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Extreme Jets Take New Shape

Menlo Park, Calif. — Jets of particles streaming from black holes in far-away galaxies operate differently than previously thought, according to a study published today in *Nature*. The new study reveals that most of the jet's light—gamma rays, the universe's most energetic form of light—is created much farther from the black hole than expected and suggests a more complex shape for the jet.

The research was led by scientists at the Kavli Institute for Particle Astrophysics and Cosmology, jointly located at the Department of Energy's SLAC National Accelerator Laboratory and Stanford University, with participation from scientists from around the world. The study included data from more than 20 telescopes including the Fermi Gamma-ray Space Telescope and KANATA telescope.

High above the flat Milky Way galaxy, bright galaxies called blazars dominate the gamma-ray sky, discrete spots on the dark backdrop of the universe. As nearby matter falls into the black hole at the center of a blazar, "feeding" the black hole, it sprays some of this energy back out into the universe as a jet of particles.

"As the universe's biggest accelerators, blazar jets are important to understand," said KIPAC Research Fellow Masaaki Hayashida, who serves as corresponding author on the paper with KIPAC Astrophysicist Greg Madejski. "But how they are produced and how they are structured is not well understood. We're still looking to understand the basics."

Researchers had previously theorized that such jets are held together by strong magnetic field tendrils, while the jet's light is created by particles revolving around these wisp-thin magnetic field "lines."

Yet, until now, the details have been relatively poorly understood. The recent study upsets the prevailing understanding of the jet's structure, revealing new insight into these mysterious yet mighty beasts.

"This work is a significant step toward understanding the physics of these jets," said KIPAC Director Roger Blandford. "It's this type of observation that is going to make it possible for us to figure out their anatomy."

Locating the Gamma Rays

Over a full year of observations, the researchers focused on one particular blazar jet, located in the constellation Virgo, monitoring it in many different wavelengths of light: gamma-ray, X-ray, optical, infrared and radio. Blazars continuously flicker, and researchers expected continual changes in all types of light. Midway through the year, however, researchers observed a spectacular change in the jet's optical and gamma-ray emission: a 20-day-long flare in gamma rays was accompanied by a dramatic change in the jet's optical light.

Although most optical light is unpolarized—consisting of light rays with an equal mix of all polarizations or directionality—the extreme bending of energetic particles around a magnetic field line can polarize light. During the 20-day gamma-ray flare, optical light streaming from the jet changed its polarization. This temporal connection between changes in the gamma-ray light and changes in the optical light suggests that both types of light are created in the same geographical region of the jet; during those 20 days, something in the local environment altered to cause both the optical and gamma-ray light to vary.

“We have a fairly good idea of where in the jet optical light is created; now that we know the gamma rays and optical light are created in the same place, we can for the first time determine where the gamma rays come from,” said Hayashida.

This knowledge has far-reaching implications about how energy escapes a black hole. The great majority of energy released in a jet escapes in the form of gamma rays, and researchers previously thought that all of this energy must be released near the black hole, close to where the matter flowing into the black hole gives up its energy in the first place. Yet the new results suggest that—like optical light—the gamma rays are emitted relatively far from the black hole. This, Hayashida and Madejski said, in turn suggests that the magnetic field lines must somehow help the energy travel far from the black hole before it is released in the form of gamma rays.

“What we found was very different from what we were expecting," said Madejski. “The data suggest that gamma rays are produced not one or two light days from the black hole [as was expected] but closer to one light year. That’s surprising."

Rethinking Jet Structure

In addition to revealing where in the jet light is produced, the gradual change of the optical light’s polarization also reveals something unexpected about the overall shape of the jet: the jet appears to curve as it travels away from the black hole.

“At one point during a gamma-ray flare, the polarization rotated about 180 degrees as the intensity of the light changed,” said Hayashida. “This suggests that the whole jet curves.”

This new understanding of the inner workings and construction of a blazar jet requires a new working model of the jet’s structure, one in which the jet curves dramatically and the most energetic light originates far from the black hole. This, Madejski said, is where theorists come in. "Our study poses a very important challenge to theorists: how would you construct a jet that could potentially be carrying energy so far from the black hole? And how could we then detect that? Taking the magnetic field lines into account is not simple. Related calculations are difficult to do analytically, and must be solved with extremely complex numerical schemes."

Theorist Jonathan McKinney, a Stanford University Einstein Fellow and expert on the formation of magnetized jets, agrees that the results pose as many questions as they answer. "There's been a long-time controversy about these jets—about exactly where the gamma-ray emission is coming from. This work constrains the types of jet models that are possible," said McKinney, who is unassociated with the recent study. "From a theoretician's point of view, I'm excited because it means we need to rethink our models."

As theorists consider how the new observations fit models of how jets work, Hayashida, Madejski and other members of the research team will continue to gather more data. "There's a clear need to conduct such observations across all types of light to understand this better," said Madejski. "It takes a massive amount of coordination to accomplish this type of study, which included more than 250 scientists and data from about 20 telescopes. But it's worth it."

With this and future multi-wavelength studies, theorists will have new insight with which to craft models of how the universe's biggest accelerators work.

The gamma-ray observations used in this study were made by the Large Area Telescope on board the Fermi Gamma-ray Space Telescope, an astrophysics and particle physics partnership developed by NASA in collaboration with the U.S. Department of Energy Office of Science, along with important contributions from academic institutions and partners in France, Germany, Italy, Japan, Sweden, and the United States. LAT collaboration members were key participants in the development of this research. SLAC National Accelerator Laboratory managed construction of the LAT and now plays the central role in science operations, data processing and making scientific data available to collaborators for analysis.

The optical polarization data that played a crucial role in this study was taken by the KANATA collaboration, using the KANATA telescope located in Higashihiroshima, Japan. The KANATA telescope is operated by Hiroshima University.

The GASP-WEBT observatories participating in this work are Abastumani, Calar Alto, Campo Imperatore, Crimean, Kitt Peak (MDM), L'Ampolla, Lowell (Perkins-PRISM), Lulin, Roque de los Muchachos (KVA and Liverpool), San Pedro Ma´rtir, St Petersburg for the optical–NIR bands, and Mauna Kea (SMA),Medicina, Metsahovi, Noto and UMRAO for the millimeter radio band.

The campaign also included data from NASA satellites Swift and the ROSSI X-ray Timing Explorer, and the Japanese satellite Suzaku.