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INTRODUCTION TO THE PHYSICS OF ACCRETION DISK

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ABSTRACT

At intermediate mass transfer rates, accretion disks in binary star systems undergo a thermally-driven limit cycle instability. This instability leads to outburst episodes when the disk is bright and the flow through the disk is rapid separated by long intervals when the disk is dim and the flow through it is low. This intrinsic outburst mechanism can help to understand a wide range of astrophysical phenomena from dwarf novae to soft X-ray transients involving white dwarf, neutron star, and black holes, and to a deeper understanding of the mechanism of angular transport and viscosity in the accretion disk.

I. INTRODUCTION

Accretion disks are observed in a variety of binary stellar systems. Under some circumstances, the flow through the accretion disk is stable and in others it appears to be episodic. For systems containing white dwarfs, the classical novae and nova-like variables appear to have high mass flow rates and steady disks. At lower mass transfer rates, however, one sees the dwarf nova phenomenon, in which the system flares for a week or so every few months. This activity has been attributed with some success to a thermal limit-cycle instability in the disk. Some of the unstable systems are also intermediate polars implying that the white dwarf is strongly magnetized. Such systems, especially GK Persei give a special opportunity to study the interaction of the disk with the magnetic field. Related phenomena are seen in systems containing neutron stars. Many show constant flux levels, but some soft X-ray transients like Aquila X-1 and Centaurus X-4 show outbursts in X-rays every few years lasting for a few months. This may also be a disk instability with the difference in time scales related to the generally larger orbital period. Other flaring X-ray sources, such as A0620-00, V 404 Cygni and Nova Muscae 1991 are suspected of containing black holes. Study of the unstable disks in this context may yield new understanding of how to discriminate neutron stars from black holes and even new insight into the mechanisms of active galactic nuclei. Here I will outline the physics of the accretion disk instability and its application. More details of intermediate polars and GK Per are given in the contribution of S.-W. Kim and of the black hole sources in the contribution of S. Mineshige.

II. THE LIMIT-CYCLE INSTABILITY

The disk instability is basically driven by simple atomic physics, and is thus qualitatively quite general. At a given radius in the disk, as the mass flow rate is increased the disk gets hotter and the surface density increases. At a certain point the temperature will reach that where hydrogen ionization occurs. The increase in the number of electrons and the onset of bound-bound and bound-free opacity causes a rapid increase in the opacity of the disk. In order to maintain thermal equilibrium so that the heat generated by viscosity can be radiated away, the disk surface density must decrease to offset the increase in opacity. The regime where the surface density decreases with an increase in the mass flow rate and the temperature is intrinsically thermally unstable. An upward perturbation in the temperature at fixed surface density will put the disk in a regime where the heating exceeds the cooling. The temperature will run away to a condition where the disk is hot and fully ionized and the opacity becomes relatively less. A negative perturbation in the temperature will cause the temperature to decline to a low value where the opacity is a minimum. The result is that as the surface density increases at a given radius, the structure reaches a point where thermal equilibrium cannot be maintained. The disk then heats to a high temperature, stable state. This results in a higher viscosity and flow rate at that point and a tendency for the surface density to decline. Eventually, the disk reaches a minimum surface density to support the disk the thermal equilibrium in the hot state, and the temperature will drop back down to a minimum level where mass flow from outside the given annulus will tend to increase the surface density and drive another cycle of the instability. The basic nature of this instability is driven by hydrogen ionization although helium ionization and convective efficiency also play a role. The quantitative aspects of the instability are also affected by the specific prescription of the disk viscosity, the physics of which is not well understood.

When applied in a disk model with finite radial extent, this local limit cycle instability drives global heating and cooling waves in the disk. It is the global heating of the disk that gives rise to increased flux from the disk itself and accounts for dwarf novae outbursts and soft X-ray transients. After the heating wave propagates through the disk, a cooling wave ensues from the outside and the whole disk drops into a cool quiescent state until the next outburst starts. For high mass transfer rates, the disk will always be maintained in the hot, high flow rate state. In special circumstances, there may be a steady state corresponding to cold, low viscosity disks that can maintain a low flow rate. At intermediate transfer rates from the companion star, however, no steady state is possible in the disk even though the transfer rate from the companion star is constant. Instability in the disk and subsequent outbursts thus do not require fluctuations in the mass transfer rate, although that may occur in some circumstances. For steady state disks, the flux from the surface of the disk does not depend on the nature of the viscosity. While the thermal instability is affected quantitatively by the viscosity, this can be turned to an advantage since for the time dependent structure, the flux does depend on the viscosity. This means that comparing time-dependent models to the observations can provide constraints on the viscosity. More generally, is it important to understand that the transfer rate into the disk is not necessarily the same as the flow through any point in the disk, and neither need be the rate at which matter flows onto the compact object that determines the X-ray flux. During quiescence, these rates are definitely not equal.

III. WHITE DWARF SYSTEMS

Classical dwarf novae like SS Cygni have a long record of observations, thanks, especially, to the contributions of amateur astronomers. The outburst are quasi-regular. The disk instability models do a fair job of reproducing the average interval between outbursts and the amplitude and duration of the outbursts. The models in their current form do not account easily for the irregularity in the recurrence time. Neither do they account for the difference in shape of the outbursts, although there is a qualitative understanding that outbursts with a steep rise and slower decline probably involve heating waves that start on the outside of the disk and propagate inward and that bursts with a more symmetric rise and decline arise when the heating wave starts in the inner portions of the disk. Qualitatively, a higher mass transfer rate will tend to raise the outer part of the disk to the instability point first and a lower transfer rate will allow matter to drift inward and reach a critical surface density deeper in the disk. Why a single system like SS Cyg oscillates between both burst types is not clearly understood. The theory of the disk instability gives a reasonable quantitative understanding of the dividing line between stable disks at high transfer rates and temperatures and unstable disks at lower mass transfer rates and temperatures. The dividing line rises monotonically to higher mass transfer rates with larger disks.

