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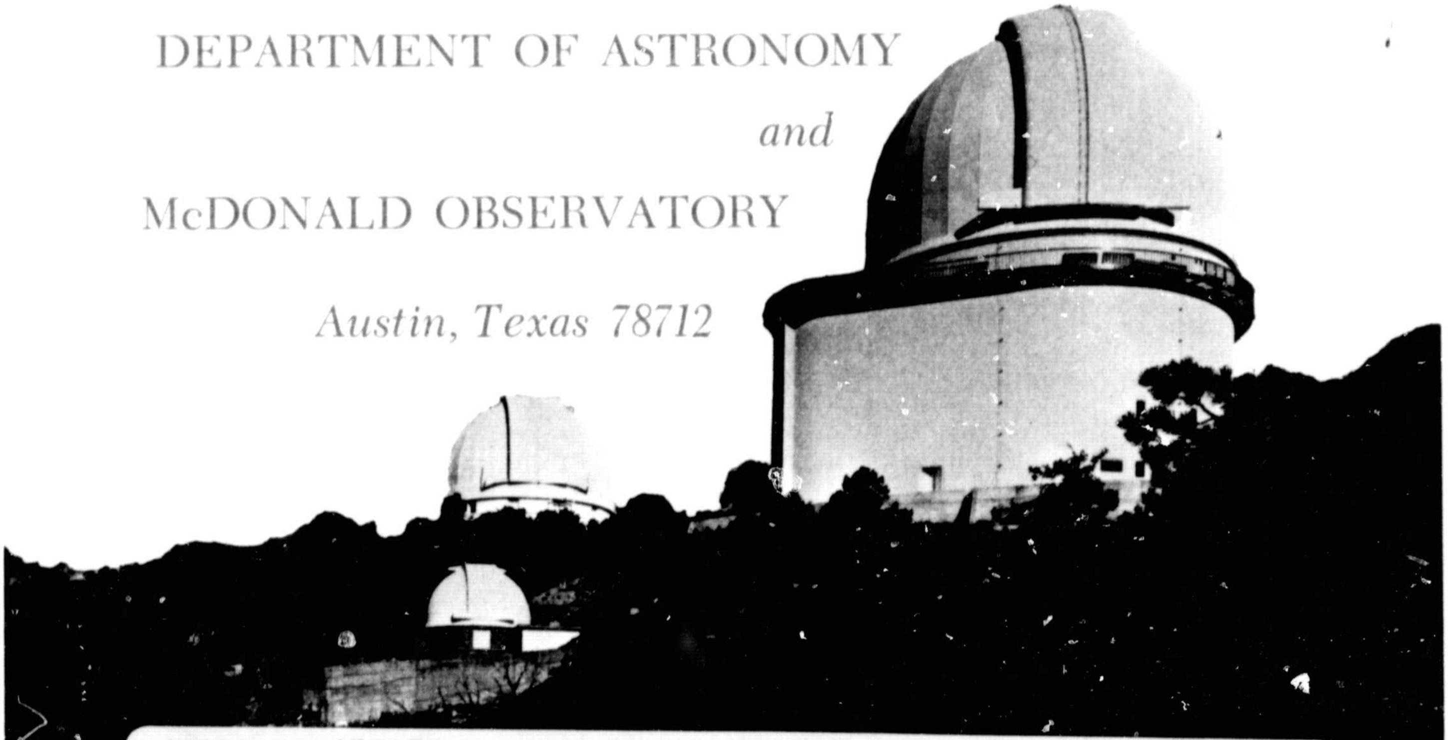

(NASA-CR-170177) ACCRETION INSTABILITY MODELS FOR DWARF NOVAE AND X-RAY TRANSIENTS (Texas Univ.) 9 p HC A02/MF A01 CSCL 03A
N83-23253
Unclas
G3/89 03318

ACCRETION INSTABILITY MODELS FOR DWARF NOVAE AND X-RAY TRANSIENTS

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To appear in the proceedings of the Cambridge workshop on Cataclysmic Variables and Low-mass X-ray Binaries.

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Steady state and time dependent calculations are presented of a model for accretion instability in which matter accumulates in a cold torus and then undergoes a thermal instability causing the matter to heat and flow down onto the central star. This model is compared to the observations of dwarf novae and certain examples of both hard and soft X-ray transients.

