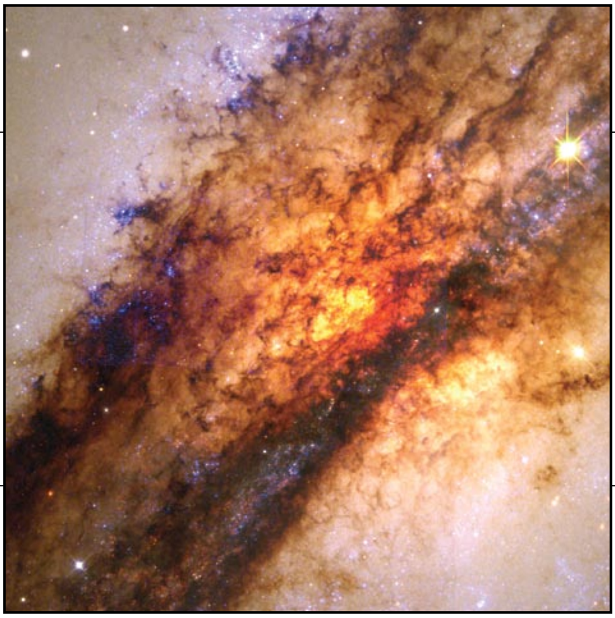
National Aeronautics and Space Administration



Outflows from Active Galactic Nuclei

Nahum Arav

Taken from: Hubble 2006 Science Year in Review

The full contents of this book include more Hubble science articles, an overview of the telescope, and more. The complete volume and its component sections are available for download online at:

www.hubblesite.org/hubble_discoveries/science_year_in_review

Outflows from Active Galactic Nuclei

Nahum Arav

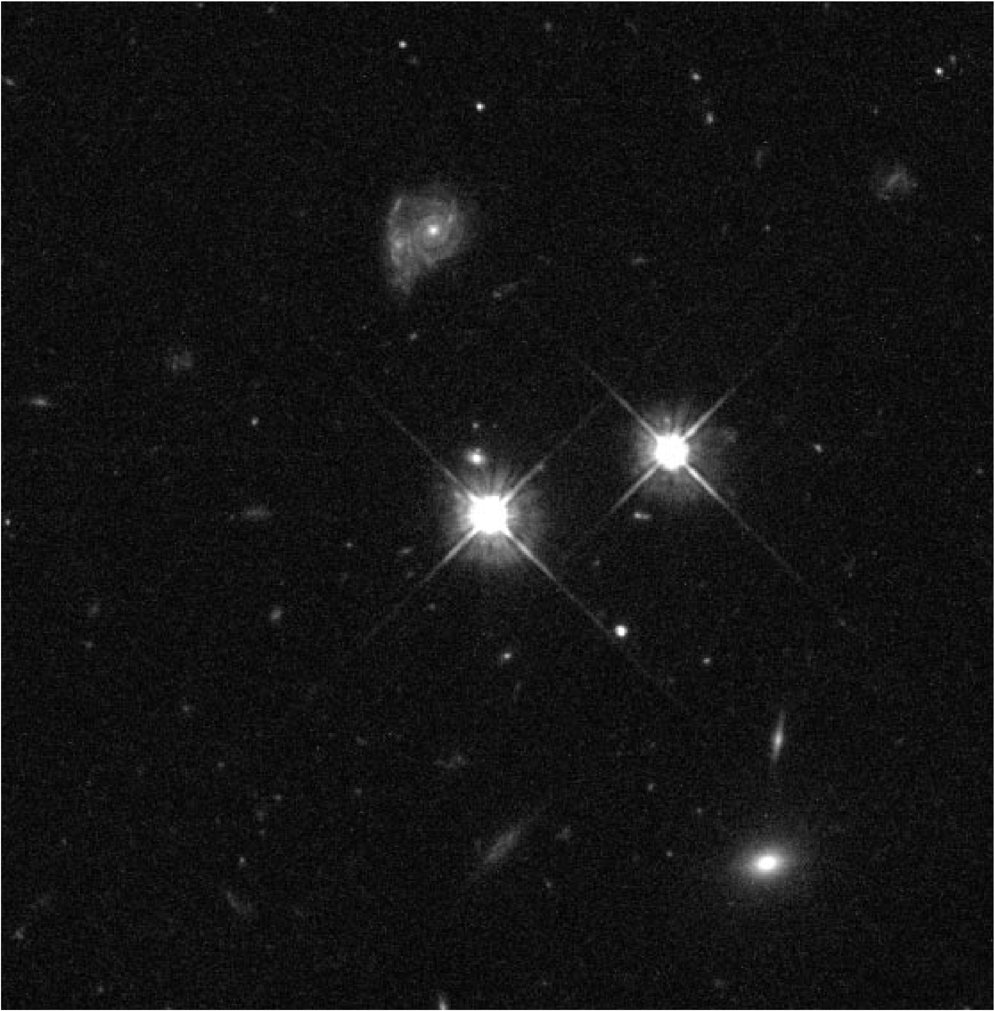
Deep in the heart of nearly every large galaxy lurks a giant black hole weighing as much as a million to a billion suns. (A black hole is a collapsed astronomical body, so dense that no light can escape from it.) In a small fraction of galaxies, interactions of gas with the black hole somehow trigger violent outflows, ejecting material from the galaxy at very high speed. The origin of outflows, and their lasting effects on galaxies, are among the most hotly debated topics in astronomy today.

