

## Galactic Jets

Eric Perlman

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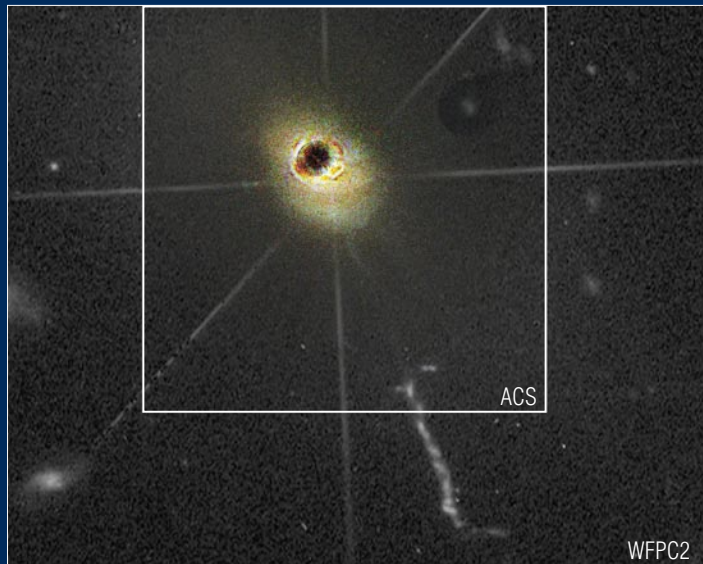
*Eric Perlman*

*Hubble's* 1993 images of the host galaxies of “quasi-stellar objects” (QSOs) cemented the link between QSOs and active galactic nuclei (AGN), which are central regions of galaxies that emit light strongly all across the spectrum, from radio waves to x-rays. For years before the advent of *Hubble*, astronomers conjectured that AGN were accretion disks in the process of capturing gas and feeding it to black holes—collapsed objects so dense that no light can escape their gravitational pull. In 1994, in another of its early coups, *Hubble* took pictures of the active galaxy M87 that revealed the AGN to be a spiral disk. Analysis of spectral data taken from opposite sides of the disk found evidence for a strong reversal of velocity, consistent with orbital motion under the force of gravity. The high orbital speed of the disk implied a central mass of 3 billion Suns gathered in a volume smaller than the Solar System. This discovery lent support to the concept of AGN as bright, swirling fields of cosmic debris, spiraling into an unseen, bottomless drain created by a supermassive black hole. (Since these early *Hubble* investigations, still stronger confirmation of the existence of black holes has come from x-ray spectra of hot gas circling close to the black-hole event horizon—the surface from which no light or matter can emerge.)

Active galaxies exhibit other energetic phenomena besides great brightness at their centers, including narrow, high-speed jets of material (described in this article) and slower-moving outflows that cover a much larger area (see the accompanying article by Arav).



Streaming out from the center of the galaxy M87 like a cosmic searchlight is one of nature's most amazing phenomena, a black-hole-powered jet of electrons and other sub-atomic particles traveling at nearly the speed of light. This article describes how *Hubble* is contributing to their understanding.



3C 273



M87

Quasi-stellar object 3C 273 and the large elliptical galaxy M87 were two of the first objects to be identified with jet-like structures, as the sidebar on the next page explains. The image on the left is a composite of two *Hubble* images, one by the Wide Field Planetary Camera 2 (WFPC2), and one by the Advanced Camera for Surveys (ACS). The ACS image was taken using its coronagraph—an instrument channel that places a black disk in front of a bright object in order to view faint details nearby.

Jets and outflows have important influence on galaxy evolution because of the vast energy they transport from the AGN, through the surrounding galaxy, and out into intergalactic space. In the process, they sweep away interstellar gas. They can cause additional gas to be blasted away by the supernovae that occur in the aftermath of star formation, which may be instigated by the impact of jets and outflows on dense interstellar clouds. The end result of gas removal may be a transformed galaxy—“red and dead” in the terminology of the accompanying article by Davis and Faber. Such a galaxy can form no more stars because of lack of gas. Furthermore, fuel ceases to fall towards the black hole, which can stall the AGN. Meanwhile, the surrounding intergalactic gas and dust is strongly heated by the vast energy ultimately deposited beyond the galaxy by outflows and jets.

