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Black Holes in Binaries (Cont'd):

Cygnus X-1 as the Archetypal HMXB:

Since its discovery, Cygnus X-1 has been closely monitored by many high-energy instruments from X-rays to γ-rays. Its spectrum has been known for decades to be a mixture of thermal and non-thermal components. The thermal component may be modeled as a multitemperature blackbody (with a flat segement feature) originating from the inner region of the accretion disk. The non-thermal component is modeled as a power law originating from the particle distribution with a spectral index of ~2. The power law extends to much higher energies than the thermal component, which falls off exponentially at ~100 KeV.

Cygnus X-1 is most often found in the low hard state (LHS), defined by a relatively low flux in soft X-rays (~1 keV) and a high flux in hard X-rays (~100 keV). Occasionally, it switches to the high soft state (HSS), in which the high-energy power law is much softer (~2.4). Sometimes, it is detected in an intermediate state (IMS), which is a transitory configuration exhibiting a relatively soft X-ray spectrum (with spectral index ~2.1-2.3), and a moderately strong soft thermal component.

Simultaneous observations of Cygnus X-1 in the radio and X-ray bands have revealed that during the LHS, strong radio emission arises from a jet-like feature extending out from a core. In contrast, the jet is rather weak during the HSS. The fact that the radio jet is present in the LHS and not in the HSS is an indication that transitions from one state to the other must be associated with significant changes in the geometry of the accretion flow.

It is believed that a transition from the HSS to the LHS is associated with the truncation of the thin disk at several hundred Schwarzschild radii. A geomertircally thick, optically thin, hot disk forms between the truncation radius and the event horizon. A switching back to the HSS results when the hot gas cools and collapses back down toward the plane, and the cold disk refills its inner region.

An important observation is a rather broad feature around ~500keV, which is due to electron-positron pair annihilation. Also, at least 80% of the radio jet in the LHS is composed of electron-positron pairs. These together suggest that the compact object is disgorging an intense flux of high-velocity electron-positron pairs into the surrounding medium. Note that production of electron-positron pairs requires temperatures that exceed the electron mass ($\sim 10^{10}$ K).

We will discuss how all these features may be explained by a physical model that is due to thermal instabilities in the accretion disk.

X-ray Novae:

There are about 200 cataloged X-ray binaries in the galaxy, each containing a neutron star or a black hole accreting from a companion. The great majority of these are persistent sources, and about 30 or so are transients with nova-like outbursts, which occur from once every several years to perhaps one per centur (or longer).

Almost all the black hole binaries are X-ray novae, which are characterized by episodic outbursts at X-ray, optical and radio frequencies. Conventional wisdom is that the outburst is caused by a sudden dramatic increase in mass accretion rate through the disk. In these systems the mass transfer from the Companion fills the outer region of the disk in order to sustain a continuous viscous flow in steady state. At some point, a critical condition that triggers an outburst is met. This has probably something to do with the strong temperature dependence of the viscosity and thermal instability, to which we will come back shorthly.

A well-known member of this group is X-ray nova GRS 1124-684. Observations of this source during the flare demonstrate the emergence of an electron-positron annihilation line in the

430 – 530 keV band. This also indicate a big rise in the temperature to kinematically allow electron-positron pair production from photon interactions.

Thermal Instabilities in Thin Disks:

In our discussion of thin disks, we assumed that the structure, once formed, remains in stable equilibrium. This requires that the dissipated heat in the disk be efficiently radiated away. However, as mentioned above, there is evidence that the inner parts of disks around stellar-sized black holes may be extended. This suggests that compact objects more massive than white dwarfs and neutron stars can create physical conditions that lead to instabilities in the disks themselves.

Thermal instabilities can occur if the emissivity of of the plasma is not large enough, so that the cooling rate cannot keep up with the heating rate. At temperatures below $\sim 10^5$ K the plasma is in a neutral state, and the line emission is the dominant source of cooling. The emissivity increases with temperature in this case, which makes the disk stable. At temperatures above $\sim 10^8$ K, the plasma is fully ionized, and (inverse) Compton scattering is the dominant emission process. Again the emissivity increases with temperature, resulting in the stability of the disk.

However, at temperatures in the intermediate range 10^5–10^8 K the most prominent emission mechanism is bremsstrahlung. The emissivity decreases as temperature rises in this case, which can lead to instability in the plasma. At temperatures above $\sim 10^8$ K the trend is reversed, but the instability can heat up the plasma to temperatures as high as $\sim 10^{10}$ K. This results in expansion of the disk in vertical direction (going from "thin" to "thick"), and can also explain electron-positron pair production.

In the case of Cygnus X-1, thermal instability arises in the inner parts of the disk. Recall the dissipation rate due to the viscous torque:

$$D(R) \simeq \frac{3GM\dot{M}}{8\pi R^3}$$

At sufficiently small R it becomes large enough to heat up the disk to temperatures above $\sim 10^5$ K. Note that D is larger for black hole binaries because of the larger value of M.

In the case of X-ray novae, thermal instability arises due to the enhanced accretion rate that leads to heating of the outer region of the disk. Again the temperature rises above $\sim 10^5$ K and the plasma enters the unstable range.

An important point is that mass transfer instabilities propagate through the disk in the radial direction on a timescale;

$$t_{visc} \sim \frac{R^2}{\alpha c_s H}$$

On the other hand, thermal instabilities propagate in the vertical direction on a timescale;

$$t_z \sim \frac{z}{c_s}$$

It can be shown that $t_z \ll t_{visc}$. Therefore, if the cooling rate cannot keep up with the heating rate, the disk will indeed expand in the vertical direction very quickly, before dynamics in the radial direction can act on the instability.