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FieldVis: A Tool for Visualizing Astrophysical Magnetohydrodynamic Flow

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Astronomers have long been challenged to test theories of observable phenomena at great distances from Earth. One such area of active research is the study of fast, collimated jets of ionized matter, or plasma, formed near massive black holes at the centers of distant galaxies. These jets drive into the hot, diffuse, and also ionized gas that fills the vast spaces between the galaxies. When the host galaxy and the jets it forms are in one of the many immense galaxy clusters that dot the universe, this behavior is especially important to understand. Galaxy clusters are the largest gravitationally bound structures in the universe, and their properties have been suggested to hold essential clues to the history of the universe's formation. Hot gas fills these clusters (in accumulation being more massive than the galaxies themselves), and astronomers use the gas's thermodynamic properties to analyze the clusters' histories. The jets' enormous power seriously complicates this analysis, because it stirs up and energizes the cluster gas, contributing substantially to its properties.

X-ray observations of the clusters sometimes show clear evidence for dramatic disturbances associated with jets; that much is now well-established. What is not theoretically resolved is precisely how and where the jets do their work, and just how efficiently they do it. The answers to these questions are behind much current astrophysical research. The questions, though, are difficult because the interactions are subtle and time variable. The gases are ionized, making them excellent electrical conductors, which means their motions induce electrical currents and generate magnetic fields. Those magnetic fields, in turn, react back on the moving gases, leading to a behavior class known as *magnetohydrodynamics*. Because of their complexity, these behaviors are best studied through numerical simulations.

Our group is involved in magnetohydrodynamic simulations that track the time and space evolution of the full 3D velocity and magnetic vector fields, plus fundamental scalar fields such as density and pressure. To accomplish the complex visualization of these jets, we developed FieldVis, a simulation tool that focuses primarily on representing 3D vector and scalar fields. Examining data from a sample 3D magnetohydrodynamic fluid simulation graphically illustrates the usefulness of our visualization package.

Visualization challenges

Simulations in this area solve the fundamental equations of ideal, compressible magnetohydrodynamics, meaning that the systems contain fluid flows and magnetic fields that dynamically interact with one another.[1] To accurately simulate these flows, we run the simulations on supercomputers. The simulation we visualize in this article took two days to run as a 32-processor job.

The flows' complexity makes it especially challenging to analyze the simulation data in a way that lets us isolate causal connections reliably. Previous approaches included volume-rendering animations (see http://www.msi.umn.edu/Projects/twj/newsite/projects/radiojets), which let us see the evolution of scalar parameters in the system over time. However, to capture the connections among the multiple quantities we desired, we needed a visualization system that could quickly handle large data sets (roughly 1 Gbyte per vector field, representing three components at each point of a 500 × 400 × 400 grid) and that could simultaneously display multiple vector and scalar fields in an uncluttered way. This task can overwhelm most visualization systems or, at best, lead to an image so cluttered with data that the sought-after relationships are obscured.

FieldVis, developed in Linux using C++ and OpenGL, can run on standard hardware. We performed the main development on a 1.7-GHz dual-processor machine with 2 Gbytes of RAM and a 64-Mbyte graphics card. Because the primary goal for this tool was to understand the relationship among multiple fields, it was crucial to depict as much information as possible without cluttering the display. Directly displaying the field vectors is a common approach. But, observers often can see patterns in vector fields more easily through the use of streaklines for the velocity and analogous flux lines for the magnetic field, represented simultaneously.[2,3]

Streaklines in a dynamic fluid resemble streamlines in a steady flow, which illuminate the paths of individual fluid elements. Magnetic flux lines trace the lines of magnetic force; their concentration, twisting, and bending reveal the strength, direction, and origins of the local magnetic forces. To depict as much information as possible, FieldVis represents streaklines visually as elongated cylinders, whose properties such as color, texture,