The study of these outflows dates back to 1967, when Roger Lynds, an astronomer at the National Optical Astronomy Observatory, uncovered unusual spectral features in the light of “quasi-stellar objects” or QSOs. There was intense scrutiny on QSOs following Maarten Schmidt’s discovery, four years earlier, that these were the most distant objects known in the universe. (See Perlman’s article on galactic jets.) Lynds discovered that in some QSOs, a large portion of their light was absorbed and scattered by intervening gas, leading to broad absorption “troughs” in the spectrum. Spectra like this had never been seen before in any astronomical object. We now know that these troughs are signatures of prodigious outflows of material driven by the same unseen engines that produce the brilliant light of QSOs—supermassive black holes. Furthermore, we know QSOs are extreme members of the family of “active galactic nuclei,” or AGN, and that most galaxies harbor supermassive black holes at their centers.

Lynds’s troughs are due to absorption by neutral and ionized atoms along the line of sight to the AGN. Today, astronomers continue to use absorption-line spectroscopy of AGN—the perfect background light sources, with no spectral absorption features of their own—to study these outflows.

The galaxy known as Centaurus A was one of the first galaxies identified whose core strongly emits radiation from radio to x-ray wavelengths. Complex mechanisms operate near the massive black holes at the centers of such galaxies, producing enormous jets and outflows of material. Here, the center of the galaxy—actually thought to be two merging galaxies—is obscured by dark lanes of dust and gas.

This picture of a typical quasi-stellar object, or "QSO," was *Hubble*'s 100,000th observation, taken on June 22, 1996. Of the two bright, star-like objects, the one on the left is the QSO, and the one on the right is a star in our own galaxy. From the cosmological redshift in its spectrum, we know that the QSO is about a million times farther away than the star (and also much farther away than the pretty spiral galaxy at the top). Because the apparent brightness of a source varies inversely as the square of its distance, and because the star and QSO appear about equally bright, we can infer that the intrinsic brightness of the QSO is a trillion times greater than the star. (The four bright spikes on each object are due to the optics of the telescope.)



We picture a supermassive black hole as a voracious feeder on the stars and gas from its surrounding galaxy. This material falls toward the black hole and fills an accretion disk. While we cannot detect a black hole directly, we *can* see the accretion disk, which converts a portion of the gravitational energy released from in-falling material into heat and light. This electromagnetic radiation emerges as the bright light of AGN—or in the most luminous cases, QSOs, which far outshine their host galaxies.

