that radiative transport is dominated by advection. Above this point radiation diffuses through the expanding wind. At lower mass loss rates the diffusive luminosity is dominant at all points outside the critical point. Outflow velocities of 500-1000 Km s^{-1}, approaching the observed values, are only obtained when the critical point lies close to the white dwarf surface. In models where the critical point lies well above the white dwarf surface the photospheric velocities are considerably reduced. These can be taken to describe classical novae only if some subsequent acceleration mechanism, such as line acceleration, is present.

Densities and temperatures are such that complete ionization and a scattering opacity are good approximations through the bulk of the wind. Near the photospheres of the highest mass-loss rate models, at temperatures below 2 x 10^4 °K, hydrogen and helium recombination occur with significant continuous absorption. KATO (15) shows that the increased opacity in this case can lead to the luminosity being locally super-Eddington.

At the critical point the diffusive luminosity is close to the Eddington limit, which, as MARLBOROUGH and ROY (16) have shown, cannot be exceeded. No restriction applies to the advective flux, and the total luminosity can be well above the Eddington limit at the critical point.

At highest $\dot{m}$ the kinetic energy of the matter is the dominant term in the energy balance above the critical point. The advected flux is largely employed in overcoming the gravitational potential by the matter. At the critical point these two terms are approximately equal. The advective flux decreases as energy is deposited into kinetic energy of the matter, and, to a lesser extent into the co-moving diffusive luminosity.

Above the critical point acceleration in the supersonic region is confined to a region close to the critical point itself. Above the acceleration region matter cruises out to the photosphere with insignificant subsequent acceleration.

At the photosphere the luminosity is always close to L_{ed}, in agreement with nova observations. The excess energy has gone both into gas kinetic energy and into overcoming the deep gravitational potential of the white dwarf. These properties of a radiative luminosity close to the Eddington limit and a high final kinetic energy when the critical point lies close to the white dwarf surface are in agreement with classical nova observations.

As the mass loss rate declines to the point where the photospheric radius is comparable with the binary separation so the assumption of optical thickness and LTE begin to break down, as does the assumption of spherical symmetry. It is likely that in these later stages line and photoelectric absorption proposed by FERLAND and YOUNGER (17) will begin to play an increasingly important role producing further acceleration near the photosphere. In no cases are the most extreme ejection velocities of

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~3000 Km s^{-1} obtained. These are observed most frequently in fast novae, that is, the class which are most poorly described by stationary conditions. None-the-less the properties of the models are in accord with the view that, at least in slow novae, the classical nova envelope has the structure of an optically-thick wind with a photospheric luminosity which is close to the Eddington luminosity over the bulk of the optical decline.

3 The Continuous Spectrum

Model atmosphere calculations can be used to check on the validity of the photospheric boundary conditions and also represent the next stage towards detailed understanding of the spectral evolution of novae. HARKNESS (18) has computed model atmospheres allowing for the effects of scattering and including the frequency dependence of the radiation field to compute the emergent continuum flux.

The optically-thick wind models achieve terminal velocity well below the photosphere, hence the photospheric region and the optically thin exterior have a density distribution which varies as $1/r^2$. As a consequence the nova atmosphere suffers extreme atmospheric extension. The radiative transfer equations must be solved in spherical geometry and cover an extremely large range in temperature, density and radius. As stated above the main source of opacity above the critical point is electron scattering. Continuous absorption opacity is only present in a narrow region near the photosphere at high mass loss rates. In these conditions large opacity changes occur at the ionization edges of the most abundant ionic species. As a consequence the radius of unit optical depth varies considerably with frequency. The LTE model atmospheres computed by HARKNESS (18) exhibit emission edges in the continuous spectra through a combination of scattering and geometrical effects (CASSINELLI (19), GEBBIE (20)). These extreme extended model atmospheres show major departures from a blackbody spectrum. Models show an infrared excess due to the Schuster mechanism acting in scattering dominated atmospheres and to the geometrical effect which increases the effective emitting "surface area" at longer wavelengths. There is effectively a larger emitting volume of cool matter. In comparison with an equivalent black body spectrum at the same effective temperature as the atmosphere the models exhibit both an infrared excess and an ultraviolet excess up to a major absorption edge. Departures from LTE may be large especially in low $\dot{m}$ models with higher temperatures and lower density.