## Galaxies, QSOs, Black Holes, and Jets

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In the history of astronomy, Michigan-born Heber Curtis is best known for taking the correct side in a highly publicized 1920 debate with fellow astronomer Harlow Shapley regarding the scale of the universe and the nature of spiral nebulae. He argued that they were galaxies beyond our own, which now we know is true. Curtis's role in other areas of astrophysics is less well known, yet his seminal study of jets has lasting significance. Two years before the famous debate, he noticed a linear feature in photographs of a bright nebula in the constellation Virgo known as M87—a “curious straight ray,” he called it—aligned with the nebula's bright core. This was the first discovery of a galactic jet, one of nature's most powerful phenomena.

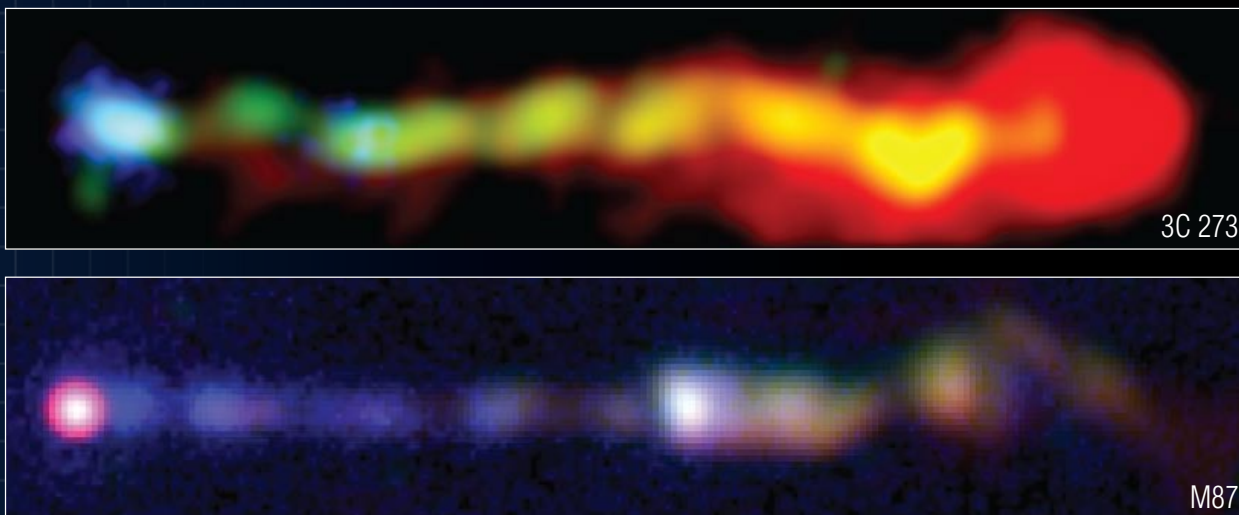
In the late 1940s, Australian astronomers studying the sky at radio frequencies sought to identify cosmic radio sources by timing lunar occultations—the moments that the radio signals were eclipsed by the passing Moon. In this way, they established that M87 and the strong radio source Virgo A are, in fact, the same object. In 1962, they measured the celestial position of 3C 273, another strong radio source in the constellation Virgo. The next year, working from Mt. Palomar, Cal Tech astronomer Maarten Schmidt reported a star-like object at that position, and noted its jet-like feature; 3C 273 was the first “quasar” or quasi-stellar object (QSO) to be discovered. Its distance was the greatest ever measured to that date—about 2 billion light-years—implying a prodigious energy output a hundred times brighter than the most luminous known galaxy, and radiating as much energy per second as a large galaxy of hundreds of billions of stars.

Two years later, Carnegie astronomer Allan Sandage showed that the optical light of 3C 273 varied in brightness on timescales of months, meaning that this immense power must emerge from a region only light-months across. This was the first hint that the ultimate power source for these objects might be the gravitational energy released by a massive black hole in the process of accreting matter. Black holes are bodies so dense and massive that even light itself cannot escape their gravitational pull.

