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THE RELATIONSHIP BETWEEN ACCRETION DISKS AND JETS

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RESUMEN

Presentamos resultados recientes de una serie de simulaciones de acreción y flujos colimados realizados con un código tridimensional MHD en Relatividad General. Los flujos son producto directo de la acreción y poseen una forma geométrica genérica: un embudo de baja densidad e intensos campos magnéticos helicoidales se forma a lo largo del eje de rotación del agujero negro. Este está rodeado a su vez por una pared de flujo con mucha mayor densidad de masa. Como consecuencia de la acreción, y a pesar de la ausencia de un campo magnético intenso en la condición inicial, se crea espontáneamente un campo a gran escala dentro del embudo. El flujo de la pared del embudo es acelerado y colimado por presión coronal. Todas las cantidades asociadas al flujo colimado dependen fuertemente de la rotación del agujero negro, a través del parámetro de momento angular adimensional, a/M. En términos de eficiencia energética con respecto a la masa en reposo, las componentes material y electromagnética son comparables con la radiativa, proveniente del disco.

ABSTRACT

Recent results are reported from a program of large-scale numerical simulation of accretion and jet flows utilizing a code that computes 3-d MHD in full general relativity. We find that outflows arise as a direct consequence of accretion and have a generic geometric form: a funnel along the black hole rotation axis that has very low matter density but strong helical magnetic fields, surrounded by a funnel-wall flow of much greater matter density. Large-scale field is created spontaneously in the funnel as a consequence of accretion, despite the absence of large-scale field originally. Coronal pressure both accelerates and collimates the funnel-wall outflow. The strength of all quantities associated with the outflow is a strongly increasing function of black hole spin parameter a/M. Measured in terms of conventional rest-mass efficiency, both the matter and the electromagnetic components of the outflow can be comparable in power to the radiation expected from the accretion disk.

Key Words: **ACCRETION, ACCRETION DISKS — BLACK HOLE PHYSICS — GALAXIES: JETS — INSTABILITIES — MAGNETOHYDRODYNAMICS**

1. INTRODUCTION: THE KEY PHYSICAL PROCESSES

It is the goal of this meeting to advance our understanding of how relativistic jets are filled, accelerated, and collimated. Although it is possible that jets may occur even in the complete absence of continuing accretion (that was the idealized case contemplated by Blandford & Znajek 1977), there are two good reasons why, in fact, accretion and jet-creation are likely to be intimately related: Jet-like phenomenology (superluminal motion, strong variability, etc.) is frequently seen in association with the phenomenology usually associated with disks (a quasi-thermal continuum spectrum). And accretion onto black holes is an excellent way to deliver and maintain the magnetic field that is almost certainly a critical ingredient of the jet-creation process. Therefore, the primary focus of this talk will be the *relationship* between disks and jets, rather than the dynamics of either part separately.

Three principal physical elements need to be included in any consideration of the dynamics of matter near black holes. Relativistic gravity, of course, is the first. All the usual grab-bag of special relativistic effects needs to be recalled: the increase in inertia when objects move rapidly, appropriately frame-dependent treatment of electromagnetic fields, etc. In addition, however, general relativity introduces two new qualitative elements (in addition to the very existence of event horizons) that do not appear in special relativity. Within distances a few times the radius of the event horizon, stable circular orbits disappear. Described in terms of the most commonly-

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used coordinate system (Boyer-Lindquist), the innermost stable circular orbit (the ISCO, also called the radius of marginal stability) lies at 6 gravitational radii ($r_g \equiv GM/c^2$; from here on out, we will adopt gravitational units in which $G = c = 1$, so that $r_g = M$) for non-spinning black holes, and moves in to just outside the event horizon at M as the black hole's rotation approaches the maximum possible. Secondly, when the black hole spins, there is a region (the "ergosphere") within which zero angular momentum orbits exhibit rotation as viewed by a distant observer. This zone spans the radial range from the event horizon to $2M$ in the equatorial plane but shrinks to zero radial thickness on the rotation axis.

