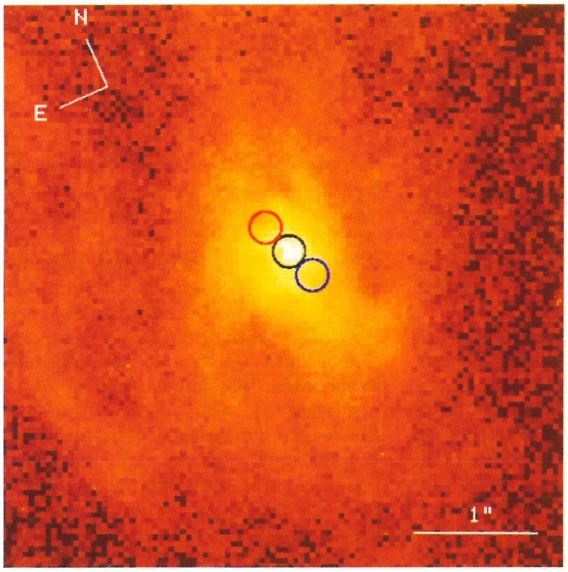
REPAIRED HUBBLE SEES STRONG EVIDENCE OF A SUPERMASSIVE BLACK HOLE IN M87



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Disk of ionized gas at the core of M87 as imaged by the Hubble Space Telescope's Wide Field–Planetary Camera, showing the locations of three spectral observations: at the center of the disk (black circle) and 0.25 arcsec to either side along the major axis of the disk (red and blue). The elliptical shape is consistent with a circular disk tilted about 42° from the line of sight. Spiral structure is also evident.

Researchers using the refurbished Hubble Space Telescope to study the galaxy M87 have seen new and compelling dynamical evidence that a supermassive black hole lurks at the galaxy's core. Using the Wide Field–Planetary Camera, the astronomers obtained an image of what seems to be a gaseous accretion disk[1] centered on the point of origin of a relativistic jet[2] that emanates from M87. (See the figure at right.) Spectrographic measurements reveal that relative to M87's overall motion, one side of the disk is receding from us at about 500 km/sec and the other is approaching at a similar velocity, strongly suggesting that the gas is orbiting the center of M87 at that velocity.[3] (See the figure on page 18.) Given the 60-light-year distance of the two points from the center of the motion and assuming stable circular orbits, one readily deduces with ordinary Newtonian mechanics that material amounting to about 2.4×10^9 solar masses ($M_\odot$) lurks at the center of M87, in a volume that contains far too few visible stars to account for so much matter.

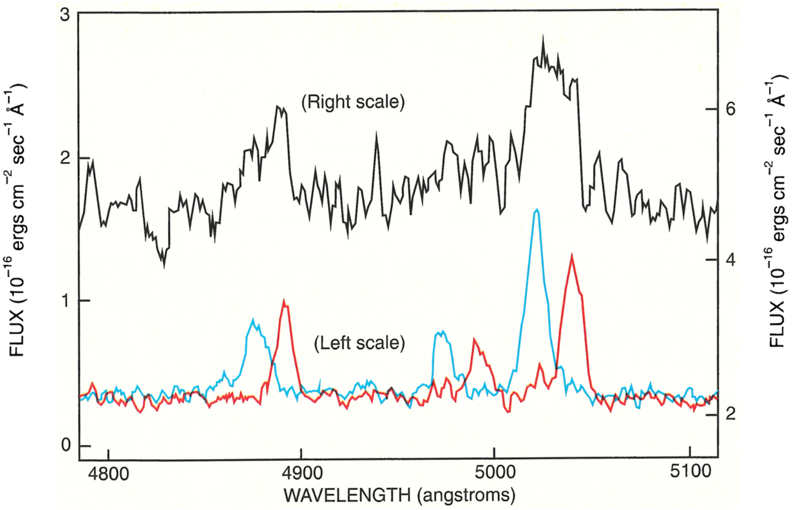
Edwin Salpeter (Cornell University), one of the pioneers of the theory of astrophysical consequences of black holes, says the observations are "beautiful in a way that makes the science easier to believe and understand. The Hubble group has very clean data, combining two different types of observation: the spatial picture of a nice circular disk and the clean, accurate spectra on each side of the disk."