We have proposed a model of accretion instability leading to dwarf novae and related phenomena in which mass is considered to be transferred from a companion star at a constant rate. The mass is stored in a cold torus from which the accretion timescale is longer than the transfer timescale. The density builds up until a critical point is reached at which the rate of viscous heating exceeds the cooling and a thermal instability ensues. The resulting hot torus spreads out into a disk and onto the central compact star causing the outburst. The accretion is then envisaged to rebuild the torus.

Steady state, geometrically thin, alpha model accretion disks are constructed by explicit vertical integration using realistic opacities to identify points of thermal instability. The behavior of the post-instability hot torus is calculated with a vertically averaged time dependent code again using realistic opacities. This work has been introduced in Cannizzo, Ghosh and Wheeler (1982) and Cannizzo, Wheeler and Ghosh (1982). Many of the basic principles are discussed in Meyer and Meyer-Hofmeister (1981, 1982), Smak (1982a,b,c), and Bath and Pringle (1981, 1982). The work is similar in spirit to that discussed in this workshop by Faulkner, although there are important differences in application.

The loci of steady state models in the effective temperature, surface density plane are calculated for different values of radius and alpha. Portions of the optically thick steady state locus for which the effective temperature varies as a negative power of the surface density are thermally unstable and hence not accessible to evolving disks (Bath and Pringle 1982). There is general agreement that partial ionization induces thermal instability in models with effective temperature of about 5000 - 7000 K. For steady state solutions computed at a typical dwarf nova outer disk radius of 3 x 10^{10} cm, however, the rate of accretion at these effective temperatures, > 10^{17} g/s, exceeds the deduced transfer rate by about an order of magnitude. For r = 10^{10} cm the rate of accretion associated with this feature is smaller, but the amount of material stored is also smaller. We have argued that this partial ionization instability can only operate at small radii to give frequent, low luminosity bursts. Otherwise, the accretion rate prior to the outburst is greater than the transfer rate, and steady accretion at the transfer rate should occur.

We have chosen to invoke a change in alpha at the point where convection first breaks out. This also serves to induce a thermal instability. At these low temperatures, about 2000 K, the accretion rate is less than 10^{16} g/s and storage of an appreciable amount of matter at reasonable radii can occur before instability . We find values of alpha of order 0.01 in the cold state and alpha of order several tenths in the hot state reproduce the observations of a variety of astrophysical objects.

The steady state models have been used to estimate timescales and delineate regions of steady and unsteady accretion, as shown in Figure 1. For cataclysmic variables with orbital periods of several hours we predict that transfer at a rate in excess of 10^{17} g/s should result in steady accretion since the accretion timescale after the instability is less than the transfer rate and steady accretion at the transfer rate should be driven. At very low transfer rates, the accretion rate in the cold material should exceed the transfer rate, so that the matter should leak steadily in. The upper boundary, in particular, seems to divide the steadily accreting novae and nova-like variables from the dwarf novae. The classic soft X-ray transient Aquila X-1 has a larger orbital period and longer repetition time than dwarf novae. We estimate that it falls well within our instability region. A plausible case can also be made for Cen X-4. There are some reasons to be encouraged to pursue a similar argument for the hard X-ray transients such as 4U0115+63, although the existence of Be star companions complicate these systems considerably. Her X-1 falls within our instability region for nominal parameters, but does not display the type of unstable behavior we are discussing. It would be predicted to be stable if the disk began at slightly larger radii, or the accretion rate were a bit less.

For the time dependent models we construct initial models of the hot torus and then calculate its evolution, including the spectrum and the total luminosity. The material spreads out into a configuration resembling a steady state disk, but only approximately. The accretion rate, for instance, is not independent of radius, but decreases linearly with increasing radius. Although we do not trust the