The second crucial element is magnetic fields. It has long been suspected (since Blandford & Znajek 1977) that magnetic fields are the way rotating black holes couple to external matter in order to produce jets. However, the magnitude and character of these fields was for an almost equally long time a matter of guesswork and speculation (e.g., Begelman, Blandford, & Rees 1984; Nitta, Takahashi, & Tomimatsu 1991; Ghosh & Abramowicz 1997; Livio, Ogilvie, & Pringle 1999). More recently, as a result of the work ofBalbus and Hawley and followers (e.g., Balbus & Hawley 1998), we have learned that magnetic fields are naturally created under a wide range of circumstances in accretion disks and readily grow to such a strength that they can mediate accretion. One might then reasonably ask what strength and topology magnetic fields are brought near the black hole by the accretion flow and made available for jet-driving. This question was, in fact, the motivation for the work by Krolik (1999), in which it was shown that, if magnetic torques drive inflow in the main body of the disk, in the plunging region, the zone between the ISCO and the event horizon, magnetic stresses should increase dramatically in relative importance.

The third element driving dynamics near black holes is pressure, whether gas or radiation or magnetic, or, in some circumstances, neutrino. In reasonably bright accretion systems, radiation pressure should be at least as great as gas pressure (Shakura & Sunyaev 1973). When this is the case, the opacity is usually large enough that the radiation and gas are well-coupled dynamically where most of the matter is. Understanding the nature of the pressure is important for a number of reasons. Pressure forces (of whatever nature) are the only way to support matter against the vertical component of gravity. Information can be transmitted within the accretion fluid by acoustic waves supported by pressure. Unfortunately, it is very hard to determine the equation of state of matter in these circumstances. Dissipation of turbulence should lead to local heating, but calculating the detailed behavior of turbulent fluids is famously difficult. Even given a local rate of heating, creation of photons (or neutrinos) and their diffusion outward combine to balance the local heating and fix the temperature. Computing radiation transfer in coordination with a dynamical calculation is also a very complex problem (see, e.g., Hirose, Krolik, & Stone 2006). For all these reasons, in most accretion studies, the matter's thermodynamics is the worst-known element.

2. COMPUTATIONS

The only stove we know of on which we can cook this three-ingredient stew is that of large-scale numerical simulation. At the present state of the art, there are several existing codes capable of following fully general relativistic matter dynamics in the MHD approximation, although, as just discussed, they all handle thermodynamics more poorly than dynamics. Two in particular (see De Villiers & Hawley 2003; Gammie, McKinney, & Tòth 2003) have been used to study these processes over time-spans of thousands of relativistic time-units (1 time-unit $\equiv GM/c^3 = M$). The discussion in this paper will rely most heavily on the former code, but the results of the latter are, in many respects, qualitatively similar. In making this comparison, one must, however, allow for the contrasts imposed by the fact that most of the simulations published using the De Villiers-Hawley code have been in 3-d, whereas the Gammie code has as yet been employed only on problems having axisymmetry (Gammie, Shapiro, & McKinney 2004; McKinney & Gammie 2004).

The De Villiers-Hawley code rests on two principal physical assumptions: that ideal MHD applies; and that the equation of state of the matter is adiabatic except to the degree that additional entropy is acquired as a result of applying an artificial bulk viscosity to damp the ringing that would otherwise occur at shocks. There is no radiative cooling of any kind. Because the code does *not* solve the total energy conservation equation, energy can be lost as a result of, for example, numerical reconnection of magnetic field. This sort of process can very crudely mimic radiation losses, particularly in regions where the inflow time is longer than the cooling time.

Because this code tracks the physics in relation to a Boyer-Lindquist coordinate system for the Kerr metric, it is most convenient to define its problem area as a thick spherical section with conical cut-outs along the rotation axis. That is, the simulation's radial span runs from a very short distance outside the event horizon to a maximum radius of $120M$. To avoid the (non-relativistic) coordinate singularities associated with the polar axis, cut-outs along the rotation axis 0.05π radians in opening angle are removed. Lastly, in order to economize on grid-cells, the azimuthal angle is restricted to the range $[0, \pi/2]$, with periodic boundary conditions imposed in the azimuthal direction. Within this grid, cells are apportioned so that they are densest at small radius and near the equatorial plane.