We also observe AGN ejecting material by two powerful processes: jets and outflows. We observe jets *directly*, as linear features consisting of *fully* ionized gas moving at nearly the speed of light. We observe outflows *indirectly*, as absorption features in the spectra of AGN. Outflows consist of partially ionized gas moving outward at lower speeds than jets, but still up to one-third the speed of light. ("Partially ionized" means *some* bound electrons, which are required to produce spectral lines.)

The total amount of energy released in feeding the black hole is much larger than the gravitational binding energy of the galaxy. Jets and outflows carry this energy to the far reaches of a galaxy. While most of the *light* from the AGN escapes without interacting strongly with the galaxy, the jets and outflows—because of their material nature—do interact strongly, particularly with the interstellar gas. If only a small fraction of the released energy is imparted to the gas, it would be driven out, altering the course of the galaxy's physical and chemical development. (See the accompanying article on "red-and-dead" galaxies by Davis and Faber.)

Observations from *Hubble* and other observatories have revealed that most large galaxies today harbor supermassive black holes in the center, but only a small percentage of these are accreting large enough amounts of material to appear as active nuclei. Observations of the distant universe reveal that the nuclei of galaxies were more active in the past. (See the accompanying article by Barger on AGN populations.) These observations are consistent, because the jets and outflows produced by AGN are *feedback* processes—meaning that they can slow down the supply of material feeding the black hole, thereby lowering the level of nuclear "activity" and shutting down the jets and outflows. We seek a better physical understanding of AGN jets (see accompanying article by Perlman) and outflows (as in this article) in order to learn how they may have contributed to the development of early galaxies into the nearby galaxies we see today.

Because images of QSOs reveal only point-like sources, we turn to their spectra—brightness according to wavelength—in order to study their characteristics. Laboratory measurements allow us to identify the position and relative strength of the spectral features caused by different atoms and ions. Using these laboratory results, we can interpret the troughs in AGN spectra and translate them into estimates of the physical parameters of the outflow, including the speed, temperature, density, distance from the AGN, rate of mass outflow, and kinetic energy.