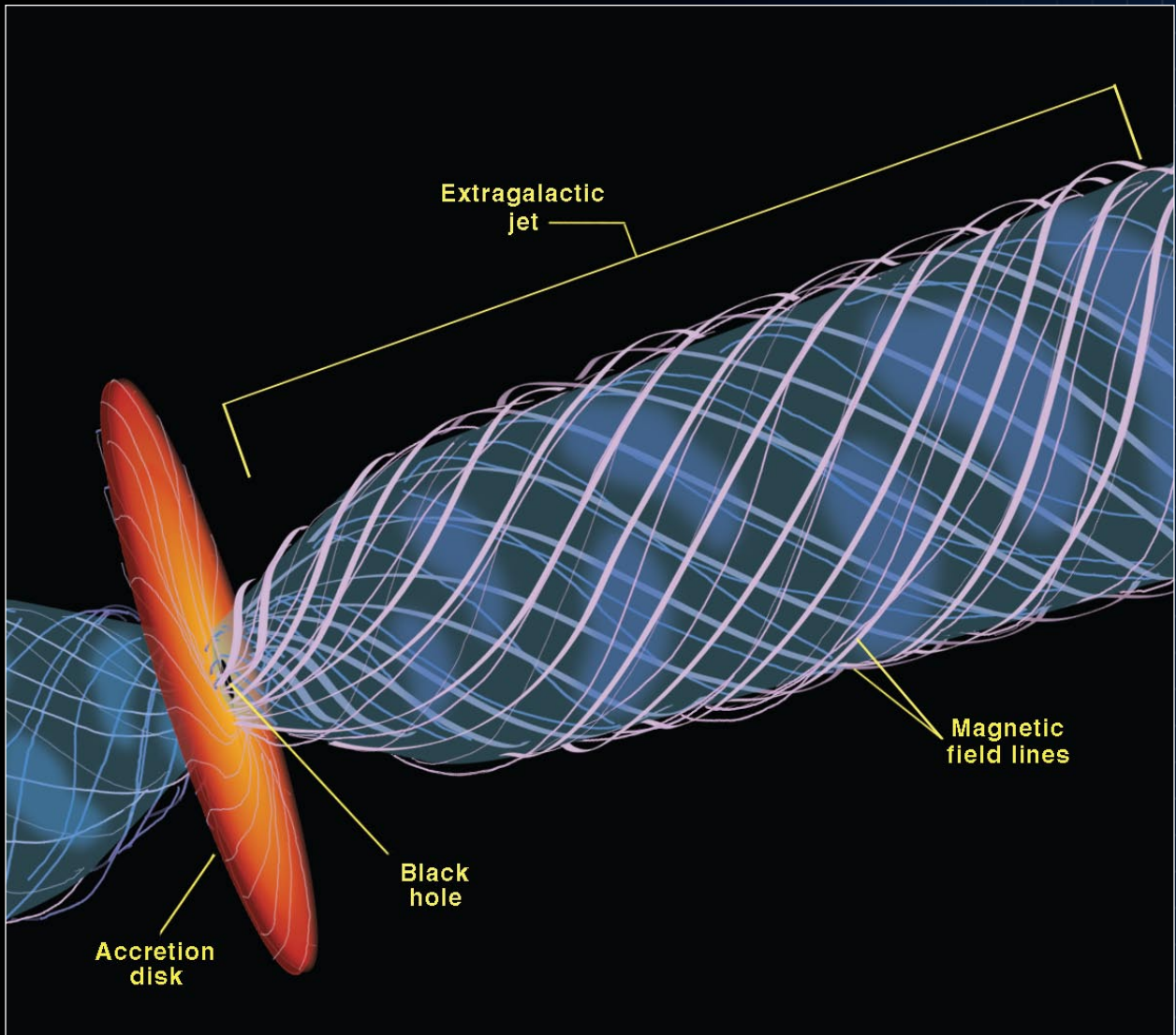
The clear similarities between M87 and 3C 273—bright radio sources, aligned jets, and sharp, bright cores—suggested that the QSOs resided in the center of an unseen host galaxy, which was indeed revealed by *Hubble* in 1993, two years after its launch.