The initial state of the simulations is always taken to be a hydrostatic torus orbiting in the black hole's equatorial plane with aspect ratio $h/r \simeq 0.1$ and pressure maximum at $r = 25M$. To start out, the magnetic field is axisymmetric and purely poloidal. Running along isodensity contours, its magnitude is set so that the mean plasma β (ratio of gas to magnetic pressure) is 100. Thus, we have zero net magnetic flux. This magnetic field structure is chosen because it requires the least number of arbitrary choices to specify. At the radial edges, the boundary conditions are pure outflow.

We have now completed a suite of simulations, each run for a duration of $10,000M$, differing only in the spin of the central black hole. Described in terms of the parameter a/M, we have explored what happens when a/M = 0., 0.5, 0.9, -0.9, 0.93,0 .95, 0.99, and 0.998.

3. RESULTS

Although there are strong trends with black hole spin, certain features are common to all cases. At radii smaller than the initial pressure maximum, a statistically stationary inflow is eventually achieved (although it may take anywhere from $\sim 3000M$ – $10,000M$ to achieve). The main body of the accretion flow occupies a roughly wedge-shaped region with an aspect ratio roughly equal to the initial condition, within which the angular momentum distribution quickly settles into very nearly a Keplerian dependence on radius. Inside the disk, the flow becomes strongly turbulent as the magneto-rotational instability stirs it, and the magnetic field grows in intensity. Nonetheless, in the midplane the plasma β (the ratio of gas to magnetic pressure) rarely falls below 50–100. Above and below the main body of the disk, there is a large volume (which we call the disk corona) where the gas and magnetic pressures are crudely comparable, but in which the ratio of gas to magnetic pressure varies over a couple of orders of magnitude from place to place and from time to time.

Not surprisingly, the most dramatic dynamics take place near the rotation axis, both in the equatorial plane and out of it. As material accelerates inward through the region of the innermost stable circular orbit, the field lines are strongly stretched azimuthally. When the black hole rotates rapidly, frame-dragging accentuates this effect. Early in the simulation, there is very little matter directly above the plunging region, so the strong vertical gradient in $|\vec{B}|^2$ pushes these toroidal field loops out along the rotation axis, creating a "magnetic tower" resembling the structure predicted by Lynden-Bell (2003) and seen in the simulations of Kato, Mineshige, & Shibata (2004). However, after a short time, the shape of the magnetic field lines in this tower ceases to resemble the predictions made by Lynden-Bell or Kato et al. The same magnetic gradient strongly accelerates the top of the structure, making the field lines stretch out helically, winding relatively tightly near the base, and more loosely at large radii. Thus, although no large-scale magnetic field was present in the initial conditions, one is created *spontaneously* by dynamical processes embedded in the very basic character of accretion.

At late times, the winding of the fieldlines has a simple and intuitive dependence on the rotation rate of the black hole: they are tighter wound and rotate more rapidly when the black hole spins faster. When the magnetic field is neither time-steady nor axi-symmetric, even the definition of fieldline rotation rate becomes a bit fuzzy, but it is possible to construct a quantity that reduces to the standard definition in the limit of stationary and axisymmetric flow:

$$\omega \equiv V^\phi - \mathcal{B}^\phi \frac{V^r \mathcal{B}^r g_{rr} + V^\theta \mathcal{B}^\theta g_{\theta\theta}}{(\mathcal{B}^r)^2 g_{rr} + (\mathcal{B}^\theta)^2 g_{\theta\theta}}. \quad (1)$$

Here V^i is the so-called "transport velocity", the velocity of fluid motion in coordinate terms. In terms of the four-velocity u^μ, it is $V^i \equiv u^i/u^t$. The magnetic field components $\mathcal{B}^i \equiv [ijk]F_{jk}$ are the magnetic field components as found in the Maxwell tensor $F_{\mu\nu}$, and $g_{\mu\nu}$ is the metric tensor. This quantity, averaged both along lines of constant polar angle and over time is shown in Figure 1. Although this figure is for a particular simulation (with $a/M = 0.95$), the others are qualitatively similar. Generally speaking, the fieldlines rotate with somewhat less than half the rotation rate of the inner boundary.