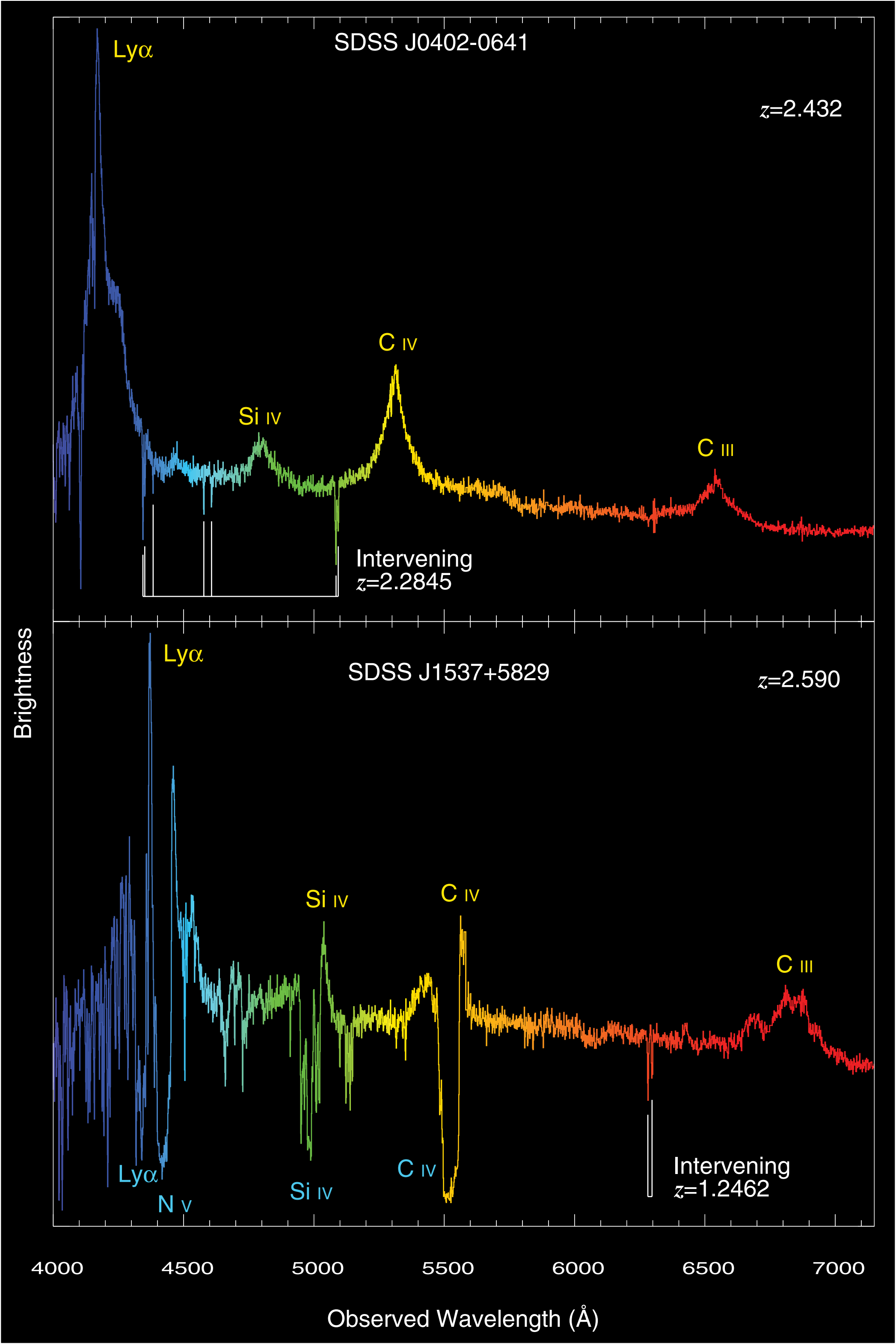
Lyα = Lyman alpha line of hydrogen

Si IV = triply ionized silicon
(three electrons removed)

C IV = triply ionized carbon
(three electrons removed)

C III = doubly ionized carbon
(two electrons removed)

N V = quadruply ionized nitrogen
(four electrons removed)



Guide to a QSO spectrum

The spectrum of a QSO divides the light into different colors to measure the brightness versus wavelength and identify diagnostic features. The top panel shows a typical QSO spectrum with no evidence of outflows. The brightness rises slowly towards the blue. Superimposed are emission lines of hydrogen atoms, triply ionized silicon, and doubly and triply ionized carbon (labeled in yellow), which originate on the accretion disk immediately around the supermassive black hole. The great distance of the QSO is evident in the large redshift, $z = 2.432$, which tells us that the light from this QSO started its journey towards us 11 billion years ago, or about 7 billion years before the Sun and Earth were formed. In the laboratory, the C IV line is located at 1549 Å, but because of the redshift of this QSO, we observe it at $(1 + z)$ 1549 = 5316 Å. At some point along its path towards us, the QSO's light encountered intervening clouds of gas, which produced a few absorption features at a somewhat lower redshift, $z = 2.2845$. These clouds are hundreds of millions of light-years away from the QSO and not physically related to it.

The bottom panel shows a QSO spectrum containing evidence for a massive outflow: absorption troughs due to Lyα, N V, S IV, and C IV (labeled in blue), located on the blue side of corresponding emission features. The magnitude of the blue shift indicates the absorbing material is moving towards us at speeds up to 6000 km per second relative to the QSO accretion disk. These troughs are caused by outflows of material in or near the QSO that happen to be on the line of sight to the active nucleus—the supermassive black hole and its luminous accretion disk—at the center of the unseen host galaxy. By studying the troughs in QSO spectra, we can determine physical parameters of the outflows, including temperature, distance from the QSO, rate of mass outflow, and kinetic energy.