Jets appear as brilliant, narrow beams—a spine with knots—shooting out from the AGN of host galaxies. The spine is the linear organization of the light, and the knots are bright condensations—large and small—along the spine. From the apparent displacement of knots between observations taken at different times, astronomers know that the material in jets moves at astonishing speeds, nearly up to the speed of light. Some jets are as long as a million light-years end to end, which is 10 times the diameter of our own Milky Way galaxy.

The linearity and the alignment of galactic jets with the AGN—the black hole and accretion disk—must be due to the magnetic forces experienced by charged particles in motion. While ions and electrons move freely *along* magnetic field lines, they move only with great resistance *across* them. Because the particles and fields react against each other, the ionized gas of the accretion disk traps the magnetic field lines and wraps them up as the disk revolves. The same principle confines the ionized gas of jets in a twisted rope of magnetic field lines, even at great distances from the black hole.



Multispectral appearances of portions of the jets of M87 and 3C 273. These panels were assembled from data from the Very Large Array (radio waves; red), *Spitzer* (infrared; yellow), *Hubble* (visible; green) and *Chandra* (x-ray; blue). Redder shades represent regions that are brighter in the infrared and/or radio, and bluer shades represent regions that are brighter in x-rays. Such multispectral images allow astronomers to study the spatial relationships of higher and lower energy regions in jets. For 3C 273, the quasar itself is well off the image to the left. (Image credit: E. Perlman, Y. Uchiyama.)



Schematic structure of the core of an active galaxy. (Illustration credit: John Biretta.)

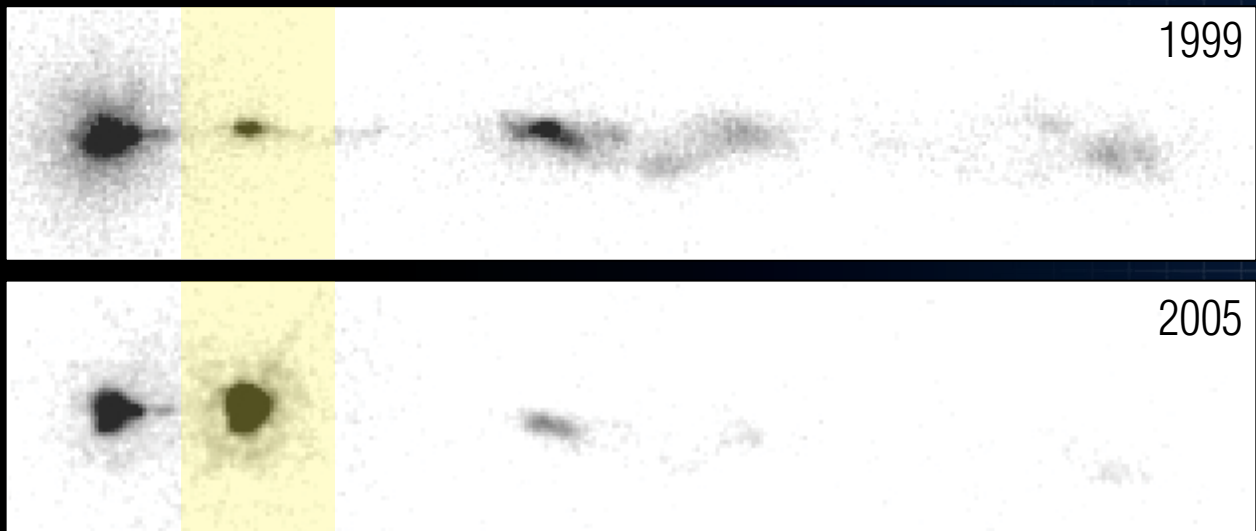
The broad, smooth spectra of jets—their distributions of intensity with wavelength—suggest that jet light is produced by accelerated electrons spiraling along magnetic field lines. Light produced in this manner is called “synchrotron radiation,” because it was first observed in 1947 in a laboratory device for accelerating electrons called a “synchrotron.”