As models with decreasing mass loss rates are compared they exhibit the expected gradual increase of excitation and ionization. Thus at highest mass loss rates neutral atoms dominate the spectrum. This agrees with observations near maximum light and in the early post maximum. The low "photospheric" temperature of ~9×10^3 °K is also in agreement with observational estimates. At lower mass loss rates the main features remain. The hydrogen emission edges become stronger. The absorption edges due to ionization from excited states of NI become progressively more apparent.

As the temperature in the "photospheric" region increases with decreasing $\dot{m}$ singly ionized and then doubly ionized species become more and more important in the optically thin part of the envelope. At mass loss rates of a few times 10^{21} g s^{-1} the properties are roughly consistent with the Orion stage of the nova decline. The dominant ions at this stage are OII and NII.

The model may be expected to break down when the photospheric radius is only a few times larger than the binary separation. However, it is evident that the trend of increasing excitation/ionization will continue as the mass loss rate declines further. The nova wind will finally increasingly resemble the strong stellar wind of an early-type star. Regarding models with successively decreasing $\dot{m}$ as a time-ordered sequence, then the increasing degree of ionization and the shift of the emergent flux towards the ultraviolet is in agreement with the spectral development of classical novae described by MCLAUGHLIN (13) and the ultraviolet observations of the slow nova FH Ser by GALLAGHER and CODE (10). Further refinements of atmosphere models will require that non-LTE is included and, due to cool temperatures at large radii in the spherical extended atmosphere, molecule and grain formation require inclusion.

The mechanism which causes the runaway to super-Eddington limited outflow is widely thought to be runaway nuclear burning of accreted hydrogen and helium rich fuel on the white dwarf surface. However all nova-like behaviour may not be restricted to this mechanism. This is particularly true of symbiotic stars which show nova-like eruptions (e.g. CI Cyg, Z And and T Cor Bor). In these, some events of the classical nova type may be caused by runaway accretion at abnormally high rates. If these remain sub-Eddington then disc evolution of a giant accretion disc is the relevant model. However, if the accretion rate reaches super-Eddington rates then outflow and optically thick winds surrounding the accreting component are to be expected.

4 Viscous Disc Evolution

The effects of dynamically driven bursts of mass transfer in the sub-Eddington regime can be studied with time-dependent disc evolution models. The general evolution equation for a thin, viscous, Keplerian disc is

$$\frac{\partial \Sigma}{\partial b} = \frac{3}{R} \frac{\partial}{\partial R}\left(R^{\frac{1}{2}} \frac{\partial}{\partial R} (\nu \Sigma R^{\frac{1}{2}})\right) + \frac{1}{2\pi R} \frac{\partial \dot{m}}{\partial R} + \frac{1}{\pi R}\left(R \frac{(1 - R_K^{\frac{1}{2}})}{R^{\frac{1}{2}}} \frac{\partial \dot{m}}{\partial R}\right) \tag{9}$$

The vertical structure is described by averaged "one zone" vertical structure equations (LIGHTMAN (21), BATH ET AL. (22)). Here ν is the kinematic viscosity, Σ the surface density, $\partial\dot{m}/\partial R$ the rate at which matter is supplied from the mass transfer stream impacting into the disc, and R_K is the circular Keplerian radius at which the mass transfer stream would orbit if there were no viscous angular momentum transfer due to viscosity within the disc.

