entation with respect to the laser beam. Further, this feature provides a handle to determine the precise frequency of rotation of such a crystal. This measurement could be crucial in the utilization of the transitions in these ions as possible frequency (time) standards, because their containment in the trap keeps them free of any environmental interactions, and the effects of rotation can be corrected if they are precisely controllable.

A new state of infinite solid matter is apparent in these experiments; the matter is certainly "visible" because of the fluorescence of the ions in laser light, and yet its density is that of what would normally be considered a respectable vacuum. The question of what may be done with this form of matter remains to be seen. The applications to time standards are promising, but perhaps there are other, more far-fetched applications on the horizon. Could ions in such a solid be linked by resonant photon exchange between them? This possibility may introduce additional classes of phenomena. Or could one engineer such materials with perhaps different species of ions imbedded as impurities, or perhaps eventually in a regular array, allowing new properties to be developed? At the moment, these possibilities are still speculative but, the field is moving rapidly.

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ASTROPHYSICS

What the Wild Things Are

James H. Buckley

In 1962, Schmidt discovered that the bright quasi-stellar radio source known as 3C-273 was not a star at all. From its redshift, he found that it was as far away as the most distant galaxies (*1*). Its intrinsic luminosity was enormous, with an energy output higher than any other body in the known universe. Now, 3C-273 and other such quasi-stellar objects (quasars) are thought to be members of a broader class of extragalactic objects, the active galactic nuclei (AGNs), in which a compact nucleus may outshine the rest of the galaxy by a factor of as much as 1000. Recent Hubble Space Telescope observations reveal that material swirls around these galactic nuclei with huge orbital velocities. From the data on AGN M84, for example, one obtains an estimate of a mass of as much as 300 million suns concentrated in a region less than 20 light years across. This incredible concentration of mass suggests that these active galaxies harbor supermassive black holes at their centers, the gravitational potential of which provides the enormous power output.

On page 684 of this issue, Mannheim (*2*) discusses how high-energy gamma ray data on the active galaxy Markarian (Mrk) 501 might provide an important means of understanding the energetic processes at play in these enigmatic objects. In keeping with the energy of AGNs, the debate surrounding their mechanisms is vigorous, and I shall consider Mannheim's conclusions from a somewhat different perspective.

The most extreme members of the family of AGNs, the BL Lac objects and optically violent variable quasars (collectively known as the blazars), show dramatic variability in their emission on incredibly short time scales ranging from days down to less than 1 hour. These observations imply a very compact emission region limited by causality to have an extent less than the product of the speed of light and the variability time scale. Shortly after the discovery of the extragalactic nature of quasars, Rees (*3*) pointed out that an outflow with a relativistic velocity could decrease (Doppler shift) the apparent variability time scales: Blazars appear to correspond to AGNs in which the relativistic jet happens to be pointed nearly in our direction, and we are being provided with a view of the energetic processes in a very small region, probably near the base of the jet close to the central engine.

The broadband spectra of blazars (stretching over eight orders of magnitude in wavelength, from the radio to x-ray wavebands) is nothing like the ordinary thermal black-body radiation emitted by more mundane astrophysical objects such as our own sun. This nonthermal emission is well described by synchrotron radiation emitted by a population of energetic electrons, an effect caused by the bending of electron trajectories in the relatively strong magnetic fields in the jet.

Gamma ray emissions from blazars are another story, however. Emission has been seen at energies greater than 100 MeV from some 50 AGNs, including 3C-273 (*4*). The energy of these photons lies well above the point at which the relatively well understood synchrotron spectrum appears to cut off, signifying a new component of the spectral energy distribution in these objects. It came as a surprise that over the entire electromagnetic spectrum, the power output for many of these objects is peaked in the high-energy gamma ray waveband. Perhaps still more surprising was the discovery that the high-energy emission of some of these objects (Mrk 421 and Mrk 501) extended up to 10^{12} eV (*5*, *6*).

For Mrk 421 and Mrk 501 (and other similar objects referred to as the x-ray selected BL Lacs), the emission from the radio up to the high-energy x-ray waveband is almost certainly synchrotron emission produced as electrons gyrate in the relatively strong magnetic fields in an AGN jet. However, the origin of the gamma ray emission is still poorly understood. Models in which electrons or protons dominate the gamma ray emission have been proposed, but as pointed out by Mannheim (*2*), they lead to different predictions of magnetic field strength and Doppler factor. Because these are potentially observable quantities, we have a possible means of discriminating between these models. In a constant magnetic field, particles of a given momentum are deflected by a perpendicular force, which produces an angular acceleration, and this in turn results in electromagnetic radiation. Furthermore, particles of high momentum gyrate in circular orbits of larger radii. From these basic deductions, a number of important conclusions can be reached that have a direct bearing on the question of proton versus electron models.

