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Mass Transfer in High-mass X-Ray Binaries: from Roche Lobe Overflow to Hoyle–Lyttleton Accretion

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Abstract

We use a new overset dual spherical grid system to evolve the circumstellar gas flow in the High-Mass X-Ray Binary Vela X-1 to investigate the gravitational capture of the donor star's wind and subsequent accretion onto the neutron star companion. For a fast, relatively undistorted stellar wind (small filling factor) we find results consistent with classical Hoyle–Lyttleton accretion with the formation of a steady, nearly axisymmetric bow shock. For models with a filling factor near unity, the mass transfer is dominated by a tidal stream feeding into a thin accretion disk. Finally, for slow winds without Roche Lobe Overflow we find the formation of a wind bow shock but with enough post shock angular momentum to form a thin, stable accretion disk.

1. Accretion-driven X-Ray Binaries

The discovery of extra-solar X-rays from Sco X-1 in 1962 [1] launched the study of accretion onto compact stars in close binary systems. In little more than a decade, the UHURU satellite had discovered numerous other binary X-ray sources and two seminal theories of mass accretion were introduced to explain the intense X-ray luminosity of these systems. In 1972 Davidson and Ostriker [2] proposed gravitational capture of the stellar wind from a companion star while Shakura and Sunyaev [3] described the structure and appearance of an accretion disk formed around a black hole in a close binary system. The former theory is most directly relevant to High Mass X-Ray Binaries (HMXBs) in which a massive donor star possesses a strong stellar wind. These two theories led to classifying X-ray binaries as either Roche lobe overflow in which a tidal stream feeds directly into an accretion disk or wind accretion in which the compact object accretes gas from the wind of the donor star.

These two ideas constitute extremes of what is likely a continuum of possibilities for HMXBs based on the wind properties and how close the donor is to filling its Roche lobe. Early gas dynamic simulations demonstrated that a tidally distorted wind could lead to enhanced wind accretion, although these simulations were limited to two dimensions and lacked spatial resolution near the accreting star [4]. More recent three dimensional simulations have shown that a tidally enhanced wind could lead to the capture of sufficient angular momentum to form an accretion disk [5].

2. Hydrodynamic HMXB Model

We use the VH-1 gas dynamics code to evolve the gas flow on a coupled grid system designed to model interacting binary stars. Each star is modeled on a spherical grid composed of two overset partial spherical grids [6, 7]. This Yin Yang grid system avoids the coordinate singularity and grid convergence associated with the z-axis in spherical coordinates and possesses roughly uniform angular resolution at approximately one degree in the models presented. The donor star grid is centered on the primary star and extends out to twice the binary separation. The accretor star grid is centered on the companion neutron star with an outer radius that is large enough to enclose the wind bow shock in wind accretion models and that reaches out close to the inner Lagrange point in semi-detached models. The inner radius is as small as 10,000 km. We do not include the effects of magnetic fields, which can be expected to be dynamically important at small radii in the accretion disk. At some point the accretion disk is dominated by interaction with a compressed magnetosphere. Even before this point, angular momentum transport by weak fields are expected to drive accretion through the disk.

We map the donor star surface onto the donor grid by setting the density equal to $10^{-11}\,\mathrm{g\,cm^{-3}}$ at an equipotential surface and initialize an isothermal atmosphere above this radius. The equipotential surface is defined by the chosen volume filling factor of the donor star, f. We employ the CAK [8] formalism to drive a wind off the donor star, adjusting the CAK parameters to produce a desired terminal velocity and mass loss rate. We impose a floor temperature corresponding to the effective temperature of the donor star and include cooling of shock-heated gas with a minimum cooling rate given by thermal bremsstrahlung. This cooling is necessary for the formation of an accretion disk. Radiative feedback on the wind through photo-ionization and heating is not included.

Here we present preliminary results from this new computational model, specifically focusing on the different modes of mass transfer observed in a series of simulations of Vela X-1. We use a donor mass of $23\,M_{\odot}$, an accretor mass of $1.8\,M_{\odot}$, and an orbital period of 8.96 days [9]. We consider both fast ($\sim 1{,}700\,\mathrm{km\,s^{-1}}$) and slow ($\sim 600\,\mathrm{km\,s^{-1}}$) winds from the donor star and several values of the filling factor, f.

3. HMXB Accretion Modes

Wind Accretion, illustrated in Fig. 1, occurs for systems with a fast wind and $f < 1$. The mass accretion rate is in rough agreement with the classical Hoyle–Lyttleton accretion rate [10]. However, the flow behind the bow shock is turbulent as a result of density fluctuations in the upstream wind. This turbulence leads to a decrease of Mach number as the gas flows toward the neutron star, in contrast to idealized HLA where the gas accelerates in laminar flow as it approaches the accreting star [7].