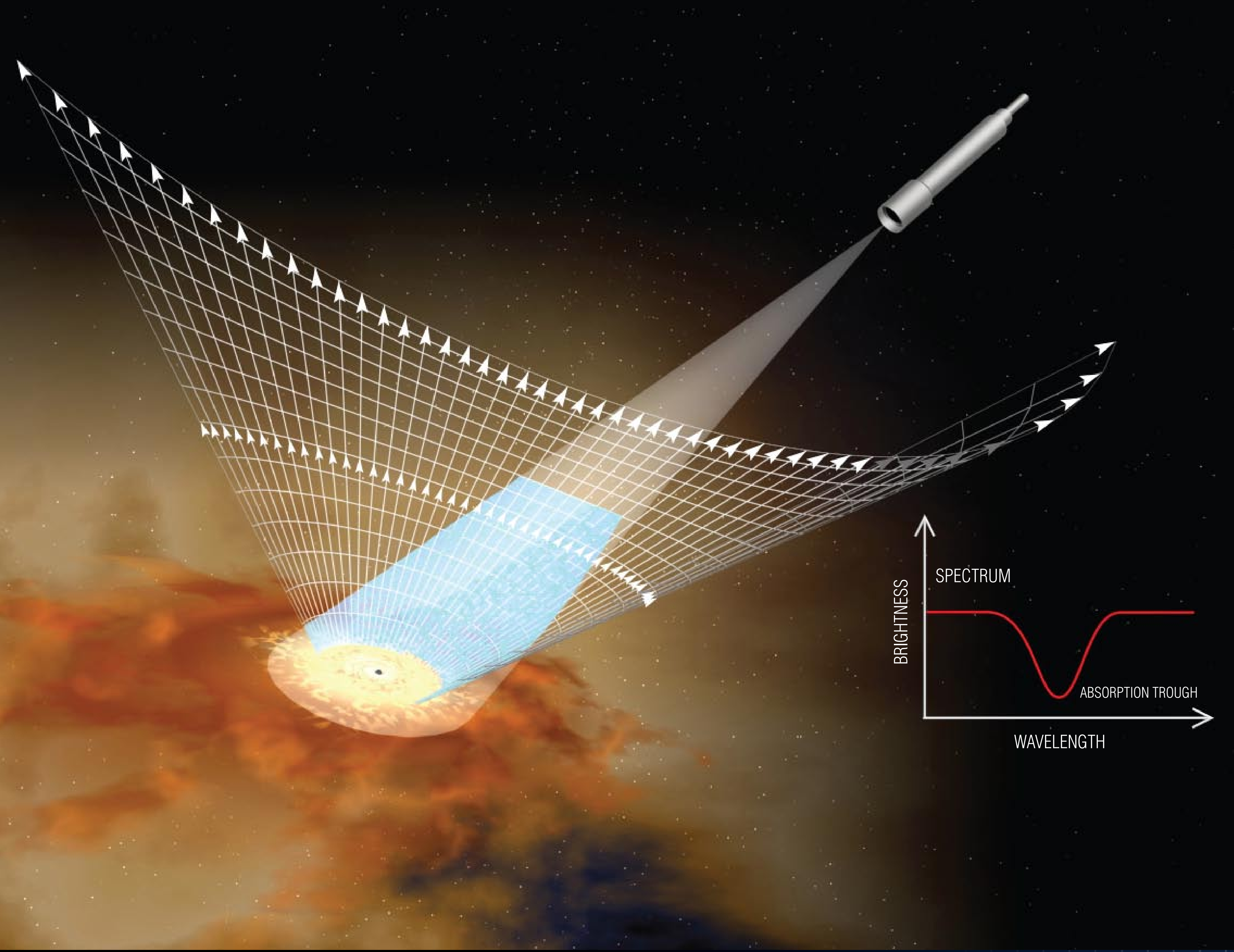
The early spectroscopic interpretations by Lynds established the significance of AGN outflows. Because the wavelengths of the absorption troughs are *close* to those of the AGN emission, he could deduce that the absorbing material is associated with the AGN. Because the trough wavelengths are also somewhat *shorter* (bluer) than those of the emission lines, he knew that the material is moving *toward* us. Furthermore, the *amount* of blue shift measures the outflow velocity and the *width* of the trough indicates the spread of line-of-sight speeds, which can be tens of thousands of kilometers per second. This is much larger than the speed needed to escape the gravity of the host galaxies!

