New Light on Quasars: Unraveling the Mystery of BL Lacertae

For nearly as long as quasars have been a puzzle, some equally curious objects named—or actually misnamed—BL Lacertae have been on the agenda of unsolved astrophysical problems. Quasars were discovered first, and until recently they have captured more of the limelight. But the situation is changing as a result of new observations, and the objects known as BL Lacs, for short, are moving to center stage. "Perhaps they would have attracted more attention if they had had a dramatic name like blazars," quipped Columbia's Ed Spiegel during a recent after-dinner speech on the subject. What is becoming clear is that both BL Lacs and quasars are astronomical powerhouses of uncertain origin, at once superluminous and extremely compact.

The first BL Lac object was originally studied in 1929, and at the time it was thought to be a variable star. As is the astronomer's custom for variable stars, it was named according to the constellation in which it is located, Lacerta (meaning "the lizard"), and designated by a two-letter code indicating that it was the 90th variable star discovered in that constellation. Not until 1969, when it was found that the presumed star was also a radio source, did the stellar classification come into question. The radio emission was a strong clue that BL Lacertae was not a star in our galaxy since most objects that have its type of radio spectrum either are in other galaxies or are quasars. More objects like BL Lacertae were quickly found, and by 1972 astronomers realized that the erstwhile variable star was one member of a class of objects which were almost certainly extragalactic. They looked starlike in an optical telescope, were extremely variable in brightness, and were also powerful and compact radio sources. But until quite recently the peculiar BL Lac objects could not be placed at any particular location in the universe because they seemed to have no trace of the spectral features by which cosmological (large astronomical) distances are measured.

The question of distance was an acute one. If BL Lacs were as remote as quasars, then the problem of explaining how they produce enormous power in a small volume might be even more severe than it is for the most violent quasars. (Several lines of evidence indicate that the energy equivalent of 10 billion suns must be produced inside a region the size of the earth's solar system.) In fact, when one of the brightest BL Lac objects flared up in 1975, it was for several months the most luminous object known in the universe. But that is getting ahead of the story.

The primary reason that BL Lacs were set aside as a separate class of objects 6 years ago was that their spectra were nearly devoid of sharp features. Like quasars, BL Lacs appeared pointlike on photographic maps of the sky, but, unlike quasars, they had no sharp lines in their optical spectra attributable to either emission or absorption of light from ionized gases. Without emission or absorption features, no red shifts could be determined for BL Lacs and the basic cosmological distance scale was not applicable. (The red shift is a measure of the Doppler effect on the spectral lines of various atoms and ions, shifting the lines from the ultraviolet into the red portion of the spectrum. The magnitude of the shift is proportional to the distance of objects receding from our galaxy, as was first shown by Hubble.)

The Case of the Missing Red Shift

Without any features by which to measure a red shift, the troublesome conclusions about the power of BL Lacs were open to question. If the objects were closer than assumed, then the energy needed to produce the apparent brightness would be markedly reduced. The power production problem would thus abate. Certain eminent astrophysicists, however, added objection to uncertainty. These skeptics, championed by Geoffrey Burbridge, a British theoretical astrophysicist who was recently named head of Kitt Peak National Observatory, questioned whether red shifts would be a valid measure of distance for objects as unusual as quasars and BL Lacs, since the red shift–distance relation was derived from normal, quiescent galaxies. There was no evidence that either quasars or BL Lacs were embedded in the middle of normal galaxies, although many astronomers believed that they were.

The developments of the past year and a half have erased these uncertainties, and caused astronomers to rethink the role of BL Lacs altogether. BL Lacs have been found to have faint but observable spectral lines and they have been shown to lie in galaxies. Even Burbridge now accepts the conclusion that BL Lacs are at cosmological distances. Thus energy production in BL Lacs must now be seen as a problem at least as challenging as that of energy production in quasars. Furthermore, there are physical reasons to think that the characteristics that minimize (but, it is now clear, do not entirely eliminate) the spectral lines in BL Lacs may make it easier to unravel the nature of the energy source.