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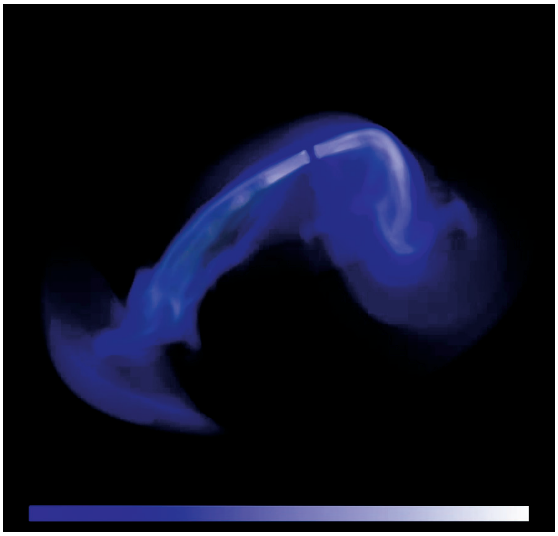
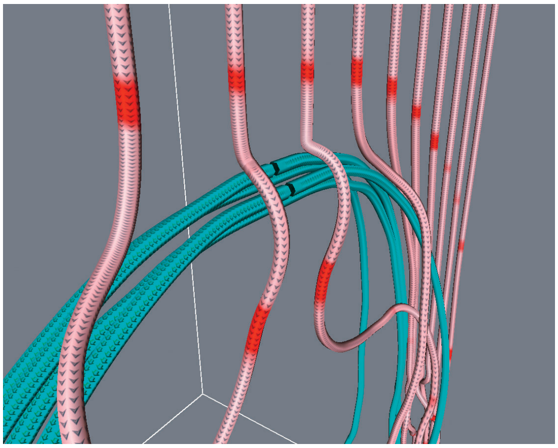


Courtesy Hierarchical Volume Renderer developed by the Laboratory for Computational Science and Engineering, Univ. of Minnesota

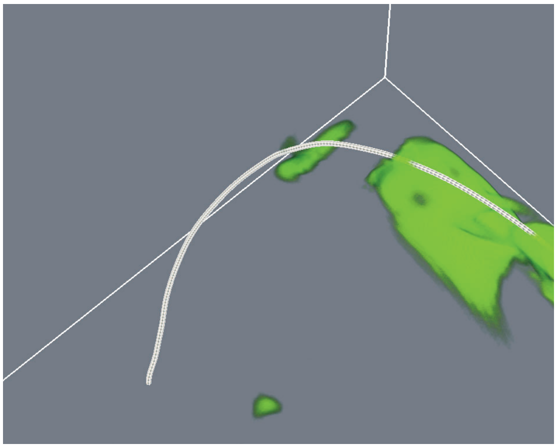
1 A pair of oppositely directed plasma jets seen by volume rendering the simulation's flow velocity magnitude. The relative motion between the jet source and the ambient medium swept the jets back into a U shape.



2 Visualizing a portion of the flow in Figure 1. The cyan streaklines are seeded at the jets' source (near the center, moving toward the sides). The pink streaklines represent flow of the ambient medium downward. We use scale and texture color to illustrate vector magnitude and orientation, which reveals the bow shock of the ambient medium as it interacts with the jets.

radius, and twisting we can adjust to provide information about additional parameters.

This particular simulation was meant to model a so-called head-tail radio galaxy's evolution. The simulation represents a region extending over 500,000 light-years in each direction that has evolved over a period of roughly 10 million years. As Figure 1 (a volume-rendering of the flow speed) illustrates, this object class has a distinct morphology with jets and plume structures that are preferentially bent in one direction. In our model, the higher-density ambient material streams past the oppositely directed jets like a uniform wind, bending them as the jets move into and interact with the environment.

