FINAL REPORT

Warping and Precession of Accretion Disks in X-Ray Binaries (NAG5-4061)

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This proposal covers research on the radiation-driven warping instability discovered by Pringle (1996). In the first two years of funding under this proposal we concentrated on and essentially completed study of the eigenmodes of the radiation-driven warping instability in the linear regime.

In our first paper (Maloney, Begelman, & Pringle 1996) we assumed, as did Pringle (1996), that the disk surface density Σ scales with cylindrical radius R as $\Sigma \propto R^{-3/2}$; in the usual α–disk formalism (Shakura & Sunyaev 1973), this corresponds to an isothermal disk, with the same temperature at every radius. (The disk is assumed to be thin; no vertical structure is considered.) In Paper II (Maloney, Begelman, & Nowak 1998), we generalized our study of the instability to consider radial power-law surface density distributions, $\Sigma \propto R^{-\delta}$, with δ ranging from 3/2 (the isothermal value) to $-3/2$, which characterizes a disk in which radiation pressure dominates over gas pressure (e.g., Frank, King, & Raine 1992). This range of δ covers the entire range which is likely to be of relevance for real astrophysical disks.

We also considered how the warping modes depend on the choice of outer boundary condition. We generally calculated the warping modes by searching for the zero-crossing eigenfunctions, i.e., those which return to the original disk plane. However, in active galactic nuclei, the disk is likely to become optically thin to its own radiation – thereby switching off the radiation torque – before the outer boundary is reached. In accretion disks around compact objects in X-ray binary systems, the disk probably remains optically thick, but the behavior of the disk outside the circularization radius is different, since there is no net transport of matter there, only angular momentum. This leads to a constraint on the gradient of the disk tilt at the circularization radius, but the tilt itself is not necessarily zero. We examined how the nature of the instability is modified under both of these assumptions about the boundary conditions; in all cases, the warping modes are in fact very similar to the zero-crossing modes. In Paper III (Maloney & Begelman 1997), we showed how the inclusion of torque from the companion star in a binary system allows retrograde as well as prograde modes to exist.

During the latter half of the grant period, a dispute arose over the development of the warp instability in X-ray binaries. Wijers & Pringle (1999) claimed that it is possible to obtain retrograde modes without any external torque. The disk outer boundaries in these models do not return to the binary plane of the system. This struck us as implausible; furthermore, these results were obtained using Pringle's nonlinear evolution code, which has never been demonstrated to reproduce the linear theory results. These conclusions were amplified by Ogilvie & Dubus (2001), who found similar results using a more sophisticated model for disk stiffness. We have undertaken to assess these claims by solving the linearized but now time-dependent equation, i.e., we are not looking for eigenmodes, but are instead solving for the time evolution from an arbitrary starting condition. The goal is to see if the eigenmodes form a essentially complete basis set for the evolution of the instability, or if there are growing modes which are not well described by the eigenmodes.

We are also at work on calculating the nonlinear evolution of the instability. This involves the development of a numerical code to follow the time-dependent evolution of the disk, and development of an algorithm to incorporate the effects of shadowing of the outer parts of the disk by warped inner regions. The former requires a much more sophisticated numerical scheme than the simple first-order method used in Pringle (1997); in particular, it is necessary to be extremely careful about the coupled transport of mass and angular momentum, in order to avoid non-physical results. When completed, the code will be rigorously tested against the linear theory to verify its accuracy. We also plan to investigate whether it is possible to include the effects of shadowing into the linear theory calculations.

References

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