New Instrument Decodes Astronomical Signals

Pulses from M87 hint that the energy source for that galaxy may be a massive black hole

Two astronomers working at a small, independent observatory have developed an instrument that has detected for the first time powerful radio pulses emitted by an object outside our galaxy. The source of the pulses is the nucleus of M87, a giant elliptical galaxy in the Virgo cluster of galaxies. Teamed with the largest radio telescope in the world, the instrument revealed the pulses, although they are nearly swamped by the continuous, strong emissions from M87—one of the brightest radio objects in the sky. The pulses support the notion that in the nucleus of M87 there may be a massive black hole—a superdense object with a gravitational field so strong that nothing, not even light, can escape—surrounded by irregular, turbulent clouds of gas.

The pulses were discovered with an instrument capable of analyzing the wave form of astronomical signals. Until this year, astronomers had never looked at the wave form of incoming celestial signals in the detailed way that seismologists monitor earthquakes and neurophysiologists study electrical activity in nerve and muscle fibers. By studying the wave form of a seismic signal, for instance, seismologists learn a great deal about the source event—the earthquake—and the medium the signal travels through—the earth. In May, Ivan Linscott and Joseph Erkes of the Dudley Observatory, an observatory informally associated with Union College in Schenectady, showed that astronomers, too, can learn about astronomical sources—the stars and galaxies—and the interstellar and intergalactic gas, if they pay attention to the wave form of the signal.

Conventionally, radio astronomers monitor only the power of the radiation received at a selected frequency. The procedure is analogous to listening to the carrier frequency of a radio station and measuring the broadcasting power, while completely ignoring the music, the news, and the advertisements. "That analogy has appealed to us," says Linscott. Information about the nature of the source can be gleaned only by examining the wave form of the radiation and by looking at the timing—the phase—of the frequencies comprising the signal; but there was no astronomical instrument available capable of doing that. With $300,000 from the National Science Foundation, the two astronomers designed and built such an instrument during the past 3 years.

The instrument, called the Mark II signal processing system, uses a fast Fourier transform to analyze the radio signal as it is received—in real time. Two extremely fast analog-to-digital converters digitize the signal at a rate of 10 million points per second. Both sets of data (20 million points per second) are fed into a fast Fourier transform processor—one of the fastest in the world—built specially for the task by Noble Powell of General Electric in Syracuse, New York. Out of the processor comes information about the strength and timing of the signal in each of 1024 different frequency channels. The processor analyzes only a short signal segment—a "frame" of 2048 digitized points—at one time. When the Fourier transform of the frame is computed, then the processor analyzes the next segment of signal.

The output of the fast Fourier transform processor is stored in a memory capable of receiving data as fast as the processor generates it—at 20 million words per second. Although the memory is fast, it is not big. It has room for the transforms of only 64 sequential frames—6.4 milliseconds of signal when the digitizer and processor are operating at their peak rate.

When the memory is full, data acquisition must stop so that the memory can be read out for permanent storage on magnetic tape. It takes 10 seconds to store the data on tape, and during those 10 seconds, the incoming signal cannot be analyzed. "The memory is limiting right now," says Linscott. "Actually we have four times as much memory as we expected to—fortuitously, memory came down in price as the rest of the system was being designed and built."

To test and perfect the Mark II, the astronomers used the Dudley Observatory's Fullam telescope, a 100-foot-diameter radio telescope near Lake George, New York, to look at pulsars—objects that emit radio-frequency pulses like clockwork. They also looked for evidence of black holes, which are still hypothetical objects, although many of their properties have been deduced. Whether black holes exist in the universe is currently an active controversy in astronomy. Yet more and more astronomers are suggesting that certain puzzling and energetic celestial objects contain black holes. Among other things, it has been proposed that black holes may be the nuclei of some galaxies, particularly energetic ones such as M87.

It has even been suggested that a black hole may be at the center of our own, not-so-energetic galaxy. Black holes are supposed to devour matter, and it has been proposed that pulses of radio waves might be produced during the digestion process. The Mark II is ideally suited for detecting pulses—events during which radiation is emitted at many frequencies simultaneously. Erkes says, however, that the observations of the center of our galaxy "were indeterminate, certainly nothing publishable."

But there was a hint that something exciting might be going on near the nucleus of M87, an extremely energetic galaxy more than 70 million light-years away. To tell for sure, the astronomers needed a bigger telescope with greater "light-gathering" ability. In May, they and the Mark II journeyed to the 1000-foot-diameter radio telescope in Arecibo, Puerto Rico. To identify faint pulses in the signal. Erkes and Linscott had developed a sophisticated data analysis method they call the phase compensation dedispersion technique.

The sophisticated technique was not needed: with the larger telescope the pulses from M87 "could be detected visually from the record," says Linscott. Any signal traveling through a medium becomes dispersed—higher frequencies travel faster than lower frequencies. If all frequencies are emitted simultaneously, as in a pulse, then the first components to arrive will be high-frequency ones. The frequency of the dispersed, incoming pulse will decrease with time.