Holland Ford (Johns Hopkins University and Space Telescope Science Institute, Baltimore) says of his team's work: "Hubble lets us measure velocities two to four times closer to the center of M87 than is possible with terrestrial telescopes. And by observing the circular motion of ionized gas in a rotating disk, we can finesse the technical difficulties of measuring and interpreting the line-of-sight velocities of stars near the nucleus. The large velocities in the disk are possible only if there is a high concentration of mass in the very center of M87. It sure looks like a black hole to us."

A very brief history of holes

Objects with the light-trapping properties of black holes were theorized as long ago as 1783, when John Michell noted that for sufficiently large and compact "stars" the force of gravity would prevent particles of light from escaping.[4,5] As Pierre-Simon Laplace noted in 1795, "the largest luminous bodies in the universe may, through this cause, be invisible."[6] The more modern theoretical incarnations are Karl Schwarzschild's 1916 solution of the general relativity equations, which describes the warping of spacetime due to a compact nonrotating mass, and Roy Kerr's 1963 solution, which describes the effects of a rotating mass. In 1939 J. Robert Oppenheimer and Hartland Snyder described how such objects might form: A star will collapse indefinitely if it is heavier than about 3 $M_\odot$ after exhausting its thermonuclear fuel. The nature of such collapsed stars remained ambiguous, however, until 1958, when David Finkelstein greatly clarified the nature of the event horizon around a point mass. Salpeter in the US and Yakov Zel'dovich in the USSR suggested in 1964 that matter falling into such a compact object would emit radiation before being engulfed, making the object visible despite its light-trapping properties. Salpeter and Zel'dovich suggested that quasars could be powered by this mechanism. In 1967 John Wheeler coined the psychologically potent moniker "black hole," which has stuck ever since.[5]

Experimental verification of black holes has been a long and uncertain process. The only rigorous proof of a black hole would be observation of relativistic motions caused near one, which would require seeing to within a few Schwarzschild radii of the hole's center. For a hole of mass M the Schwarzschild radius is $2GM/c^2$. Even a billion-$M_\odot$ black hole has a Schwarzschild radius of only about 20 astronomical units. (The Earth's or-



Doppler-shifted spectra seen at the locations marked in the figure on page 17 with Hubble's Faint Object Spectrograph. The peaks are from Hβ (4861 Å) and O^{2+} (4959 Å and 5007 Å). One side of the gas cloud (red curve) is receding at 500 km/sec relative to the center, while the opposite side (blue) is approaching at the same velocity. The peak of the spectrum for the center of M87 (black) shows no significant Doppler shift relative to M87's overall motion, but is broadened, as expected for the central region of circular motion. The observed velocities are consistent with the gas cloud's orbiting a 2.4-billion-$M_\odot$ black hole. (Data courtesy of Richard Harms and Holland Ford.)

bit has a mean radius of 1 AU.) At extragalactic distance scales (on the order of millions of light-years) the observation of such fine detail is many orders of magnitude beyond current astronomical capabilities. Less direct evidence must be sought.

Since black holes are thought to form from stellar collapse, an obvious place to look is star systems where one visible star can be observed to be orbiting a dark companion with mass greater than about 3 $M_\odot$. One of the best candidates of this type is Cygnus X-1. Orbital data and estimates of the mass of the visible star indicate that the dark companion in this binary system has a mass[7] of $16 \pm 5\, M_\odot$. Another extremely good candidate is the x-ray nova V404 Cyg. Observations of V404 Cyg by Philip Charles (Oxford University) and coworkers indicated that the compact partner in that system has a mass of at least 6 $M_\odot$, independent of any assumptions about the visible companion's mass, orbit orientation and so on.[8] (Adding reasonable assumptions of this sort allows a mass as high as about 30 $M_\odot$.) Soft-x-ray spectra of V404 Cyg recently obtained by R. Mark Wagner (Ohio State University), Sumner Starrfield (Arizona State University) and coworkers using the satellite ROSAT suggest that the large x-ray outbursts from Cyg V404 are due to the collapse of an accretion disk occasionally dumping material into the black hole.[9]

"Evidence for stellar black holes is quite persuasive," says John Kormendy (University of Hawaii, Honolulu). "We understand the dynamics of binary systems very well, and we understand how a star can evolve to form such a black hole."