The first term describes angular momentum redistribution through viscous stress. It leads to the spread of material initially orbiting at R_K into a disc configuration. In this disc matter spirals inward, losing angular momentum to more slowly rotating outer regions and radiating the energy dissipated as a consequence through both sides of the disc. The second term describes the transfer of matter from the mass transfer stream into the disc by stream-disc impact. The third term describes the way in which this new material attempts to squeeze the disc into an annulus orbiting at radius R_K, deep within the outer radius at R_{OUT}. At the outer radius it is assumed that angular momentum can be removed by tidal forces of the companion with complete efficiency. In general $R_K \approx 0.1\ R_L$ while $R_{OUT} \approx 0.8\ R_L$.

$\partial\dot{m}/\partial R$ describes the rate of matter input in the stream. This may be parametrized as

$$\frac{\partial \dot{m}}{\partial R} = \beta \Sigma \left(\frac{GM}{R}\right)^{\frac{1}{2}} \tag{10}$$

where $\beta < 1.0$. If β equals 1.0 then all disc energy is used in accelerating stream material into circular orbits. A reasonable estimate of β is less than 0.5 which corresponds to equipartition of energy.

The resulting time-dependent disc evolution models can be compared with dwarf nova outbursts, whose eruptive behaviour is widely agreed to be due to sudden enhancement of the accretion flux through the disc. Simultaneous optical and UV spectral evolution of the dwarf nova system VW Hydri have been described by HASSAL ET AL. (23). They find that the ultraviolet flux is delayed on the outburst rise by some 12 hr. The optical flux rises first with the ultraviolet flux unaffected. 12 hrs later the ultraviolet flux rises to produce a normal disc-like spectrum.

The spectral evolution of a theoretical disc, with the spectrum computed assuming a black-body spectral distribution from each radial point in the disc, shows essentially the same features. The model assuming $\beta = 0.3$ shows the same spectral reddening on the rise and is a general feature of all models subject to a rapid increase in the transfer rate. The reddening on the rise is a direct result of enhanced dissipation in cool outer-disc regions as the mass-transfer burst first penetrates and mixes in the outer disc regions and then diffuses inwards through viscous transport.

There exists a relation between the outburst decay time and the binary period in dwarf novae. The eruption decay time increases with the binary period. Theoretically the eruption decay time is determined by the size of viscosity, and the observed decay time provides a test of its quantitative value. Disc evolution models fit the observed relation for a value of $0.5 < \alpha < 3.0$. The cause of the relation discovered by BAILEY (24) is simply the increase in the time taken for material to diffuse through larger discs of longer period systems.

The influence of stream penetration is to generate a delay in the response of the bright spot at the point of impact of the stream with the outer disc edge. Theoretical models show that for $\beta \approx 0.5$ the bright spot development is delayed. This is due to the time taken for the disc to evolve, transport material to the outer regions, and strip the impacting stream sufficiently close to the disc edge to generate an anisotropic radiation pattern at the edge. When the stream penetrates a distance deeper than the outer edge thickness, then that fraction of material which penetrates further radiates its excess kinetic energy through top and bottom of the disc and produces no obvious anisotropic radiation component.

An alternative to bursting mass transfer models of dwarf nova outbursts are the disc instability models. These oscillate between states of high and low viscosity, generating periods of disc storage and disc accretion. They may be physically produced through the existence of two stable branches in the integrated viscosity/surface density plane. The strong and oppositely directed temperature dependence of the opacity in the temperature range where hydrogen ionizes leads to the characteristic 'S' shaped form for the μ/Σ relation, where μ is the integrated viscosity ($= H\nu$). With the usual assumption of complete azimuthal symmetry, outbursting or eruptive behaviour is obtained in accretion discs which are fed by a constant supply of material in the mass transfer stream. The type of behaviour produced depends strongly on the form of the μ/Σ curve. The wide range of behaviour does not seem to give natural outbursts of precisely the form observed in cataclysmic variables, but individual cases can be found which do give large eruptions. Eruptive cases occur when the unstable region migrates unrealistically out of the inner disc boundary. The more normal behaviour is a continuous oscillation.