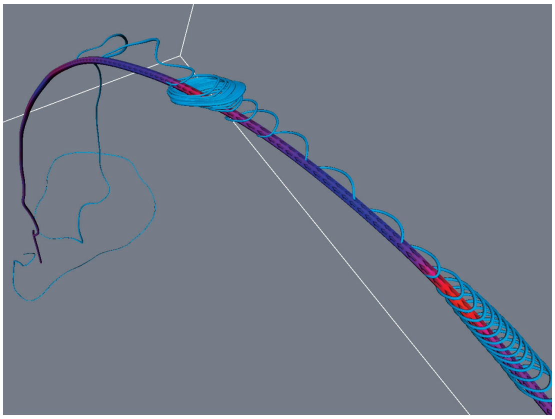


3 A volume-rendering of the compression rate, with a single velocity streakline originating from the jet source.

Visualizing multiple components of a single velocity field

An important component of the magnetohydrodynamic system we are examining is the influence that the ambient medium and the jets have on each other. We can visualize simultaneously multiple properties of the same field (velocity, for example) to better understand the nature of these interactions. Color and texture can visually depict data features, such as a bow shock formed as the ambient flow moves supersonically around the jets (see Figure 2). Flow lines emerging from the jet source are cyan, while the ambient medium streaklines are colored according to the flow compression rate $(-\nabla \cdot \mathbf{v})$. Pink indicates little or no compression, and red indicates strong compression. The coloring lets us distinguish the two types of flow and quickly identify the locations of strong compressions, or shocks. The flow lines are also textured with arrows to indicate flow direction. The textures stretch proportionally to the velocity magnitude. These simple features provide a full qualitative measure of flow character in a manner that is easy to visualize and comprehend.

Figure 2 indicates how the jet modifies flow in the ambient medium, which wraps around the jets as they penetrate upward into the ambient medium. In return, the jets bend strongly, so that the two flow fields align. Eventually, they become entangled near the bottom of the computational grid. The flow compression's color mapping reveals an important feature of the interaction: above their wrapping over the jets, the ambient streaklines pass through a bow shock (indicated by the upper red regions). The image also indicates the presence of a tail shock, which is an oblique shock formed in the wake of the flow around the jets (shown by the lower red regions). These shock structures are interesting because they are a source of vorticity, alerting us to the potential for magnetic-field growth downstream from the shock. Because of the flow's complexity, the tail shock is difficult to isolate using other techniques, and more conventional visualization techniques initially did not detect it. FieldVis's visualization techniques let us quickly isolate such structures.



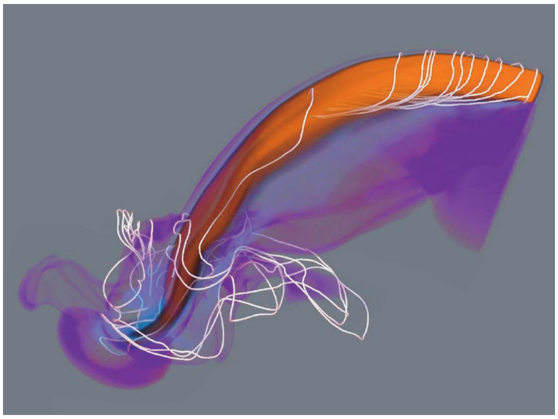
4 **A correlated relationship between the magnetic vector field and the velocity vector field. A color map, ranging from blue (rarefaction, the opposite of compression) to red (high compression) depicts the flow-compression level along a velocity streakline. The cyan textured magnetic flux line illustrates how the magnetic field is concentrated along regions where the flow field is compressed until the magnetic breaks free from the jet and becomes increasingly chaotic in the upper-left region of the image.**

Visualizing multiple vector fields

In a complex magnetohydrodynamic system involving multiple vector fields, the expectation is that the magnetic and velocity vector fields self-organize, showing local alignments as well as more complex but quantifiable relations. Simultaneous viewing of the vector fields offers the best viewing for some of these relations. It's important to recognize that in highly conducting astrophysical fluids, the fluid and the magnetic field are expected to be highly correlated—that is, the magnetic field drags along, twisted, compressed, and stretched in response to variations in the velocity field. However, when the magnetic intensity is large enough, it exerts forces that modify the plasma's motions in return. The associated feedback is both complex and nonlinear, so the instantaneous relationships between fields are not altogether obvious unless we visualize them together.

In Figure 3, we volume-render the magnetic field's compression rate, and we add a single velocity streakline originating from the jet source. The figure illustrates how the jet passes through two areas of high compression, but it gives no additional directional information about the magnetic field. To solve this drawback, in Figure 4, we visualize both magnetic and velocity vector fields in a region near a jet's origin. The thinner cyan cylinder follows one magnetic flux line in the jet plasma.