Most dramatically, even in the retrograde simulation, the *sense* of fieldline rotation in the jet is the

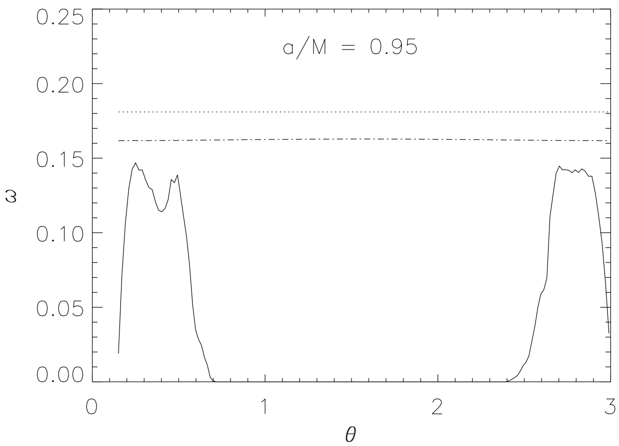

Fig. 1. Fieldline rotation (as defined in text) in the outflow for the simulation with $a/M = 0.95$. The horizontal lines show half the rotation rate of the black hole (dotted) and half the rotation rate of the inner boundary (dash-dot). The inner boundary may be more directly relevant here than the event horizon because, in our simulation, the event horizon is off the grid.

sense of rotation of the black hole, not the sense of rotation of the orbiting matter. That this should be so demonstrates that the source of fieldline rotation is the rotating spacetime of the black hole itself.

Matter is also expelled outward, following helical paths around the black hole rotation axis. In rough terms, the typical specific angular momentum of matter in the outflow is comparable to or a bit larger than the specific angular momentum of a particle following the innermost stable circular orbit, and changes rather little with radial distance. One can therefore usefully define an effective potential for that mean specific angular momentum that combines the effects of gravity and angular momentum conservation:

$$\mathcal{U} = \frac{\langle u_\phi \rangle}{g^{tt}} \left\{ -g^{t\phi} + \left[\left(g^{t\phi}\right)^2 - g^{\phi\phi} g^{tt} - g^{tt} / \left(\langle u_\phi \rangle\right)^2 \right] \right\} . \quad (2)$$

Here u_ϕ is the conserved angular momentum; weighting by proper rest-mass density ρ, its mean is $\langle u_\phi \rangle$. As is usually the case, the effective potential rises steeply toward the rotation axis, producing a dynamically forbidden zone around the axis. Similarly, there is a low point in the effective potential surrounding the region in the equatorial plane for which that angular momentum would be consistent with a circular orbit. Running between those two regions, there is a flat "channel" or "shelf" connecting the region very near the black hole with infinity, and that

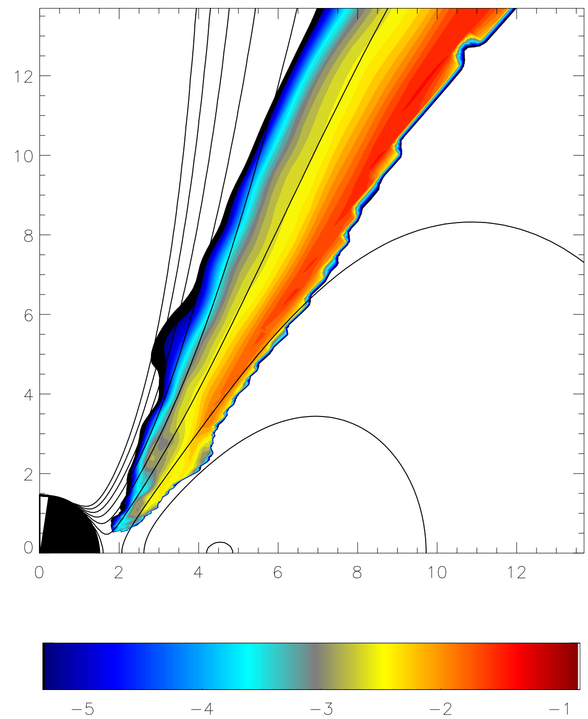

Fig. 2. Mass outflow ($\sqrt{-g}\rho u^r$) and effective potential contours at a late time in a simulation with $a/M = 0.9$. Color contours are logarithm of the mass outflow rate, while the line contours are linear in the potential with separation 0.025. The mean angular momentum used to define the effective potential is 2.5.

is the path taken by the massive part of the outflow (Figure 2).