Supermassive holes

Black holes with masses orders of magnitude greater than that of the Sun are the other prime candidate for searches. Nondynamical evidence of supermassive black holes at the centers of certain galaxies has been accumulating for decades. Such evidence tends to be qualitative and indirect: Quasars and active galactic nuclei emit energy at astonishingly large rates, sometimes ejecting jets of material at relativistic velocities. Short-time variations of the luminosities of such objects and very-long-baseline radio interferometry indicate that the "engines" driving these processes are tiny relative to the sizes of galaxies. An entire paradigm has arisen that explains all these observations reasonably well in terms of the effects of supermassive black holes. In essence, black holes are the only known plausible explanation. But we shouldn't be complacent. As Kormendy says, "we need independent dynamical tests of the black hole paradigm. For instance, do the models predict the correct black hole masses?"

M87 is a prime candidate in which to seek such dynamical evidence. At a distance of about 50 million light-years M87 is one of the closest highly active galaxies known. A bright jet of plasma moving at relativistic velocities extends over 2600 light-years out from the core of the galaxy. Very-long-baseline interferometry measurements of the intense radio source at the origin of the jet suggest that the central engine is contained in a space comparable to the size of the solar system. For some astrophysicists such evidence is a smoking gun, but others will not be satisfied until we see the fingerprints on the trigger.

In 1978 Wallace Sargent (Caltech) and coworkers analyzed spectra from the core of M87 to glean information about the velocities of the stars there. The group showed that the results could be explained by the presence of a 5-billion-$M_\odot$ dark object, plausibly a black hole.[10] Concurrent work by Sargent's student Peter J. Young and coworkers on the light profile of M87 suggested a 3-billion-$M_\odot$ hole there.[11] The star-velocity analysis is complicated, because we can only observe the line-of-sight component of the velocities, averaged over many stars. Furthermore, M87 is a giant elliptical galaxy, and in such a galaxy one must contend with stars moving in a variety of directions, unlike the comparatively orderly cartwheeling of spiral galaxies. Sargent's analysis assumed isotropic velocity dispersions, and it was soon pointed out that by a judicious choice of anisotropy, his results could be explained without a black hole. However, further analysis strengthened the case for a black hole by showing that the models without a black hole would evolve to produce a bar-like structure, which is not seen in M87.

In the years that followed, others such as Kormendy, Douglas Richstone (University of Michigan) and Alan Dressler (Carnegie Observatories) studied star velocities in spiral galaxies, and in a number of examples made a strong case for the presence of supermassive black holes. Kormendy argues that in a couple of cases, in particular the Andromeda galaxy (M31), a mere 2 million light-years away,[12] "the evidence for central dark objects of 10^6–10^9 $M_\odot$ is very strong. Are they black holes? The alternatives, such as dense clusters of neutron stars and white dwarfs, are astrophysically implausible but not rigorously excluded," he says.

Although such results are of interest in their own right, bolstering the dynamical evidence for black holes and suggesting that black holes might be common at the centers even of inactive galaxies, they don't fingerprint the spectacular smoking guns like M87 that got everyone looking for supermassive black holes in the first place. The main constraint on the quality of observations of black hole candidates is angular resolution. In the absence of adaptive optics techniques (see PHYSICS TODAY, February 1992, page 17), atmospheric turbulence limits ground-based telescopes to resolutions of about 0.5 arcsecond. Over extragalactic distances, this is not quite adequate to reveal conclusive dynamics close to the black hole. The fingerprints are still a little smudged; the ID is not completely certain.

Results using Hubble

Enter the Hubble Space Telescope, riding high above the turbulence of the atmosphere. Tod Lauer (Kitt Peak National Observatory) and collaborators used the Hubble to take observations of the M87 galactic core in 1992. After being deconvolved to correct as much as possible for the spherical aberration of the telescope, these observations indicated that the brightness of starlight I increases near the center of M87 in a manner ($I \propto r^{-1/4}$) predicted[11] by Young in 1978 and consistent with a 2.6-billion-$M_{\odot}$ black hole. Such observations are inconclusive, however, because a black hole is not the only possible explanation.

The Hubble's faulty optics were corrected by NASA's high-flying opticians in December of last year (see PHYSICS TODAY, March, page 42). Just two months later the Hubble was pointed at the center of M87 by the team of Ford, Richard Harms (Applied Research Corporation, Landover, Maryland), Zlatan Tsvetanov, Gerard Kriss and Arthur Davidsen (Johns Hopkins University), George Hartig and Ralph Bohlin (Space Telescope Science Institute), Linda Dressel and Ajay Kochhar (Applied Research Corporation) and Bruce Margon (University of Washington, Seattle).