The velocity streakline in Figure 4 is again colored to indicate the flow-compression rate. This combined information reveals the magnetic field's response to flow variation along the streakline. As the jet flow emerges, it first compresses in a recollimation shock, which is analogous to structures seen in jet airplane exhausts. As the flow expands, the pitch (the distance between successive coils) in the magnetic field line expand correspondingly. Farther downstream is another shock, where the magnetic helix again compresses. After the flow carries the magnetic field line beyond the sharp jet bend, the magnetic field line breaks free from the jet and becomes increasingly chaotic. The visualization validates the theory that the magnetic field and the velocity field are highly correlated in systems of magnetohydrodynamic supersonic jets.



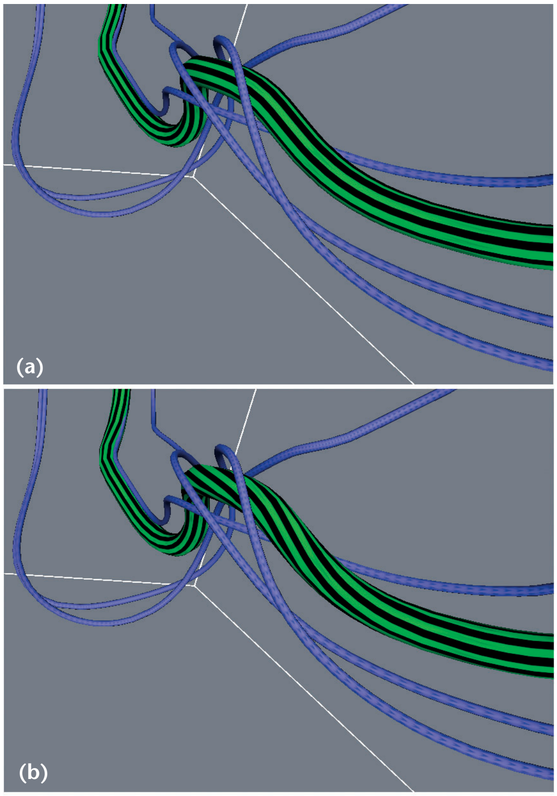
5 **Volume rendering lets us define a scalar variable in detail while simultaneously displaying vector field qualities through streamlines. High flow speed near the expulsion point of the jets (orange) is accompanied with a toroidal structure of the magnetic field lines. As the velocity speed decreases, the magnetic field tangle continues to coincide with significant velocity flow.**

Visualizing vector and scalar fields

The previous examples emphasize the value of visualizing vector and scalar information together. Volume rendering allows for the effective visualization of 3D scalar fields.[4] However, volume rendering multiple quantities can quickly become visually confusing. This problem is further complicated by introducing vector fields, which do not immediately lend themselves to simple volume-rendering techniques. A more effective strategy is to incorporate vector and scalar displays so that we can simultaneously and interactively view vectors and scalars together in a comprehensible fashion.

In Figure 5, we volume render the scalar flow speed. The orange opaque region represents flow speeds comparable to the emergent jet, which flows from the upper-right corner. The purple and blue regions represent the flow speed's deceleration from interacting with ambient material. In addition to the flow speed, we add a single magnetic field line caught in the turbulent flow to visualize the correlation between the magnetic field and flow speed.

Close to the jet source, the flux line once again exhibits a toroidal structure around regions of high flow speed (see Figure 5, upper right). As the flow progresses farther from the jet source, it slows and becomes turbulent—that is, no longer well-ordered. Careful analysis reveals that the magnetic field is, in fact, correlated with the flow, as regions of tangled magnetic field coincide with increased velocity (represented in purple). The figure illustrates how the magnetic field behaves in a transition from a smooth to chaotic flow.



6 Controlling how the texture is wrapped around the streakline cylinder lets us visualize the scalar attribute, helicity. This figure shows the same region of the flow rendered both (a) without and (b) with a helicity surface map.