One might next ask what pushes the matter outward? This is not a magneto-centrifugal wind, for the effective potential corresponding to a constant angular momentum is flat along the entire course of the outflow, and the matter's angular momentum hardly changes as a function of radius. The answer lies in the mutual obliquity of the effective potential contours and the coronal pressure contours. The pressure gradient points obliquely across the effective potential contours, pushing matter onto the "shelf", and squeezing it against the centrifugal barrier beyond. Because the only escape is toward larger radius, the matter is squeezed outward.

The maximum speed achieved by the matter in this fashion is modest: typically only a few tenths of c; on the other hand, in the interior of the funnel, where the high centrifugal barrier keeps the density extremely low, the flow is much faster: for numerical stability, we cap the Lorentz factor at 6–10. For this reason, we describe the outflow as comprising two

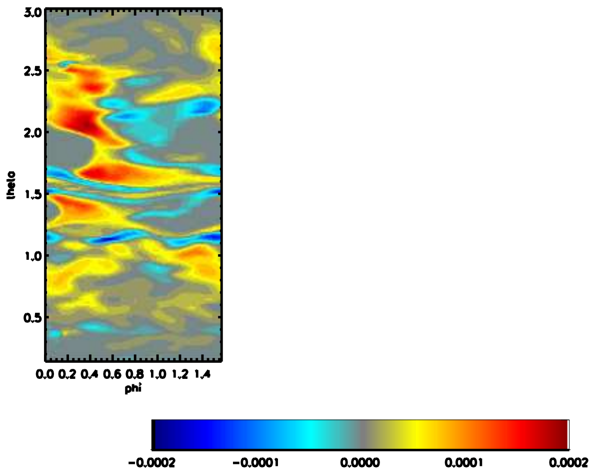

Fig. 3. Poynting flux on the inner boundary of the simulation at a late time in a simulation with $a/M = 0.9$.

pieces: a magnetically-dominated, highly-relativistic jet core and a funnel-wall outflow.

Energy input into the outflow can similarly be divided into two pieces: mechanical and electromagnetic. Acceleration of the matter-dominated funnel-wall flow is accomplished by the pressure gradients in the corona that squeeze matter into and out through the channel in the effective potential. The ultimate source of much of the electromagnetic power is the black hole itself. As illustrated for a particular case ($a/M = 0.9$) in Figure 3, integrated over the inner boundary, there is a consistent *outflow* of electromagnetic energy in all the simulations with non-zero black hole spin. There are always some places, particularly near the equatorial plane, where the accretion flow is the dominant feature, in which the black hole absorbs Poynting flux, but in net, spinning black holes radiate electromagnetically.

This radiation does not in any way violate the principles of black hole mechanics. Its energy source is the rotational kinetic energy of the black hole, the difference between its mass and its irreducible mass. Moreover, this process may also be viewed as a sort of electromagnetic analog of the Penrose process: it is a capture of electromagnetic field energy whose energy-at-infinity is negative (Koide 2003; Krolik, Hawley, & Hirose 2005).

In terms of gross contributions to the outflow, the electromagnetic component and the matter component tend to be comparable. However, one cannot be too precise about their relative importance because energy and momentum can easily be exchanged between the two in the course of the outflow. We show numbers in Table 1 (drawn from Hawley, Krolik, & Hirose 2006), but they are only indicative: they are time-averages for $r = 100M$, and measuring them at different radii would in general give results differing by factors ~ 2. What they do demonstrate clearly is how sharply the strength of the outflow depends on black hole spin.

TABLE 1

GLOBAL MEASURES OF THE OUTFLOW

a/M	$\dot{M}_{\rm jet}/\dot{M}_{\rm acc}$	$\eta_{\rm NT}$	$\eta_{\rm m}$	$\eta_{\rm EM}$
-0.9	0.035	0.039	0.088	0.023
0.00	0.005	0.057	0.0022	0.00031
0.5	0.037	0.081	0.063	0.0063
0.9	0.089	0.155	0.22	0.046
0.93	0.079	0.173	0.065	0.038
0.95	0.085	0.190	0.13	0.072
0.99	0.237	0.264	0.41	0.21

One gauge of the matter outflow is the ratio between the rate at which rest-mass is sent off to the outside world and the rate at which it is swallowed by the black hole ($\dot{M}_{\rm jet}/\dot{M}_{\rm acc}$). Entirely negligible when the black hole spins slowly, this ratio rises as high as $\simeq 25\%$ when $a/M = 0.99$.