The group intended to do studies of star velocities near the galaxy's center. Three spectra were taken near the nucleus of M87 as a test of the success of the newly installed corrective optics (COSTAR) working in conjunction with the Faint Object Spectrograph.[3] These spectra, taken using a 0.26-arcsec aperture (giving resolution about twice as good as in the best ground-based studies), verified that the repaired optics were working superbly. Unfortunately a pointing error meant that the spectra were taken 0.35 arcsec and more to one side of the nucleus and so shed no light on the presence of a central black hole.

About two weeks later the team imaged M87's nucleus with the second-generation Wide Field–Planetary Camera in a narrow bandwidth at about 660 nm, which isolates the redshifted Hα and N^+ lines. To their surprise WFPC2 saw a 500-light-year-wide cloud of gas, apparently a large-scale accretion disk around the central object.[1] (See the figure on page 17.)

Several clues bolster the identification of the gas as a rotating disk: A spiral structure is evident, a common feature of the much larger rotating gaseous disks seen in spiral galaxies. The gas cloud appears elliptical, consistent with a circular disk of gas with its normal inclined $42 \pm 5°$ to the line of sight. M87's relativistic jet is approximately aligned with the minor axis of the ellipse, suggesting that it is normal to the disk, as expected from models of such processes. A further consistency check is the inclination of the jet from the line of sight: A 40° inclination has been independently inferred.[2]

The presence of the gas cloud opened up a much better opportunity to look for dynamics characteristic of a black hole. Determining the motion of a cloud of gas is much simpler and cleaner than analyzing star velocity dispersions. In May the team was granted time to redo the spectral observations, this time carefully aligned with three locations: the center of the cloud and 0.25 arcsec to either side along the major axis of the ellipse. (See the figure on page 17.)

M87 as a whole is receding from Earth at about 1300 km/sec, and the data from the central spectra are consistent with this motion. Relative to this overall recession, the two major-axis spectra show Doppler shifts corresponding to velocities of 500 ± 50 km/sec, one away from us, one toward us. (See the figure on page 18.)

These results are entirely consistent with the model of the gas cloud inclined at 42° and rotating at about 750 km/s. In addition, the spectral lines observed at the center are broadened to a full width at half-maximum that corresponds to a velocity differential of about 1700 km/sec, consistent with the notion that the more central gases are rotating even faster.

The researchers conclude that a mass of $(2.4 \pm 0.7) \times 10^9\ M_{\odot}$ lies within about 0.25 arcsec of M87's center. The excessiveness of this quantity of matter can be expressed by the region's mass-to-light ratio M/L, normalized to the solar value. With the exceptions of locations suspected of harboring a supermassive black hole (or the far outer parts of galaxies, which are dominated by a different kind of dark matter) one always observes $M/L < 10$ in old stellar populations. The Hubble results imply $M/L \approx 170$ for the region within 60 light-years of M87's center. The alternatives to a massive black hole, such as an extraordinary concentration of dim stars, stellar remnants or other forms of dark matter, are implausible.

"They've really seen the whole quasar paradigm," says Richstone, who has sought black hole evidence from terrestrial observatories. "You see the jet, you see the disk, and the disk is perpendicular to the jet, wrapped around a very massive object."

Closing the loopholes

There is one caveat on the gas velocity measurements: Gas is easy to push around. It is possible that the velocities measured by the Hubble team are not simple orbital velocities but instead reflect some other process, such as ejection, fortuitously mimicking rotation. If the gas really is moving in Keplerian orbits about a central compact mass then measurements even closer to the center should show higher velocities, following the law $v \propto r^{-1/2}$. Keplerian motion is already somewhat verified by ground-based measurements further from the core, at about 0.6 and 2.0 arcsec, and by the misplaced Hubble spectra at 0.35 and 0.56 arcsec.

Details of the 0.25-arcsec spectra also hint at a Keplerian increase closer in. Emissions from O, O^{2+}, N, N^+ and S^+ were observed by the Hubble researchers. Because it needs more energy to be produced than the other species, O^{2+} is expected to occur preferentially closer to the source of excitation and consequently should show a greater redshift. It does.