The system GK Per is a particularly interesting case. It was a classical nova in 1901, but then started a series of fairly regular outbursts every three years or so. The most recent occurred in July of 1992 and the system was near maximum at the time of this workshop. Kim, Wheeler, and Mineshige (1992) have made successful disk instability models of these outbursts of GK Per. The models require a large inner edge of the disk, presumably due to truncation of the disk by the magnetic field of the white dwarf. Kim will discuss further the use of the outbursts to study this system and the disk/magnetosphere interaction.

Ⅳ. NEUTRON STAR SYSTEMS

One can use the basic accretion disk instability models to survey what systems with neutron stars might be subject to disk instabilities. For the best estimates of accretion disk radii and mass transfer rates, one would predict that systems like Aquila X-1 and Centaurus X-4 would both contain unstable disks. Both of these systems are soft X-ray transients with outbursts every few years. They are known to be neutron stars because both have shown classic Type I X-ray bursts on the tail of the longer term soft X-ray outbursts which are interpreted as thermonuclear flashes on the surface of a neutron star. It is very plausible that the soft X-ray outbursts are related to a disk instability in which the increased mass flow through the disk gives rise directly to a strong soft X-ray flux from the hot inner regions of the accretion disk. The outbursts from these systems are again not strictly periodic, a challenge for the current rather simple, and periodic, thermal limit cycle instability models.

Hercules X-1 represents an interesting challenge to the disk instability models of a different type. Her X-1 would also be predicted to be unstable to the disk instability, but it is not observed to undergo the same bursting as Aql X-1 and Cen X-4. This may be due to the magnetic field of Her X-1 or to associated effects of irradiating and heating the disk and thus stabilizing it. In the meantime, Her X-1 remains as an interesting counter example for the disk instability models.

Ⅴ. BLACK HOLE SYSTEMS

Several of the systems which are candidates for black holes with massive companions are also in the regime where the disk instability might be expected. Among these are Cygnus X-1, LMC X-1 and LMC X-3. Cygnus X-1 has displayed episodes of soft X-ray outbursts, the so-called high states, that qualitatively resemble the soft X-ray outbursts of Aql X-1, and so there is at least reason to wonder whether a disk instability could play some role in this system. Neither of the other sources have shown this kind of outburst although they are variable on some timescales. Especially in these bright, strong X-ray sources, irradiation of the disk by the central source of X-rays or by the bright, hot companion might seriously effect the disk structure and its instability properties, but this needs to be explored more thoroughly (Tuchman, Mineshige and Wheeler 1990, Mineshige, Tuchman and Wheeler 1990).

Of great interest recently has been the black hole candidates that contain very low mass companions. These black hole candidates have been characterized by soft X-ray flares that have been attributed to X-rays from the surface of an accretion disk. The prototype of these systems is A0620-00. This system flared optically in 1916 and then again in 1975 when it was observed in the X-ray band as well. Mineshige and Wheeler (1989) have made reasonable disk instability models of this system that reproduce the amplitude and overall timescale of the optical and X-ray light curves and can give recurrence times of decades. Interestingly, more massive central stars tend to enhance the recurrence time, so the disk instability models give some separate evidence in favor of black holes. Other more recent systems of this type are GS 2000+25, V 404 Cyg (GS 2023 + 338) and Nova Muscae 1991 (GS 1124 - 68). Mineshige, Kim, and Wheeler (1990) showed that disk instability models predict an X-ray flux that declines in temperature at nearly a constant radius near the last stable circular orbit. This is in qualitative agreement with the observations of GS 2000 + 25.

A0620-00 showed both a soft X-ray flux and a hard-power law tail of the sort that characterizes Cygnus X-1 in the normal, low soft X-ray flux state. The soft X-rays are superposed on this power law in the high state of Cyg X-1. This power law spectral feature was also seen with an amplitude tha t declined but seemed to vary independently of the soft X-ray flux in GS 2000 + 25. V 404 Cygni showed essentially only a strongly time variable power law spectrum. It also has had two outbursts about 50 years apart. Nova Muscae again showed both the soft component and the hard power law tail. In addition, Nova Muscae showed evidence for positron annihilation radiation in one interval. The origin of the soft X-ray flux is strongly suspected to arise in the disk and the disk instability model provides a qualitative explanation for the outburst. The power law spectrum requires another component of the system that may or may not be related to the source of positrons in Nova Muscae and which may or may not be a special clue to the nature of the central star as a black hole rather than a neutron star. Basic understanding of the nature of the accretion disk instability that probably underlies the outburst promises to yield new insights into this class of black hole candidates. Mineshige will give more details of the nature of these systems.

VI. CONCLUSIONS

The accretion disk thermal limit cycle instability is a fundamental and ubiquitous phenomenon. It seems to occur in dwarf novae, in some intermediate polars, in soft X-ray transients, and perhaps even in quasars. The properties of the instability constrain important factors such as the very presence of a disk, the nature of the viscosity, the mass and nature of the central object, the strength of the magnetic field embedded in the central object, and the nature of the interaction of the magnetic field with the disk.

A major unsolved problem is the self-consistent, time-dependent, structure of the X-ray irradiated disk and the origin of the corona or other structure that emits the hard power law spectrum. Further work on these problems in conjunction with the recently discovered black hole transients may give important insights into a broad range of astrophysical phenomena.

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