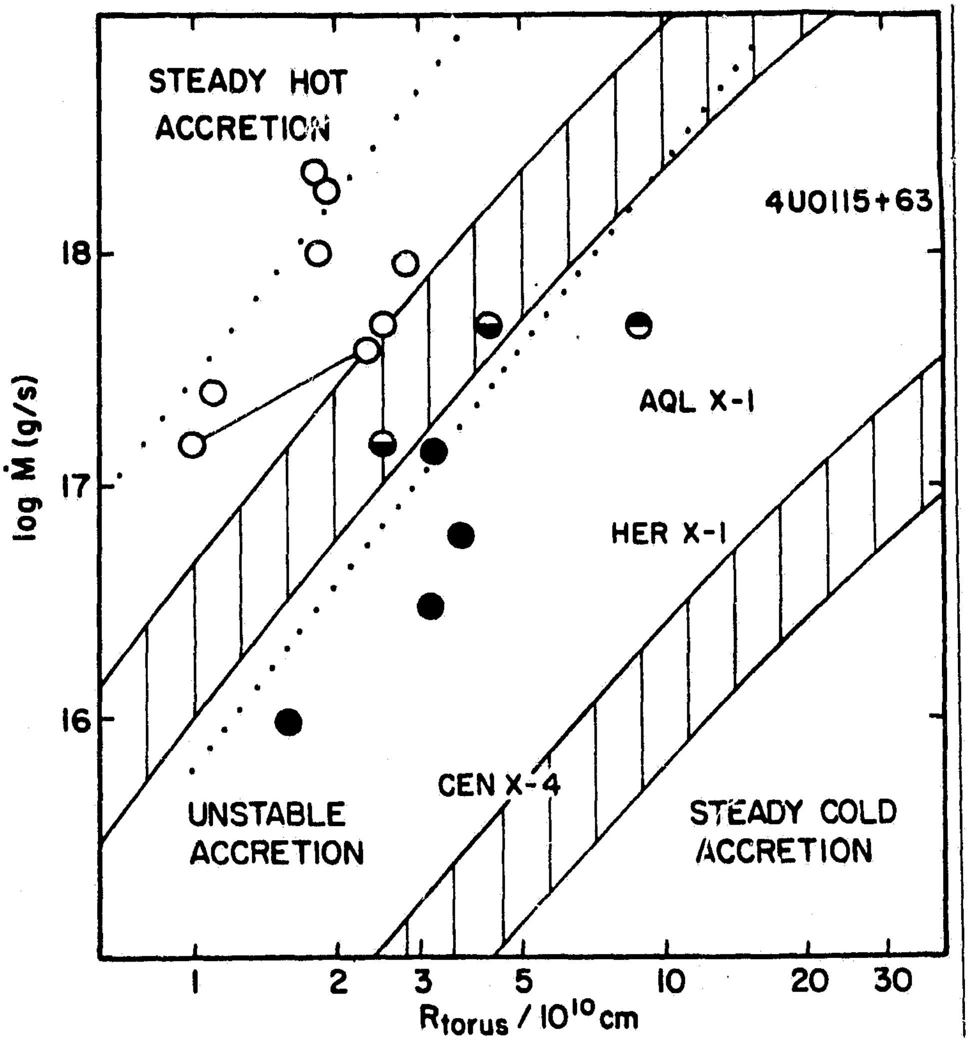

Figure 1. The stability of accretion flow is examined in the plane characterized by the steady-state mass transfer rate and the distance of the quiescent torus from the central star. An instability strip is defined such that the time between bursts is less than the spreading time in the accumulating torus (lower bound) and longer than the burst duration (upper bound). The dotted boundaries correspond to the opacity peak instability. The convective onset instability is indicated by the broad dashed bands, the widths of which represent theoretical uncertainties. Inferred parameters for a number of cataclysmic variables are taken from Smak (1982b), suppressing the large uncertainty associated with individual points. Open circles are steadily accreting novae, closed circles, dwarf novae. Partially filled circles are objects with both steady and transient behavior. Cen X-4, Aql X-1, and 4U0115+63 are X-ray transients that lie in the convective onset instability strip. Her X-1 does not show periodic bursts but also lies in the strip for canonical parameters. The opacity peak strip lies at higher steady-state transfer rates that do not conform as well to observations.

particular results because, among other things, we have not yet included radial heat transport in the models, the code does iterate to find material in the cold state after the density drops and the hot state is no longer accessible in thermal equilibrium. We have not yet explicitly calculated a complete cycle including the rebuilding phase and repetitive outbursts.

Smak (1982b) estimates the transfer rate in SS Cyg to be 1.5×10^{17} g/s, and the outer edge of the disk in outburst to be $2\text{-}5 \times 10^{10}$ cm. The mean time between bursts is about 31 days and the visual band e-folding time after outburst is about 4 days. Using the steady state models and analytic estimates of timescales we estimate that alpha in the cold state should be about 0.004 and in the hot state 0.5. We estimate the luminosity after one e-fold to be about 10^{35} erg/s.

As shown in Figure 2 the time dependent models give a reasonable representation for the decline rate of an optical outburst of SS Cyg with the torus at 3×10^{10} cm and alpha of 0.7. This agrees with Bath and Pringle (1981). We find a peak bolometric luminosity of about 2×10^{35} erg/s and, assuming a distance of 100 pc, a maximum visual magnitude of slightly in excess of +8, both in good agreement with observations. Kiplinger (1979) finds a peak luminosity of 7.5×10^{35} ergs/s for SS Cyg. The models have some difficulty accounting for the range in outburst profiles.