Energetics are most conveniently communicated in terms of an efficiency: the ratio between the energy release rate and the rest-mass accretion rate. This is the same sort of definition as the more familiar radiative accretion efficiency; the traditional efficiency numbers, computed under the assumptions (local radiation of dissipated energy; no stress at and inside the ISCO) of Novikov & Thorne (1973) are denoted by $\eta_{\rm NT}$. We define $\eta_{\rm m}$ as the ratio to rest-mass accreted of the energy carried outward at $r = 100M$ associated with the matter flow ($\rho h u^r u_t$ integrated over all cells where $-hu_t > 1$ so the matter is unbound: h is the relativistic specific enthalpy) minus the rest-mass flux (ρu^r similarly integrated). This is the usable energy in the matter outflow because, of course, far from the black hole, the rest-mass cannot easily be tapped. The electromagnetic energy-loss efficiency $\eta_{\rm EM}$ is similarly defined ($-B^r B_t/4\pi$ integrated over the unbound outflow, where $B^\mu \equiv u_\nu * F^{\mu\nu}$ is the magnetic four-vector).

As the table shows, the energy outflow is a similarly strong function of black hole spin. It also demonstrates that the energy delivered to large radii by the outflow is in general comparable to that expected to be radiated from the disk, and often exceeds it by factors of a few. In most cases, the energy associated with the matter is greater than that associated with Poynting flux, but the contrast is not large, and we stress that it is a moving target in the sense explained above.

4. SUMMARY

Perhaps the most important fact to carry away from this presentation is that it is now possible to perform numerical simulations that contain a very large part of the most important physics involved in black hole accretion and jet systems: 3-d MHD in full general relativity. The codes are stable and efficient enough that the simulations can easily be run for times very long compared to the duration of any initial transients.

Even these first attempts have already answered several important questions. One such is whether large-scale fields are required to create magnetized jets. We have seen that, whether or not they are imposed from outside, they can form spontaneously from the magnetic field brought in with the accretion flow, provided it has at least some initial poloidal component (De Villiers et al. 2005). Once in place, they then serve as the backbone for an electromagnetically-dominated relativistic outflow of substantial power. In further work, we plan to explore what happens when large-scale fields *are* present from the start.

Another question has to do with how jets are shaped. We have seen that they are likely always to be divided in two pieces: an electromagnetic core and a matter-dominated funnel wall. The separation between the two rests on simple angular momentum conservation: unless there is significant matter somewhere in the region with extremely small angular momentum, the density in the interior of the outflow cone must be extremely low. The outer edge of the electromagnetic part, which is the inner edge of the matter part, is then set by the typical specific angular momentum of the matter in the outflow; we find here that this is comparable to the angular momentum of the inner accretion disk. The outer edge of the matter outflow is collimated by the pressure of the corona. Thus, yet another important aspect of jet mechanics is due to the outflow's intimate connections with the accretion disk.

This last point underlines an important piece of physics missing from these simulations: a true account of the matter's thermodynamics. In this simulation, because the internal energy equation is solved rather than the total energy equation, numerically-dissipated energy simply disappears. Thus, we do not track the genuine dissipation that must occur in association with the MHD turbulence. At the same time, the internal energy equation that we solve contains no terms describing radiative cooling, so just as there is no heating, there is also no cooling. As a result, the gas pressure in real accretion flows could behave quite differently from the way it does in our simulations.

Still a third question whose answer we are beginning to provide is the relation between black hole spin and outflows. It has long been conjectured by many people that spin promotes outflow (e.g., Blandford et al. 1990; Wilson & Colbert 1995). Our work certainly supports that speculation. We hesitate to proclaim a specific relation between energy output in the jets and black hole spin because, as we have emphasized, to define properly how much energy is delivered in what form to truly large distances requires a calculation that covers a much larger radial span as well as a better accounting for thermodynamics. However, we certainly see (as has also been reported by Gammie et al. 2004) that black hole rotation is capable of driving outflows whose power is comparable to that likely from accretion disk radiation, and that the output in jets rises very sharply with increasing black hole spin.

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