Synchrotron radiation provides another diagnostic tool for studying jets: *polarimetry*, which is the measurement of the direction of the vibration of an electromagnetic wave (light). Synchrotron radiation is strongly polarized by the magnetic field. By measuring the degree of polarization and its direction, astronomers can estimate the dominant direction of the magnetic field at any point in the image of a jet. Furthermore, the regions of a jet that display stronger polarization are likely to be regions with the more orderly magnetic field. Conversely, where the polarization is weaker, but the synchrotron radiation is still bright, astronomers can infer less uniformity and greater disorder in the magnetic field.

Before *Hubble*, radio astronomers had discovered dozens of galactic jets like those of M87 and 3C 273, the first identified QSO. Still, only five jets had been identified at optical or shorter wavelengths, and almost nothing was known about their physical mechanisms and energy sources. In the 16 years since *Hubble* was launched, astronomers have produced images of over 50 jets in radio, infrared, optical, and x-ray emissions. Of these, the historic jets of M87 and 3C 273 are still the best-studied and most compelling examples.

Even though galactic jets are very luminous, it is maddeningly difficult to obtain physical information about them from their light. Spectroscopy is ineffective, because the jet material is so hot that the atoms have been fully ionized—stripped of all electrons. Therefore, jets produce no spectral lines, which astronomers customarily use to measure composition, density, temperature, and motion along the line of sight. Nevertheless, images of jets do reveal movement, varying appearance at different wavelengths, and sudden flare-ups. For example, between 2000 and 2005, a knot in the M87 jet increased in brightness nearly a hundredfold at both optical and x-ray wavelengths—bright enough to outshine the AGN core, located about 200 light-years away. Astronomers strive to learn what they can from such phenomena about the structures, sizes, dynamical processes, and light production of jets.

## M87



A flare in the jet of M87. The innermost 1,000 light-years of the M87 jet, as seen in 1999 and 2005. The flaring component “HST-1” is indicated by the yellow shading. The nucleus is located near the left edge of both panels. The contrast in the bottom panel has been decreased by a factor of 10 to emphasize the dramatic nature of the flare, which entailed a brightening by nearly a factor of 100.

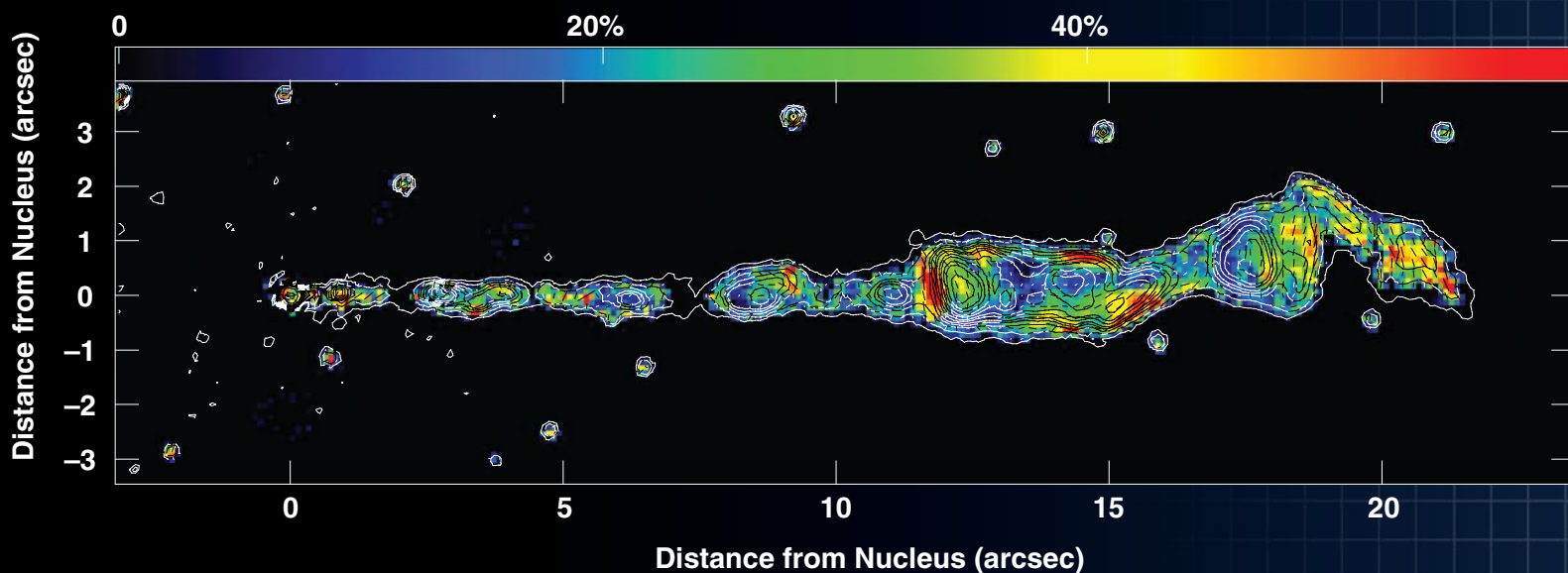
Optical and x-ray emission removes energy from jets. Yet they remain luminous, which means some refueling or reacceleration process must continue to operate throughout the jet to accelerate the high-energy electrons. Astronomers do not know what this process is. Nevertheless, they are discovering some clues that should be helpful in understanding the flow and balance of energy in jets.