As more BL Lacs are found with weak spectral lines, the differences between BL Lacs and quasars are diminishing. At a recent conference called to survey the progress made in the past year,* the discussion indicated a consensus that there is no significant difference between BL Lacs and violent quasars. The feeling was strong enough that Martin Rees, the head of the Institute of Astronomy at Cambridge, England, and perhaps the most noted astrophysicist actively modeling such processes, suggested that it was time to invent a new classification scheme. Ken Kellerman, a prominent observationalist who has been looking at the energy source of such objects with the high magnification available from very long baseline radio telescopes, went a step further to say that the name BL Lac should "never be used again." While the astronomers could not agree on new definitions, it seemed that BL Lacs might constitute an extreme form of quasar.

The properties of BL Lacs are certainly more variable than those of many quasars. Over the course of a few months, the optical energy output of BL Lacertae itself—which is by far the most thoroughly studied object in the class—will vary from the equivalent of one very luminous giant galaxy to the equivalent of ten such galaxies. The light from BL Lacs in general is also more polarized than the light from quasars, and that polarization may change quite rapidly—often varying significantly in the course of a day. The radio characteristics of BL Lacs tend to be similar to those of quasars, however. Both tend to emit radiation that has the spectral characteristics of a nonthermal source (meaning that the powerhouse inside must be generating

*The BL Lac Objects Conference was held at the University of Pittsburgh, 24 to 26 April, and was arranged by A. M. Wolfe. Transcripts of all discussions will be printed in the conference proceedings.

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radio power by a rather exotic mechanism), and the source of the radio emissions tends to be extremely compact in both cases. This comparison does not, of course, apply to the large subset of quasars which do not emit radio waves.

Optical observations, as well as radio observations, can be used to put a limit on the size of the central powerhouse. The time scale for luminosity and polarization variations is a measure of size because the travel time of light is an indicator of distance. An object that changes its light output in a day cannot be much larger than the solar system, which requires half a day for light to cross.

Class distinctions based on spectral lines began crumbling in 1974 and collapsed last year. Using an image tube scanner capable of recording extremely faint optical spectra, two astronomers at Lick Observatory, near Santa Cruz, California, showed that BL Lacertae itself had very weak spectral features that could be identified with both emission and absorption lines. The work was published in March 1977. Working with the Lick 3-meter telescope, Joseph Miller and Steven Hawley obtained a spectrum of BL Lacertae from which they could determine a red shift. The lines were extremely faint but they were there. The possibility of a line feature in the BL Lacertae spectrum had been raised by J. B. Oke and James Gunn 3 years earlier. A report of weak emission lines has also been published for one other BL Lac object, designated 1400 +142, and at least four others are now known. Speakers at the conference in Pittsburgh concluded, and the general consensus of participants did not dispute, that most BL Lac objects have weak emission and absorption features.

If the measurements of BL Lacertae had stopped with the determination of the red shift of the strong central source, the debate over the powerhouse of BL Lacs would have been stuck on the same arguing point as the debate over quasars—namely whether the red shifts were indicative of distance or not. But Miller and Hawley, along with Howard French at Lick Observatory, proceeded to examine the fuzz around the center of BL Lacertae and proved to the satisfaction of the astrophysical community that the bright nucleus is the center of an elliptical galaxy which appears normal in every respect.

Suppressing the intense light from the center of BL Lacertae sufficiently well to see the comparatively faint galaxy around it was no mean feat. An annular aperture, made by evaporating aluminum over a ring placed on a glass microscope slide, was used to block out the light from the center of BL Lacertae. Miller and his colleagues again used the Lick image tube scanner and observed the object on two successive nights when the distortion from the atmosphere was minimal. To further reduce atmospheric effects, they only observed BL Lacertae when it was almost directly overhead. They found that the galaxy around the nucleus of BL Lacertae has a normal stellar spectrum and—most importantly—has the same red shift as the bright nucleus, namely 0.07.

Finding the Galaxy Around BL Lacertae

The observation not only showed that the exceedingly bright source identified as BL Lacertae had somehow evolved in the center of an apparently normal galaxy, it also effectively quashed the argument that BL Lacertae might be less powerful than it appeared.

Geoffrey Burbridge, for one, accepts the cosmological interpretation of the BL Lacertae red shift, although he is still skeptical about quasars. ("No one has ever shown that quasars are in the centers of galaxies," he told the astronomers gathered at Pittsburgh. "The evidence isn't there.")