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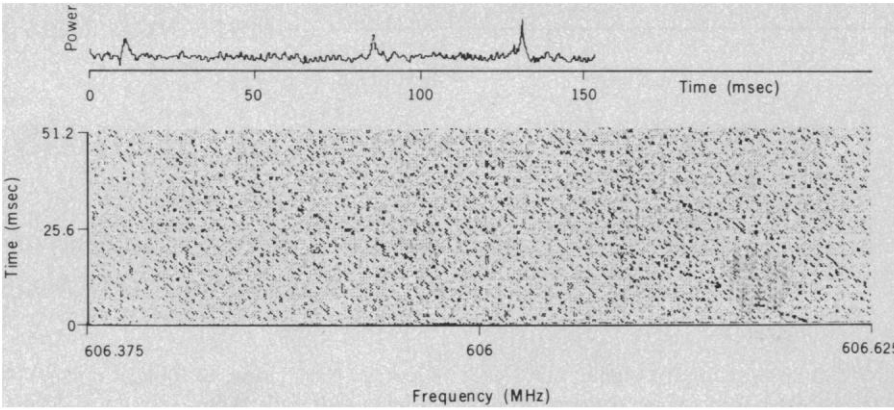

In the lower display, which is a frequency spectrum as a function of time, three pulses, probably a triple pulse from one source in the nucleus of M87, show up as diagonal lines. The Arecibo system was tuned to 606 megahertz, and Mark II was set to look at frequencies within a 1.25-megahertz bandwidth. Higher frequency components of each pulse arrive before lower frequency components. The upper trace is a summation of the signal power along a direction parallel to the slope of the pulses. It is a crude synthesis of how the pulses might have looked as they were emitted. [*Source: Dudley Observatory*]

In the data from M87, Linscott and Erkes saw distinct signals whose frequency decreased with time. To look at a record longer than the 6.4-millisecond sample collected when Mark II runs at full speed, they sampled at a slower rate—only 1.25 million points per second. Thus the memory could handle about 51 milliseconds of data every 10 seconds. Since only about 5 percent of the records included a pulse, Erkes and Linscott concluded that pulses are emitted from M87 roughly once per second.

The pulses are strong: they can be detected clearly over the background radio emissions of the galaxy. The astronomers estimate that each pulse contains about 10,000 times as much energy as the sun radiates in a second, and a billion times as much energy as the pulse in a typical pulsar. Recently, Wallace Sargent and Peter Young of the California Institute of Technology looked at the motions of stars near the center of M87 and calculated that its nucleus is on the order of 1 billion times as massive as the sun or a typical pulsar. Since both the mass of the black hole and the energy of the pulses are, respectively, about a billion times greater than the mass and pulsed energy of a pulsar, Linscott concludes that "the emission mechanism scales with mass."

A black hole of 1 billion solar masses would be a few light-hours in diameter. Yet, says Linscott, the pulses from M87 are at most 1 millisecond long; thus the source volume must be small enough for light to cross it within 1 millisecond—less than 300 kilometers across. Consequently, says Linscott, "the entire black hole is not responsible for the pulses—only a part of or a small feature on the black hole is doing the pulsing."

The dispersion of the pulses from M87 is 100 to 500 times (on the average 250 times) greater than the dispersion of pulses from pulsars, which are thought to be in our galaxy. How much a signal is dispersed depends on how many electrons lie along the path traveled by the signal. Therefore, the dispersion gives clues to the density of particles in the interstellar and intergalactic gas.

Since the signal from M87 is highly dispersed, there must be many particles along the travel path. The question, according to Linscott, is "Where do you put them?" The large variation in the dispersion of the pulses suggests that much of the gas probably is in clouds very near the black hole. The remainder, which causes the "nonlocal" dispersion, must be elsewhere along the travel path: in our galaxy, between our galaxy and the Virgo cluster, or within the Virgo cluster.

From other measurements, astronomers have a good idea how much gas is in our galaxy. That amount, says Linscott, should account for about 3 percent of the nonlocal dispersion. X-ray observations of the Virgo cluster with the Einstein Observatory (results from the observatory were described in *Science*, 29 June, p. 1399; 6 July, p. 31) indicate that there is enough gas within the cluster to account for about half of the nonlocal dispersion.

"If only 10 percent of the nonlocal dispersion is due to gas between our galaxy and the Virgo cluster, and if that density of gas is typical of space between clusters of galaxies, then we may have enough mass to close the universe," says Linscott. Cosmologists would consider the universe closed if it is shown to contain so much mass that the gravitational attraction between objects in the universe is sufficiently strong to slow and eventually reverse the universe's expansion. The amount of mass necessary for closure is thought to be about ten times the amount estimated to be included in all galaxies. When their analysis of the dispersion of the pulses is complete, Linscott and Erkes expect to have a firmer idea how the intervening gas is distributed.

"It is a bit of a mystery," says Linscott, that the pulses from M87 are not all dispersed the same amount. Thus the gas clouds around the nucleus of M87 are probably not uniform. Linscott imagines that the black hole is rotating and is "ringed with unstable regions of gas which are themselves spinning." Each little whirlpool would be similar to a miniature pulsar—a spinning source with a lighthouse-like beacon. The light from each beacon would shine through local gas clouds on its way toward Earth; if each whirlpool is in a different environment, then the emissions from each would be dispersed slightly differently. Since some of the pulses appear to be dispersed the same amount as others, Linscott and Erkes favor this explanation over a "popcorn" model. In the popcorn model, each source—a small region of gas above the surface of the black hole—fires one pulse and then is seen no more. Further analysis of the M87 data may yield insights into the temperature and magnetic field strength in the source region.

Mark II has promise as a spectrometer, although its forte is capturing and recognizing pulses of radiation. According to Linscott, the device should be able to identify pulses, even when they are much weaker than the background radiation. "Mark II is the best detector for chirped radar [radar whose frequency decreases with time] in the world." Since military radar is possibly the brightest man-made emission from our planet today, it is probable that a culture that has developed a similar level of technology would be emitting strong radar signals. In that case, another application of the Mark II would be in the search for intelligent life elsewhere in the galaxy.

Erkes and Linscott have shown that it is possible to detect and decipher messages carried in radio-frequency astronomical signals by studying their wave forms. Judging from the initial success of the Mark II, this new field of astronomy may have a bright future.

—Beverly Karplus Hartline