One clue is that knots appear smaller at shorter wavelengths. Because radiation at shorter wavelengths is more energetic than at longer ones, this must mean that the regions producing higher energy radiation are smaller. For the M87 jet, astronomers have observed this trend in *Hubble* images through the visible range, continuing all the way to the x-ray range, as documented in *Chandra* images.

A second clue is a recurrent pattern of optical polarization around knots. The typical knot itself shows low polarization at its brightest point, associating magnetic disorder with increased emission. Just upstream of the knot, the polarization is seen to peak, and the magnetic field is observed to be aligned *perpendicular* to the spine, suggesting a transition region—a shock or compression—between the knot and the smooth flow into it. Downstream from the knot, the magnetic field again relaxes *parallel* to the flow. This pattern is not observed at radio wavelengths, where there is much less variation in the amount and direction of polarization near knots. This implies that the electrons that emit high-energy radiation (optical and x-ray) do not occupy the same volume as the lower-energy electrons producing radio waves. In other words, the optical and radio emitting electrons do not occupy the same physical space, and the higher-energy electrons occupy regions closer to the central spine of the jet. This is consistent with the finding that the regions of particle accelerations are progressively smaller at higher energies.

A third clue, found recently by *Hubble*, *Chandra*, and the *Spitzer* infrared observatory, is that jets are bluer closer to the black hole and redder farther out. (“Bluer” means a higher ratio of shorter wavelength radiation to longer, and “redder” means the opposite.) This pattern, seen in both M87 and 3C 273, suggests a gradual loss of energy by the jet particles as the flow moves out from the nucleus.

Sixteen years of *Hubble* observations, supported by the other NASA Great Observatories in space and great radio telescopes on the ground, have revolutionized the study of jets. Astronomers now directly observe the high-energy processes that link emission, structure, and magnetic fields. Many puzzles remain, including the material composition of the jets, and the flow of energy from its original source near the black hole to the distant locations where it is emitted. If NASA successfully conducts another servicing mission to *Hubble* and installs the waiting Cosmic Origins Spectrograph and Wide Field Camera 3, astronomers will have powerful new tools to work on these puzzles.



Polarization image of the M87 jet, obtained with *Hubble*. Red contours represent regions of high polarization, while blue colors represent regions of low polarization (color scale shown at top). Contours are lines of constant optical brightness of the jet at visible wavelengths. Regions of maximum polarization are usually located upstream (to the left) of the brightest point in a knot, where the magnetic field (not shown) is perpendicular to the jet. Much lower—or no—polarization is observed at the brightest point in each knot. The magnetic field is parallel to the jet downstream of each knot's brightest point. (At the distance of M87, 1 arc second translates to about 250 light-years.)



Eric Perlman is an Associate Professor of Physics and Space Sciences at the Florida Institute of Technology. Over the last 10 years he has worked extensively on jets, using *Hubble*, the *Chandra X-ray Observatory*, and other telescopes. In 2000 and 2005, he was awarded five-year grants from NASA's Long-Term Space Astrophysics Program to pursue this work.