With the possibility of anomalous red shifts cleared away, the inquiry into the nature of BL Lacs is proceeding to the physical description of the central source. Some 30 or 40 BL Lacs have been identified so far, and they have generally been less remote and less luminous than quasars, but this may be an observational bias rather than a reflection of the true distribution. Nevertheless, BL Lacs as a class are more variable than quasars, and at their peak luminosity may outshine them. The nucleus of BL Lacertae itself fluctuates between one-fourth and ten times the strength of the surrounding galaxy. When a BL Lac object designated as AO 0235 +164 flared up in 1975, it increased in brightness more than 100-fold in a few months. Because it has several sets of spectral lines with different red shifts, its distance and power are uncertain. But at its peak, it may have been emitting 10^{48} ergs per second, more than 10^4 times the luminosity of our galaxy and equal to the brightest known quasar, according to Arthur Wolfe at Pittsburgh.

BL Lac objects more distant than those known today could be even brighter, but two considerations affect their detection. The emission lines are so faint that it would be extremely difficult to determine red shifts for any BL Lac objects that were as far away as distant quasars. Furthermore, instrumental limitations make it difficult or impossible to see surrounding galaxies associated with the more distant BL Lacs known now.

The size of the central source producing all this energy can be delimited but has not yet been determined. Radio measurements made with a very long baseline between telescopes, on the order of 3000 miles, show that the source is smaller than a few milliseconds of arc in angular extent. This indicates that the powerhouse is less than 30 or 40 light-years across. The rapidity of the energy variations indicate a central core that is only a few light-months across. The polarization fluctuations indicate a size more on the order of light-days. Among the quasars, only the subset known as optically violent variables and typified by objects such as 3C 446, 3C 279, and 3C 345 approach the rapidity of BL Lac variations. These exhibit light variations occurring in a few months and polarization changes on the time scale of weeks. In either case, the problem is to explain how these objects produce more than 100 times the energy of a giant elliptical galaxy in a region less than one-millionth the diameter.

The Knottiest Problem

Astronomers attending the conference on BL Lacs at Pittsburgh did not burst forth with new insight into this problem, which is one of the knottiest in astronomy. (Black holes, supermassive stars, and dense concentrations of normal stars are the three explanations that have been proffered.) But they did agree that it might be easier to learn the nature of the power source from BL Lacs than from quasars. Emission features are the key, again.

The faintness of BL Lac emission lines is generally interpreted to mean that there is relatively little gas associated with the energy source, while the prominence of emission features in quasar spectra indicates that there is a great deal of gas present (or that the central source is proportionately weaker.) This distinction can be made because the radio data indicate that the radiation from the ultimate source is nonthermal, probably produced by the process called synchrotron emission. The emission lines, however, are thermal in character.

In many respects, BL Lacs look like quasars in which the synchrotron light has been boosted to such a level that it swamps the emission features. Whether one thinks of a BL Lac as a quasar with very little gas or as a quasar with an anomalously large synchrotron component, the effect is that the synchrotron radiation is easier to study. For this reason, Geoffrey Burbridge, Martin Rees, and others refer to BL Lacs as the best available chance to see the "bare machine."

Building on a model they proposed several years ago, Rees and Roger Blandford, from Caltech, quickly developed an explanation for the relative strengths of the continuum and line radiation by postulating that BL Lacs and quasars are identical objects oriented in different ways to the line of sight from the earth. Their explanation is that the continuum radiation produced by the central object propagates out into space in a fairly tight beam, while the emission line radiation from the gas surrounding the central object propagates in all directions. If the beam is directed toward our galaxy, the continuum radiation dominates and the object is called a BL Lac. If the beam is directed away, we see mostly line emissions and call the object a quasar. This idea is new and was embraced with steadfast neutrality by the Pittsburgh attendees. Problems could arise with the model if there proved to be nearly as many BL Lacs as quasars, however. An analysis of the population question by B. Setti, of the University of Bologna, indicated that, even though observational biases make it difficult to determine the statistical prevalence of BL Lacs, the two types of objects may be equally abundant. Setti concluded, with certain limitations, that there appeared to be 100 quasars per cubic megaparsec of the universe and more than 30 BL Lacs.