Visualizing helicity

Another scalar quantity of particular interest in these simulations is flow helicity. Helicity ($\mathbf{v} \cdot [\nabla \times \mathbf{v}]$) is constructed from the velocity vector field and measures the twisting along the direction of the flow. Detecting regions with large helicity is valuable in studying magnetohydrodynamic system properties, as the twisting in the velocity field stretches magnetic field lines and amplifies their strength.

Graphically, we represent the amount of helicity by applying a texture over the cylindrical representation of the streakline. The texture pattern for each segment is offset by an amount proportional to the value of helicity in the corresponding region of the flow. Representing helicity in this manner lets us visualize what happens when the ambient medium and the jets interact. In particular, the wrapping of the ambient flow around the jet causes it to spin, as indicated by the twisting in the texture. In Figure 6, we illustrate this technique's usefulness by visualizing velocity streaklines near a vortex in the ambient flow. Figure 6a shows textures uniformly mapped to the streaklines. Figure 6b employs texture rotation to depict the helicity. The green striped streakline is centered in the region of high helicity and the blue streaklines are seeded around this region. When the streaklines are parallel (at the top of Figure 6b), the helicity is weak, which is represented by the lack of rotation in the texture. The streaklines converge and wrap around each other, indicating a helical flow; the texture twisting on the green streamline reflects the rotating property of the flow in the area.

Color

An interesting issue that we encountered in using this tool was the need to avoid ambiguity when using color. Because of its natural relation to the light wavelength, astrophysicists often use the rainbow color scale to visualize astronomical data. In this scale, the traditional color ordering, corresponding to increasing wavelength, is purple (violet), then blue, and so on up to red. However, in computer graphics, when you form a double-ended color ramp in the RGB color space with red at one end and blue at the other, and use linear interpolation within this color space to represent values between these endpoints, the result is that the intermediate values will be represented as purple. This leads to the effective color ordering: blue, purple, and red. Because each of these color orderings seems natural to users in its respective discipline, misunderstandings can easily occur when users neglect to be explicit about the correspondence between the data values and the color values they are using. Therefore, users must take special care when both designing and implementing color maps. In Figure 1, for example, we use a color map in the red hue and vary the saturation according to the corresponding scalar value. This allows both for unambiguously interpreting the visualization and for the ability to clearly see the textures on the tubes. We also use color to distinguish between distinct regions in a flow (such as in Figure 2) or to differentiate between two fields (such as velocity and magnetic fields in Figure 4).

User interaction

To help in understanding the relationships among different fields, FieldVis implements many interactive features tools. Because FieldVis looks at static snapshots from the flow simulation, it's important for the user to be able to manipulate the visualization to gather as much information as possible. Besides the basic ability to manipulate the viewing angle and distance in 3D, the most important feature is the ability to move streaklines interactively. Finding a field's interesting features can be sensitive to the choice of seed point for the integration.[3] Features cannot be revealed by simply adding more streaklines, because this quickly clutters the display. Instead, by allowing the user to move these points in an interactive fashion, interesting streaklines can be found in a quick manner. The user can also add additional streaklines or remove uninteresting streaklines on the fly. We are also developing the ability to reseed additional streaklines when zooming in on a region of interest, potentially showing more features that would not otherwise be found.

To enable a more quantitative understanding, we also plan to add the ability to directly extract numeric vector and scalar values from points in a user-selected region. To facilitate repeatability, all parameters are stored in a configuration file. This lets a user modify parameters and reload them without restarting the program, while at the same time providing a way to reproduce interesting results. The seed points for the streaklines are stored in a separate file, allowing for either a user to input them manually into the file or have an external program generate the points based on some set of criteria.

Conclusion

Through our work, we found that streaklines with varying surface properties such as texture and color are the most effective way to extract information from our data. The techniques we used are not specific to astrophysical problems and can extend to other sets of vector and scalar fields. In the future, we plan to use FieldVis to visualize tangled magnetic fields in simulated galaxy clusters, as well as velocity and magnetic structures produced by intermittent jets. ■

Acknowledgments

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