The Hubble team plans to use a 0.09-arcsec aperture this fall to take a new set of three measurements: at the center and 0.09 arcsec to each side along the major axis. "If it's a black hole," says Ford, "by being closer in, these measurements will produce an even higher mass-to-light ratio. That will confine the mass to a smaller volume, making it ever more difficult to explain in an alternative way." The precision of the mass estimate of the black hole should also be improved by these measurements. The researchers will also take some spectra along the minor axis of the ellipse. If the rotating-disk model is correct, these regions of the cloud are moving transversely to the line of sight and will show no Doppler shifts relative to the overall recession of the entire galaxy.

Ford says he and his colleagues also plan to study other black hole candidates, starting with the Andromeda galaxy and NGC 4261, a galaxy where a dark disk of gas has been seen aligned perpendicular to large radio emission lobes.

Salpeter hopes that "Hubble will be used for similar observations of a quasar, which is much harder because quasars are further away. Finding convincing observational proof that quasars sit at the centers of ordinary galaxies would be quite spectacular."

—GRAHAM P. COLLINS

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NEW HUBBLE CAMERA FINDS MANY PROTOPLANETARY DISKS IN ORION NEBULA

The Orion nebula, a glowing gas cloud studded with brilliant young stars, was discovered in the sword of Orion by Nicolas Fabri de Peiresc just one year after Galileo first looked at the night sky through a telescope. Ever since then, astronomers have hastened to train every new kind of instrument on this spectacular stellar nursery. So that's what NASA did last December, just after the second-generation Wide Field–Planetary Camera was put aboard the Hubble Space Telescope by visiting astronauts. (See PHYSICS TODAY, March, page 42.) Outfitted with corrective optics designed to compensate for the much-lamented flaw in Hubble's primary mirror, the new camera was promptly pointed at a portion of the Orion nebula that its predecessor had imaged two years earlier.

This before-and-after exercise was meant to see how well the corrective optics were doing. But Rice University astronomers Robert O'Dell and Zheng Wen, who carried out these observations, were not just interested in instrumental issues. Their 1991 exposures, despite the Hubble's impaired condition, had provided tantalizing hints of protoplanetary disks of gas and dust girdling a number of faint young stars in the Orion nebula.[1] O'Dell has coined the name "proplyds" for these presumed precursors of full-blown planetary systems. (He denies that the word, despite its Hellenic appearance, has any classical provenance.) He was, of course, eager to see what more could be seen in the much sharper images the corrective optics promised to provide.

The new images, released in June by NASA, reveal a total of 110 stars brighter than 21st magnitude in the portion of the Orion nebula under examination.[2] Many of these stars had been too blurred to identify in the older images. But the most striking new result is that 56 of these young stars, none of them older than half a million years, are seen to sport circumstellar disks. "We now have adequate statistics," O'Dell told us, "to say that at least half of the very young stars in such nurseries have proplyds. I say 'at least' because it's much easier to detect the stars than the disks."

The section of Wide Field Camera image shown on the next page captures an illustrative assortment of four faint stars in the Orion nebula. All but the second from the left have visible circumstellar disks. The two proplyds on the right glow by the radiated light of their photoionized surfaces, but the dark proplyd on the left is seen only in silhouette against the glow of the Orion nebula's ionized gas cloud. The picture is a superposition of three images taken through narrowband filters that isolate prominent gas emission lines from ionized hydrogen, oxygen and nitrogen, depicted respectively as green, blue and red.

A glowing blister

The Orion nebula is a highly visible blister on the face of a much larger, but mostly dark, molecular-gas cloud, 1500 light-years away from us, that functions as a giant stellar nursery. The gas in the nebular precincts glows primarily because it is photoionized by the ultraviolet output of a single massive star, θ^1C Orionis, one of a quartet of bright stars that appears to the naked eye as the middle star of Orion's sword. θ^1C is 20 times as massive as the Sun, and seven times as hot. A star that hot radiates primarily in the ultraviolet, ionizing all the gas in the neighborhood. Furthermore, its powerful stellar wind contributes to the asymmetric shapes of the proplyds. Presumably the one dark proplyd in the picture is much farther away from θ^1C than are the others, so its gas is not significantly ionized; the blocking of the background glow is attributed primarily to the disk's dust component.

The continuum spectrum of starlight doesn't show up very well through the narrowband filters, whose primary purpose is to image ionized gas. But it's important to see the stars at the centers of these proplyds, to clinch the case that the cir-