Aql X-1 has an orbital period of 1.3 days, a repetition time of about 400 days, a luminosity e-folding time of about 45 days, and an X-ray luminosity of about 10^4 solar luminosities. With these parameters we estimate the value of alpha in the hot state to be 0.32. The estimate of alpha in the cold state is sensitive to the accretion efficiency, distance and torus radius to the powers 2, 4, and 6, respectively. It could plausibly be of order 0.01. The transfer rate should be about 2×10^{17} g/s. A time dependent model with the torus at 10^{11} cm and a distance of 4 kpc gives X-ray and optical light curves which resemble those of Aql X-1. If anything the model gives too much power, but the similarity between the predicted and observed decline of the X-ray light curves is striking. Since reddening and X-ray reprocessing have been ignored and a maximum distance has been assumed, the surfeit of optical light may be an embarrassment to this model, although an inclination effect would temper this.

Cen X-4 has an orbital period of 8.2 hours, a repetition time of about 10 years, a luminosity e-fold of about 90 days, and a characteristic X-ray luminosity of about 10^4 solar luminosities (1969 outburst). For these parameters we estimate values of alpha of ~ 0.01 and .05, and a transfer rate of about 10^{16} g/s, putting Cen X-4 on the lower edge of our instability strip. The 1979 outburst of Cen X-4 apparently had a shorter decay time, and a peak luminosity a factor of ten smaller than the 1969 outburst. Such changes, are difficult to reconcile with the model in its current incarnation.