Tidal Stream Disk Accretion, illustrated in Fig. 2, occurs for systems with the primary star filling its Roche lobe. Mass transfer is predominately through a tidal stream from the L1 point in a process commonly referred to as Roche-lobe overflow. The mass transfer rate through the tidal stream is a sensitive function of the gas density at the Roche surface. In the model

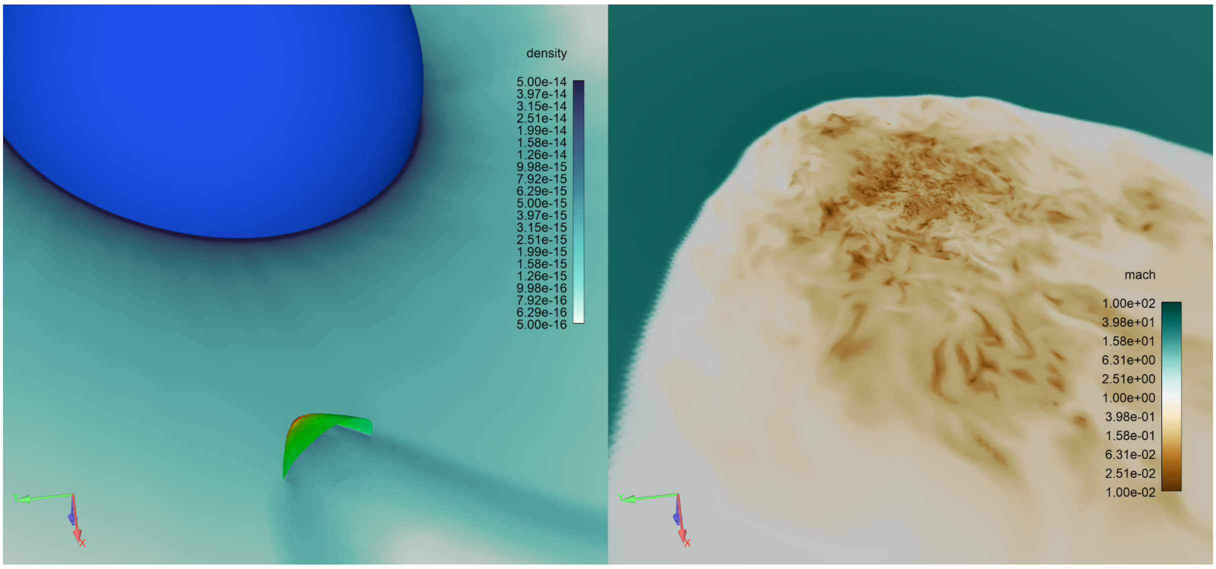

Figure 1: Wind accretion in a model with a fast, undistorted wind. The direction of orbital motion has the neutron star moving from right to left. The equatorial plane is colored by the density (*left*) and Mach number (*right*). The right image is zoomed in on the neutron star (represented by a red sphere).