Many of the most useful absorption lines of outflows are in the ultraviolet spectral range. Before *Hubble*, most spectra of outflows were obtained by observing AGN with substantial redshifts. Such observations took advantage of the cosmological redshift to move the ultraviolet features into the visible range convenient for ground-based observatories. The advent of *Hubble* instigated a revolution in the study of galactic outflows, because it could observe closer and brighter AGN in the native ultraviolet range of the spectral troughs.

While it was operating (between 1997 and 2004), the Space Telescope Imaging Spectrograph (STIS) on *Hubble* was the premier instrument for observing AGN outflows. Its great spectral resolving power produced highly detailed profiles of the absorption troughs, which allowed astronomers to separate geometrical effects from the thickness of the outflow, and thereby to better estimate the amount of gas involved in the flow. It could obtain high-quality spectra from 1100 Å to 3200 Å in the ultraviolet, which allowed astronomers not only to target closer AGN, but also to observe many spectral lines that previously could not be detected. Because closer AGN appear brighter, astronomers could obtain spectra of the same objects with the new generation of x-ray observatories, including *Chandra*. If the Cosmic Origins Spectrograph is installed, or if the STIS is repaired on a future servicing mission to *Hubble*, this line of research can resume.

The *Hubble* observations have addressed a list of fundamental questions about outflows, summarized as follows:

What are the speeds? We find a big spread, from a few hundred to over a hundred *thousand* kilometers per second. The higher speeds may pertain to material closer to the black hole, while outflows at greater distance may be slowed down by an increasing burden of matter as they plow through the host galaxy.



Best current explanation for creating the troughs observed in the spectra of active galactic nuclei. Material (reddish clouds) falls toward the supermassive black hole (black dot). As it approaches the black hole, this matter forms a bright accretion disk (yellow). The pressure of light ejects some material from the disk (white arrows are typical trajectories). Outflowing atoms and ions located at the blue portions of the trajectories are in the line of sight from the telescope to the disk. Light that is absorbed by the blue material, at wavelengths characteristic of the elements and the speed of the outflow, causes the absorption trough seen in the spectrum. Thus, interplay between geometry and moving material produces the trough seen in the inset graph. (Figure by Daniel Zukowski.)