In order to examine the dependence of disc instability behaviour on the assumption of smoothly-varying axially-symmetric orbits the viscosity has been subjected to a perturbation in the form of a sinusoidal variation in α with the local Keplerian period. This simulates in an approximate way the viscosity variations which may be present in realistic discs which allow deviations from axial symmetry. When variations in α are a factor ≈ 10 around each orbit the instabilities do not propogate globally. The behaviour adopts the form of rapid flickening. It may thus be the case that in discs which do not assume axial symmetry, the global disc instability disappears and is replaced by flickering behaviour and thereby accounts for the observed flickering behaviour in the quiescent state of dwarf novae.

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Discussion

Krolik: 1) What "α" did you use for the viscous timescale in your dwarf nova light-curves? 2) Is there a physical argument you could give to show why the amount of mass transferred by a stellar pulsation matches what is required for the dwarf nova outburst?

Bath: 1) The value of α assumed was $\alpha = 1.0$. This value is required to obtain the same rate of decline after outburst as is observed. 2) Spherical hydrodynamic models give mass loss rates over the whole stellar surface of $\approx 10^{22}$–10^{23} g s^{-1}. In practice these mass loss rates must be reduced since the instability is confined to a region a few scale heights in radius around the inner Lagrangian point. This reduces the mass loss rate during outbursts to 10^{17}–10^{18} g s^{-1}. This value matches the values required for the dwarf nova outburst.

Meyer: 1) Your questioning of the azimuthal symmetry in the pre-outburst disk offers the opportunity to remark how such symmetry could be established in disk outburst models. In these models there is a gradual buildup of the critical density after depletion by the last outburst and before ignition of the following one on the long diffusive timescale of the cold state. Azimuthal shear smoothing on the small radial scale $\approx$ H happens on the much shorter timescale $\approx$ H/v (circumference/sound speed), and even faster for larger scales. Thus the disk will be very close to "ignition" everywhere azimuthally when it ignites at any one point, and by the smallest addition of heat ignition will spread very fast. 2) The disk outburst models rest on the computed time evolution of the outburst, and yield a surprising consistency in many aspects. It would be nice to have similarly detailed computations performed for the mass overflow modulation picture.

Bath: Work has been published which shows that the dynamical instability of the red component gives outburst periods lasting between hours and days with mass loss rates in the vicinity of the Lagrangian point of 10^{17}–10^{18} g s^{-1}. We are now completing work on more complete models which take account of the red components three dimensional structure. Similar instabilities are found in these models.

Ebisuzaki: Is it possible that the luminosity can exceed the Eddington luminosity in classical novae? If so, why?

Bath: In fast novae there is a brief period at maximum light when the luminosity may exceed the Eddington limit. This occurs in a phase when the outflow is still dynamic. The Eddington limit only imposes a limit to the energy generation rate when the classical nova has settled down to an approximately steady outflow condition.

Ögelman: How does the observed X-ray emission during the outburst stage fit in with the continuous mass ejection model of classical novae?

Bath: X-ray emission in the classical nova outburst must come from shocked gas outside the "photosphere" of the outflowing wind. Only after the light curve has declined back to the quiescent level is it possible to see the white dwarf unaffected by the opaque wind. At these late stages X-ray emission may be visible from the

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boundary layer region surrounding the white dwarf.

Chanmugam: Is there a relationship between the orbital period and the occurrence of dynamical instabilities in the secondary?

Bath: Dynamical instabilities in the secondary star exist only when the star is cool enough to contain ionization zones. It is the reduced value of the ratio of specific heats to values below 4/3 (the gamma mechanism of stellar pulsations) that combined with the turnover in the gravitational potential at the L_1 point gives dynamically unstable mass transfer bursts. Low mass main sequence stars and giants are unstable. There is a relation between the outburst decline rate and the binary period (the Bailey relation). Longer period systems have longer decay rates. The cause of this is the increase in the outer disc radius in the longer binary period system. It takes longer for material to diffuse through the larger discs in such systems.