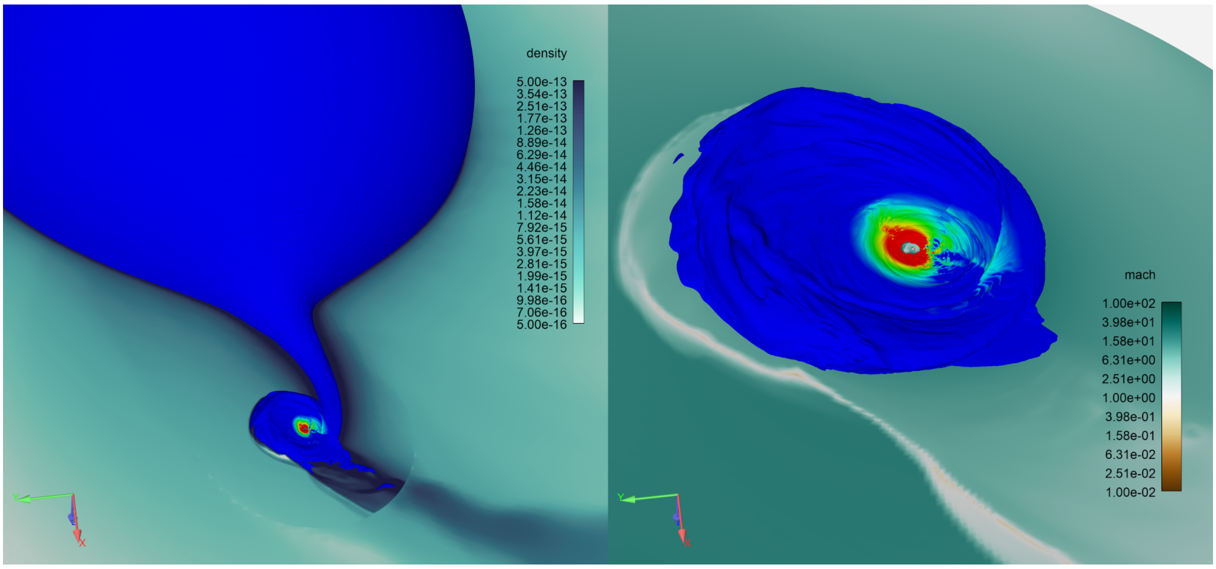

Figure 2: Stream Disk accretion in a model with the primary star filling it's Roche lobe. The star/stream/disk structure is illustrated by an isodensity surface at $\rho = 10^{-12}\,\mathrm{g\,cm^{-3}}$ (*left*). The disk is represented by an isodensity contour at $\rho = 10^{-11}\,\mathrm{g\,cm^{-3}}$, colored by velocity (*right*).

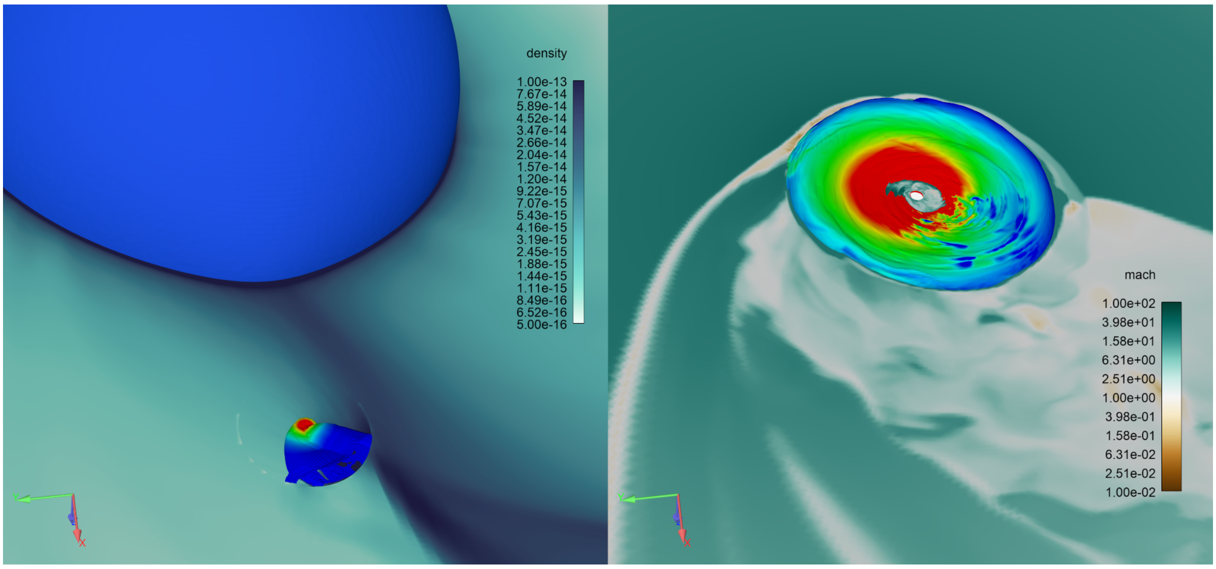

Figure 3: Wind-captured Disk in a model with a slow wind.

presented here, with the surface density set to 10^{-11} g cm^{-3} at an equipotential corresponding to $f = 0.995$, the mass transfer rate is about 7×10^{17} g s^{-1}. This is roughly equal to the mass loss rate through the wind in this model. Note, however, that the wind plays an integral role in the accretion dynamics. The wind forms a bow shock around the disk that is visible on the leading edge of the disk in Fig. 2. The interaction of this bow shock with the trailing side of the disk is also evident from the distorted velocity pattern on the right side of the disk. The wind shock plays a role in shaping the stream–disk interaction, in driving a trailing stream of gas that carries angular momentum out of the system, as well as contributing to the net mass accretion rate.

Wind-captured Disk Accretion, illustrated in Fig. 3, occurs for systems with a slow wind and $f < 1$ (ref. [5]). In this intermediate case accretion also occurs through a bow shock in the wind. However, the transverse gradients in density and velocity in the upstream wind lead to sufficient angular momentum to form an accretion disk. In the simulation shown in Fig. 3, with a slow wind and $f = 0.822$, the tidally enhanced wind leads to a much denser mass flow on one side of the neutron star than the other. This leads to an asymmetric bow shock structure similar to that seen in previous simulations [5]. With higher spatial resolution and evolving for significantly longer in time, we are able to resolve a thin accretion disk in a quasi steady state. The disk fills the volume behind the bow shock and indeed pushes the shock out to larger radii than one would expect from just a wind shock. The accretion of mass onto the disk occurs predominately from the subsonic flow in the equatorial plane on the back side of the disk.

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Further Information

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Conflicts of interest

The author declares that there is no conflict of interest.

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