Other models were also discussed, including the suggestion by Stirling Colgate that the core of a BL Lac consists of a high-density region of stars that energize the surrounding medium by frequent supernova explosions. A new finding about the polarization features of BL Lacs, however, would put severe constraints on this and every other model. J. E. Ledden, of the Virginia Polytechnic Institute, reported that during the great outburst of AO 0235 +164 the plane of radio polarization had slowly rotated through 130° in the course of several months. This argues strongly that a single, coherent source of radiation was at work, not a disconnected group of stars. The synchrotron process will produce the required coherence if all the synchrotron radiation comes from a single object. (The question of optical coherence is still open, but it is nevertheless mind-boggling to think that for some months AO may have been a 10^{41} watt laser!)

No doubt more models for BL Lacs will be proposed, more observations of their special properties will be made, and radio and optical astronomers working together will try to advance the data base for these objects to the level of completeness that characterizes quasars. At the same time, the present categorizations may change. Martin Rees suggested at Pittsburgh the "need, rather than carrying around all this classical baggage, for a more sensible and logical classification scheme for active galaxies."

The story of BL Lacs is not only the story of a small group of astronomical oddities that have found their way into the mainstream of astrophysical inquiry. It is also an outstanding example of the progression of thought that appears to be occurring throughout astronomy, as many different high-powered objects that have been discovered by different observational techniques—radio, optical, and infrared—are being seen more and more as manifestations of the same phenomenon, powered on different scales by the same machine.—WILLIAM D. METZ

Particle Physics: New Evidence from Germany for Fifth Quark

A long-shot experiment has paid off for two groups of German physicists at the Deutsches Elektronen Synchrotron (DESY) laboratory in Hamburg. On the same day last month, researchers working independently with two different particle detectors on DESY's electron-positron colliding beam accelerator found new evidence for the existence of a fifth quark to go with the four now supposed by physicists to exist. Quarks are believed to be the entities making up the bulk of the "elementary" particles, such as the proton, the neutron, and the pi meson.

The new evidence comes from the DORIS electron-positron storage ring where another kind of meson called the upsilon particle was found. The finding confirms and adds to the results of an altogether different type of experiment with the proton synchrotron at the Fermi National Accelerator Laboratory (Fermilab), where the first evidence for the upsilon was reported last year. Physicists believe that the upsilon can best be interpreted as consisting of the fifth quark and its antiquark bound together by the strong nuclear force, somewhat as the proton and the electron in the hydrogen atom are bound by the electromagnetic force. Because of certain new information not obtainable from the Fermilab experiment, researchers will accept the DESY results as a stronger (but not certain) piece of evidence in favor of the fifth quark, to be called, according to one's taste, either the bottom or the beauty quark.

Quarks come imbued with a variety of properties, such as mass, charge, and spin angular momentum, but they are usually labeled by abstract quantities called, for no apparent reason, flavors. Originally there were three flavors: up, down, and strange. With the discovery of the J/psi meson in 1974, evidence began to accumulate for a fourth flavor now known as charm. Peter Waloschek, a member of one of the groups and now in charge of public relations at DESY, says that after charm must come beauty, but U.S. physicists have tended to stick with bottom as the name for the fifth flavor.

As exciting as the particle discovery itself are the machinations of the DESY accelerator engineers to squeeze the highest possible energy out of DORIS, thus making it, for now, the world's highest energy electron-positron colliding beam storage ring. In the ring, electrons and positrons circulate in opposite directions. At certain designated points along the way, they collide and annihilate each other. The energy released in the annihilation is used to create the particles that are detected. The heaviest particle that can be created has a mass equivalent to the sum of the energies of the circulating electrons and positrons. DORIS started out in 1974 with a maximum energy of 3.5 GeV in each beam, thus the heaviest particle observable would have a mass equivalent to about 7 GeV. Various improvements in succeeding years raised the beam energy to nearly 4 GeV, quite a bit less than needed to observe the upsilon, whose mass was established at about 9.4 GeV by Leon Lederman of Columbia University and his collaborators at Fermilab last summer.

To reach the energy of the upsilon particle, the DESY accelerator engineers had to resort to numerous tricks and are, according to Waloschek, the real heroes of the experiment because, he says, any physicist with a particle detector would