The decay in the synchrotron emission caused by the declining population of energetic electrons is referred to as "synchrotron cooling." In a magnetic field, a proton,

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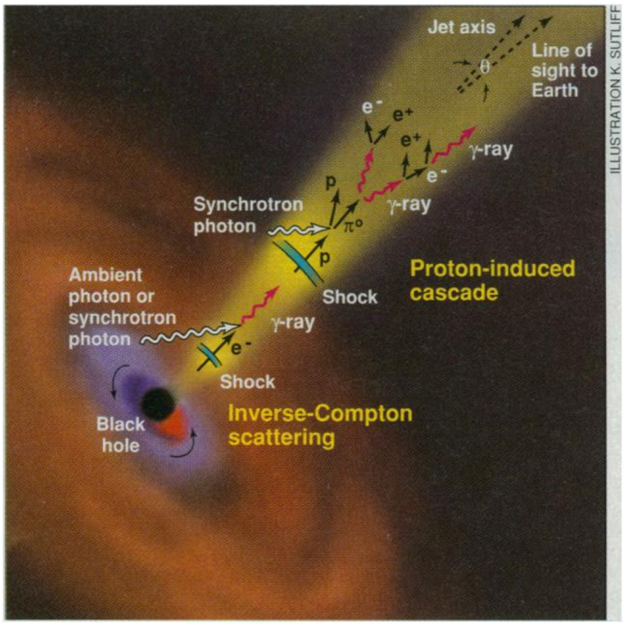
whose mass is about 2000 times that of an electron, has a smaller angular acceleration at a given momentum and thus loses energy by synchrotron radiation much less efficiently than an electron. Even though energy loss by the synchrotron mechanism is low, protons must reach very high energies before any other loss mechanism dominates. If the proton energies exceed about 10^{16} eV, they can interact with the copious lower energy synchrotron photons to produce neutral pions (unstable particles that do not comprise ordinary matter but can be produced by high-energy interactions). These neutral pions can decay into a cascade of photons and energetic electron-positron pairs (see figure). This cascade emission could eventually give rise to secondary photons, which form the observed gamma ray emission. Because the rate of proton-gamma (pion-production) interactions is orders of magnitude below electron-gamma (inverse Compton) interactions, the gamma ray flux produced by a diminishing population of protons is expected to fall off less rapidly than that produced by electrons.

The observations of short variability time scales [variations in flux by a factor of 2 are seen on time scales of 15 min for Mrk 421 (*7*)] present a bigger problem for protons than for electrons, because of the less efficient energy loss of the protons as well as the tighter constraint on the size of the emission region of the highest energy protons. To satisfy these constraints and to achieve a good fit to the observed spectra of Mrk 421 and Mrk 501, the magnetic fields must be greater than about 30 G. Such a field strength is very high compared with other estimates derived, for example, from a comparison of variability time scales in the optical to x-ray regime with the synchrotron cooling time. Therefore, the proton models are also pushed to the limit by the data.

As the magnetic field strength increases, the gyration frequency of the electrons increases, and the characteristic frequency of radiation emitted by these electrons is roughly proportional to the magnetic field strength times the square of the electron energy. The observed cutoff in the synchrotron spectrum thus contains information about both the magnetic field strength and the maximum electron energy, but there is an ambiguity between large field strengths and relatively small electron energies and small magnetic field strengths, which together with larger maximum electron energies might give the same cutoff. The gamma ray measurements provide the key to break this degeneracy.



Cosmic cascade. Artist's conception of the nucleus of an active galaxy. Two possible scenarios for the production of the high-energy gamma rays in a relativistic jet are indicated.

Now consider the alternative, where protons do not play a major role in producing the observed gamma ray emission. The energetic electrons will interact with low-energy ambient photons, which will scatter up to an energy that can approach (but not exceed) the electron energy (this process is related to the inverse process, the well-known Compton effect, whereby gamma rays lose energy when they interact with the loosely bound, essentially free electrons in target atoms). It is natural to attribute the gamma ray emission to this inverse-Compton process (see figure). In this case, the maximum observed gamma ray energy puts a lower limit on the electron energy and, in combination with the synchrotron observations, breaks the degeneracy and provides an upper limit on the magnetic field strength, typically requiring magnetic fields that are a fraction of a gauss for canonical values of the jet velocity.

But there is a major caveat: The relativistic motion of the jet implies that measured energies will appear higher than they do in the rest frame of the jet. As stated by Mannheim (*2*), the velocities measured for other AGNs imply a maximum Doppler factor of about 10. Thus, one would have to abandon the unified picture in which blazars are considered to be standard AGNs viewed directly down the jet. However, these estimates of the jet velocity are taken from the radio data and are only appropriate for regions relatively far out in the jet compared with the presumed site of the gamma ray production. Thus, it is possible that the jet is significantly decelerated by the time it extends out to the region where these measurements are made.

One strength of the inverse-Compton model is that it offers a simple explanation for why only AGNs with a relatively high energy cutoff in their synchrotron emission (in the x-ray rather than the optical) show high-energy gamma ray emission, and why flares in the x-ray band of the synchrotron emission are closely correlated with flares in the gamma ray emission (*8*, *9*). However, Mannheim's criticism (*2*) is still valid: The low magnetic field values and the high inferred electron energies (or alternatively, the high Doppler factors) are problematic for the simplest inverse-Compton models, especially in a unified picture where all AGNs harboring jets have jets of similar velocities.

Although high-energy inverse-Compton emission must be present at some level, does it dominate, or is another component present? Mannheim (*2*) argues that shock acceleration, thought to accelerate electrons should readily accelerate protons to still higher energies (if the magnetic field strength is high enough and if the acceleration region is larger than the gyration radii of these particles). This model would also offer a possible origin for the highest energy cosmic-ray nuclei (>10^{18} eV) detected at Earth. But many a beautiful theory has been undermined by a single experimental fact. The strong dichotomy in the predicted jet parameters (especially the magnetic field) offers a potential means of eventually eliminating one or the other model when other data are taken into account. It is not clear which way the ax will fall, but the gamma ray measurements will be crucial.

Although the origin of the high-energy radiation is still not resolved, with further measurements, including in the teraelectron volt waveband, it seems likely that the constraints on the inverse-Compton or proton models will eventually cause one (or both) of these models to break. When this happens, we will learn something new about the physical conditions in these jets that will hopefully lead to a fundamental understanding of the energetics of AGNs.

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