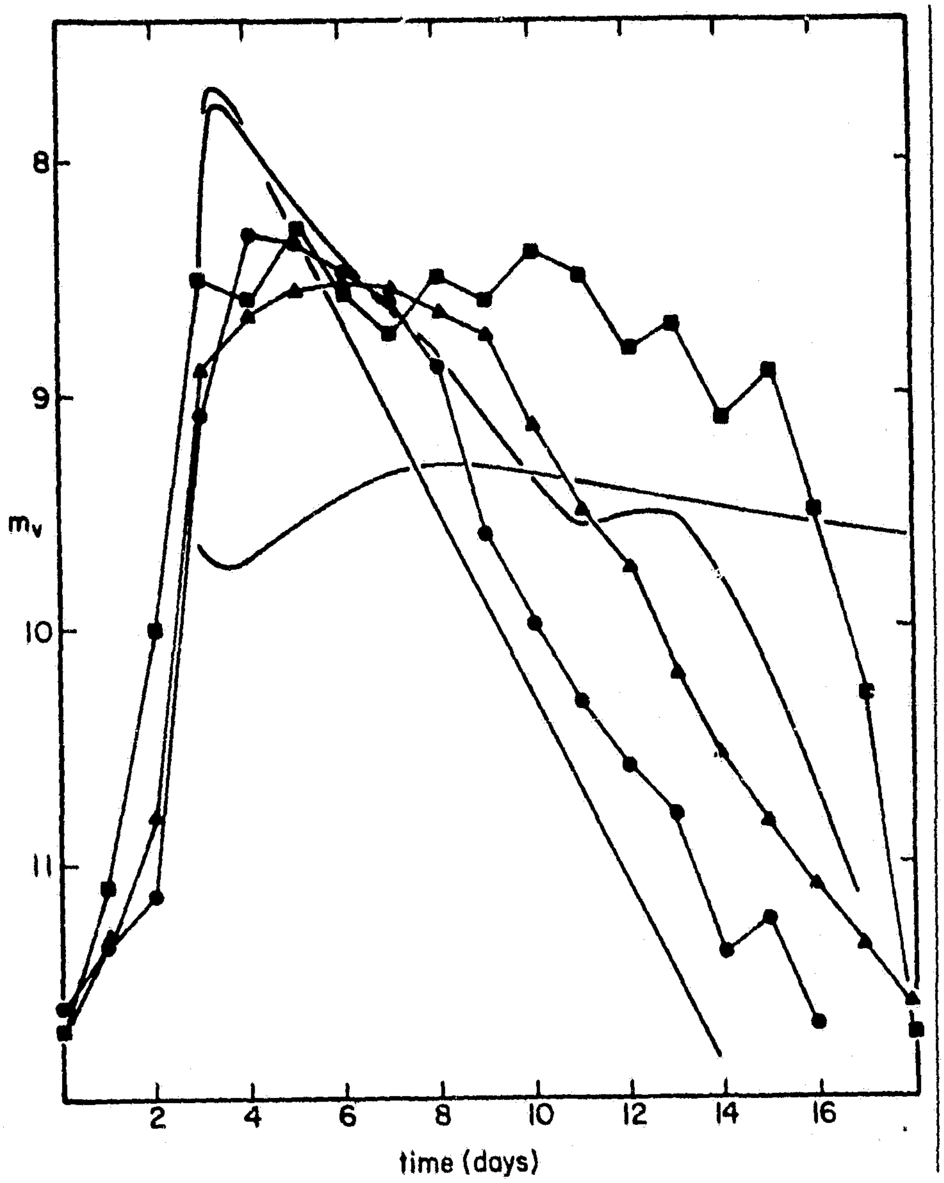

Figure 2. The apparent visual magnitudes of three outbursts of SS Cygni (Journal of the AAVSO (vol. 5, no. 1, 1976, p. 54; bursts #4 (squares) and #5 (circles) on 1st row, burst #4 (triangles) on 2nd row) are compared with time-dependent theoretical models of outburst based on the convective onset mechanism. The two theoretical curves which peak at $m_v = 7.8$ are for $\alpha = 0.7$ and 1.0, the latter being the more rapid. The curve with a peak at $m_v = 9.5$ has $\alpha = 0.1$. The parameters for the initial torus are $r_{torus} = 3.2 \times 10^{10}$ cm, $\delta r = 6.4 \times 10^9$ cm, and $\Sigma_{max} = 590$ g cm^{-2} – the critical surface density for $\alpha_{cold} = 0.01$. A distance of 100 pc is assumed. The luminosity associated with the theoretical curves is of order 10^{35} ergs/s – in accord with the observed power and a factor of order 10 higher than that typical of the opacity peak mechanism.

With a 7.8 hour period (McClintock et al. 1983), a repetition time of 60 years, a luminosity e-fold of 30^d and mean luminosity of $3 \times 10^4 L_\odot$, A0620-00 would have a transfer rate of about 2×10^{15} g/s and values of $\alpha \sim .01$ and .08. This places it very near the low boundary of the instability strip. A repetition time less than 60 years due to missed outbursts, or an accretion efficiency less than 0.1 would yield parameters very similar to those deduced for the 1969 outburst of Cen X-4.

An accretion instability model can be reconciled at some level of approximation with the optical outburst and repetition time of the hard X-ray transient 4U0115+63. Starting with a torus at 3×10^{11} cm, about half the Roche radius of the neutron star, gives an optical outburst from the disk alone about two and a half magnitudes less than that observed for 4U0115+63. The peak output is very sensitive to the initial radius, so that is not a fundamental problem. The disk is very much brighter than for ordinary cataclysmic variables. More troubling is the fact that although there is a delay between the optical and X-ray outbursts, it is only a few days, not the two months which is observed (Kriss et al. 1983). The model also predicts an accretion rate which exceeds the Eddington limit 100 km from the neutron star surface. Whether this is a fatal limitation of the model or an important physical development is unclear. This model can rather naturally account for the repetition time and the luminosity of the optical outburst. The best alternate model is one in which the Be star flares and belches and the neutron star collides with the excretion disk (Rappaport and van den Heuvel 1982). In this picture the repetition time and the magnitude of the optical flare must be chosen ad hoc, with the latter considerably larger than the flares routinely observed in Be stars.

With standard orbital and model parameters and a transfer rate of 10^{-9} solar masses per year we predict that Her X-1 should be unstable with a repetition time of about 4 years and a burst time of about 40 days. Although Her X-1 displays various sorts of transient phenomena, this behavior is not seen. Perhaps the simplest way to reconcile the model with the observations would be to invoke a transfer rate smaller by about a factor of two and a disk outer radius a bit larger than half the Roche radius which we estimated to be 10^{11} cm. Then the outer parts of the disk should be cool, but still viscous enough to accrete steadily at the transfer rate. Whether the flow would be steady through the partially ionized regions and all the way down to the magnetosphere remains to be investigated.

In summary, we find that a model in which matter piles up in a cold, 2000 K, torus and undergoes a thermal instability when convection breaks out reproduces many of the basic properties of dwarf novae and X-ray transients. The task remains to show that a complete repetitive cycle can be produced in this manner and that the model is in accord with all relevant observations.

We thank Ed Nather, Rob Robinson, Lynn Cominsky and Saul Rappaport for discussions of the observational constraints on this model. This work was supported in part by NASA and by the R. A. Welch Foundation.

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