Kritz: We have two quite different theories which both can apparently fit the observed light curves of dwarf novae. But nobody has tried to compute the distribution of energy in the spectra or in line profiles. I believe that such calculations could help to decide which theory corresponds better to observations.

Bath: The observed continuum spectra indicate that during the rise to outburst the spectrum first rises in the optical region and only after 0.5 day rises in the ultraviolet. This indicates that the mass accretion event starts in the outer regions of the disc and then propogates inward. This is exactly the behaviour predicted by mass transfer burst models and one class of disc instability model. Both black body models and models based on model atmosphere spectral distributions in stars have been used to compare with the observed spectral evolution. Further work on self-consistent model atmospheres of discs is urgently needed.

Owocki: 1) Your classical novae wind solutions seem to have the peculiar property that solutions with higher $\dot{m}$ also have higher V_∞. Can you explain how this can be so in a model with a characteristic amount of energy available to drive the wind? 2) These classical novae wind models seem very similar to the winds from Wolf-Rayet stars, which are usually described as being driven by radiation forces on spectral lines. Please comment on this similarity in general, and on the role of lines in your model in particular.

Bath: 1) The models with higher $\dot{m}$ have a much higher ratio of advected luminosity to diffusive luminosity at the critical point. This increased proportion of the advective luminosity (which can exceed the Eddington luminosity by factors ≈ 10 at the critical point) both drives the higher $\dot{m}$ values and increases the kinectic energy in the wind, resulting in larger values for V_∞. 2) In the steady-state models we have computed the dynamics only in the optically thick region of the wind. It is clear that acceleration by line forces will probably also occur above the "photosphere" of the wind models, but we have not computed the contribution from this mechanism. There is almost certainly a close analogy between optically thick wind models of novae and the outflow from Wolf-Rayet stars. They both achieve mass loss

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rates of 10^{-5} $M_\odot$ yr^{-1} at luminosities close to the Eddington limit. In the nova case one has a firm handle on the inner boundary condition since the wind must start from a region above the white dwarf surface. The same constraint does not apply to Wolf-Rayet stars.

McCray: I would like to point out that the temperature ($\sim 10^7$ K) at the base (10^9 cm) of your models for classical novae is a factor $\lesssim 1/10$ that calculated by Starrfield (or Fujimoto) in the nuclear burning region.

Bath: This is true, but is a consequence of limiting our models to the supersonic part of the wind. If we were to integrate below the critical point the temperature at the base of the wind would incrase. Kato has computed models which include some treatment of the burning region. These models suffer from having low outflow velocities ≈ 100 km s^{-1} rather than the observed values ≈ 1000 km s^{-1}, but they do reach nuclear burning temperatures at the base of the wind.

Boyle: How do your model outburst light curves depend upon the amount of penetration of the stream into the disc?

Bath: The effects of stream penetration on the outburst light curves is negligible for the disc light but is significant for the hot spot flux. At outburst the stream penetrates well into the disc and most of the stream impact energy is emitted within the disc rather than from the hot spot region. Only when the disc has evolved does the stream get pushed out to the edge by the increasing mass flux in the disc. Thus there is a delay in the brightening of the bright spot region, as is observed.

Fisher: As the outflow in classical novae is driven by radiation, the flow might be unstable to convection or Rayleigh-Taylor instability. Could you comment on what is known about this?

Bath: It is well established that the ejecta of classical novae do break up into shells. This may be due to Rayleigh-Taylor instabilities or to opacity effects that can lead to clumping in a radiatively driven outflow. There may be close similarities between these winds of active galactic nuclei in this respect.

Taylor: In your cartoon of classical novae you drew a spherically symmetric wind. Are there observational or theoretical reasons to expect that this is in fact the case, and is your model calculation critically dependent on spherical symmetry?

Bath: There is no evidence for spherical symmetry. I have made that assumption to facilitate calculation of the model. Without this assumption one would need to consider a directionally dependent optical depth, which would be difficult. I don't believe this model is severely dependent on spherical symmetry.

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