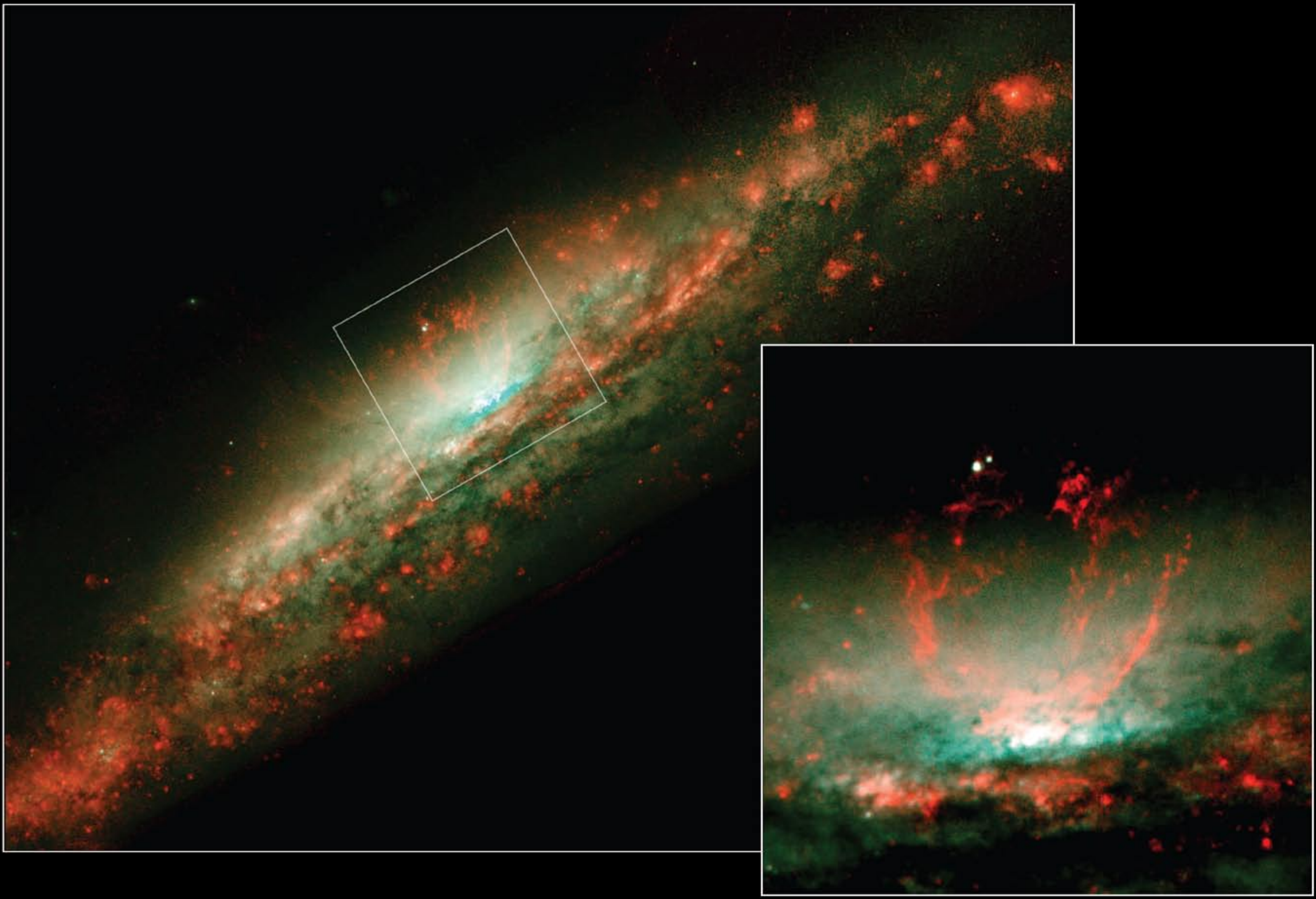
What is the material in the outflows? We find ordinary elements in various states of ionization. The relative amount of heavy elements is somewhat larger than that of the Sun. This result indicates vigorous star formation in the vicinity of the AGN, and offers a special opportunity to study chemically enriched environments when the universe was less than 10% of its current age.

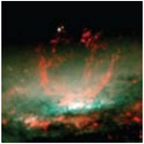
How far are the outflows from the black hole? We observe some outflows only a light-day away from the black hole—roughly five times the distance of Pluto from the Sun. We see others at tens of thousands of light-years away—the typical size of a host galaxy. These results are consistent with our picture that the high speed and momentum of AGN outflows carry them with continuity from the accretion disk to the far reaches of the galaxy. The travel time would be a hundred thousand to a million years.

What accelerates the outflows? Here, we are less certain, but the favored answer is the pressure of light. The great luminosity of the AGN pushes steadily on the gas and gradually accelerates it to high speed.

Do outflows really affect the growth of the black hole and the host galaxy? Theoretically, yes. In simulations, outflows can regulate the growth of both the black hole and the host galaxy. We are, however, still some distance from demonstrating that real AGN outflows carry enough energy and mass to play these roles. This is our main challenge in the coming decade.

Nahum Arav is a Research Professor at the Center for Astrophysics and Space Science at the University of Colorado, Boulder. He has been researching AGN outflows for more than a decade. His work includes observations with the *Hubble Space Telescope*, the *Chandra X-ray Observatory*, the *Far Ultraviolet Spectroscopic Explorer* satellite, and ground-based telescopes, as well as theoretical studies. When not researching AGN outflows, Nahum can be found in the Colorado mountains—hiking and backpacking (in the summer), or skiing (in the winter).





These *Hubble* snapshots reveal dramatic activities within the core of the galaxy NGC 3079, where a lumpy bubble of hot gas is rising from a cauldron of glowing matter.