Citius, Altius, Fortius: Astrophysical Sources Above 10[1]

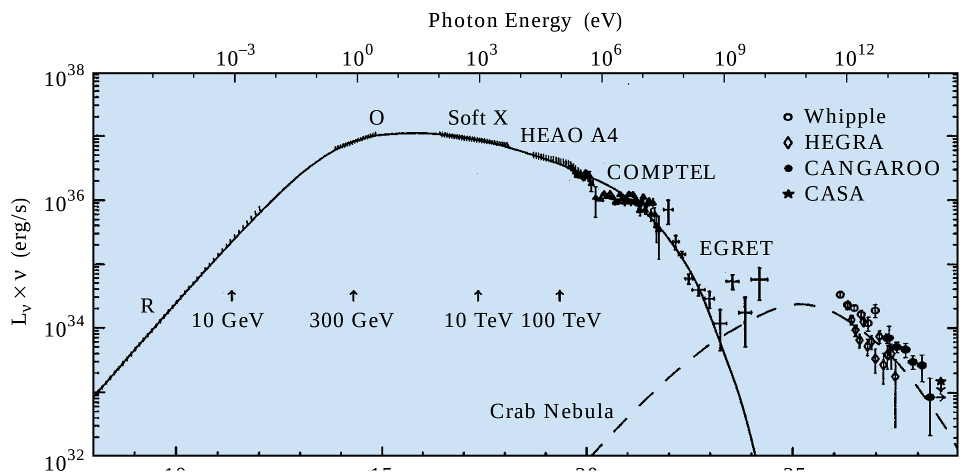
THIS WAS THE YEAR when you finally had to take your other hand out of your pocket to count the TeV sources whose detection most of us would bet a few pennies on. (If you find an astronomer who can afford to bet more than a few pennies on this sort of thing, he probably has his hand in somebody else's pocket.). The shoes should be able to stay on for at least a few more years, until the Mega-machines described elsewhere in this issue have piled up a few mountains of data.

There are, in fact, fewer sources around now than there were a decade or so ago. Up to 1991, TeV and even PeV emission had been reported for the X-ray binaries Cygnus X-3, Hercules X-1, Vela X-2, LMC X-1, 4U 0115+53, 4U 1822-37, and Scorpius X-1 and the pulsars 0532 (in the Crab Nebula) and 1509-58 (in the supernova remnant MSH 15-52). In case you wondered, "4U" means something in the Fourth Uhuru (X-ray) Catalog, and MSH is the radio astronomers Mills, Slee, Hill (rapid repetition of which counts as a sobriety test). These X-ray binaries are a fine mix of ones with high and low mass companions and with neutron star and (probably) black hole primaries. Most of the reports included evidence for variability at a rotation or orbit period (desired because positional accuracy was very poor). Truly spectacular was Cyg X-3, whose high energy emission seemed to act more like hadrons than photons, leading to the invention of cygnets.

by Virginia Trimble

eV Per Something

Most of these sources have not been seen convincingly for a decade or more, despite (or perhaps because of) the commissioning of more sensitive detectors with sharper angular resolution. Cyg X-3 and Her X-1, especially, must have a very small ratio of “on time” to “off time.” Zero is not excluded. The critical period was 1989–1991, when the Whipple Cerenkov telescope in Arizona and the Cygnus air shower array in New Mexico started scanning the TeV and PeV skies respectively, and setting a lot of upper limits.



Observed and modeled spectrum of the Crab Nebula from radio to TeV energies. Numbers under the arrows are the energies of electrons that must be present to radiate those frequencies in the known magnetic field of the nebula (Courtesy Felix Aharonian)

SUPERNOVA REMNANTS

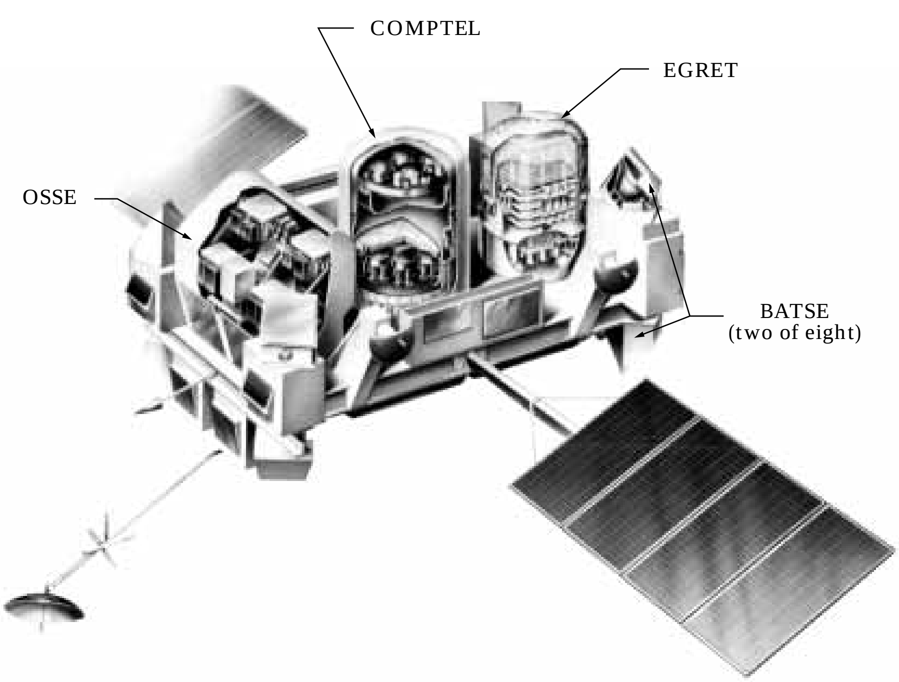
Whipple did, however, see the Crab Nebula. Not the pulsar, which phases out in the MeV to GeV range probed by the Compton Gamma Ray Observatory (as do the other six known gamma-ray pulsars), but steady emission from some part of the nebula. This emission is probably even understood as inverse Compton scattering of synchrotron photons at lower energies by the relativistic electrons that have to be there anyhow to radiate the synchrotron (this is a little like having your hand in your own pocket and pretending not to notice). The source is, therefore, indirectly the pulsar, which is responsible for accelerating said electrons, but more directly a pulsar-driven wind and nebula, as modeled back in 1984 by Charles Kennel and Ferd Coroniti.*

The basic equations are all in a 1965 paper by Bob Gould, but not much was known about pulsars in those days. Though Richard Haymes’ balloon group had already seen the Crab pulsar as a gamma ray source, they didn’t know it yet.

The same is true for the second pulsar-related source, found by the CANGAROO collaboration in the vicinity of PSR B1706-44. The pulsar is about 1.8 kpc away, about 17,500 years old, and near the center of the supernova remnant G343.1-2.3. ("G" means the position is given in galactic coordinates, and cognoscenti can figure out that either position means only southern observers can study the thing.) The radio period is 0.102 sec, but the high energy gamma rays are largely unpulsed, and no optical counterpart has been identified so far. Unpulsed emission from the vicinity of the Vela pulsar may be a third, similar case.

Shell-type supernova remnants, with no evidence for central pulsars or neutron stars, are frequently also synchrotron sources, opening up the possibility for inverse Compton gamma rays from them as well. The brightest supernova of historic times, SN 1006, left such a remnant, whose gamma rays, up to 100 TeV, have recently turned up in the CANGAROO data, along with upper limits for a number of other supernova remnants and pulsars. It is another southern source, and the supernova barely peeked above the horizon in China and Switzerland where it was discovered.

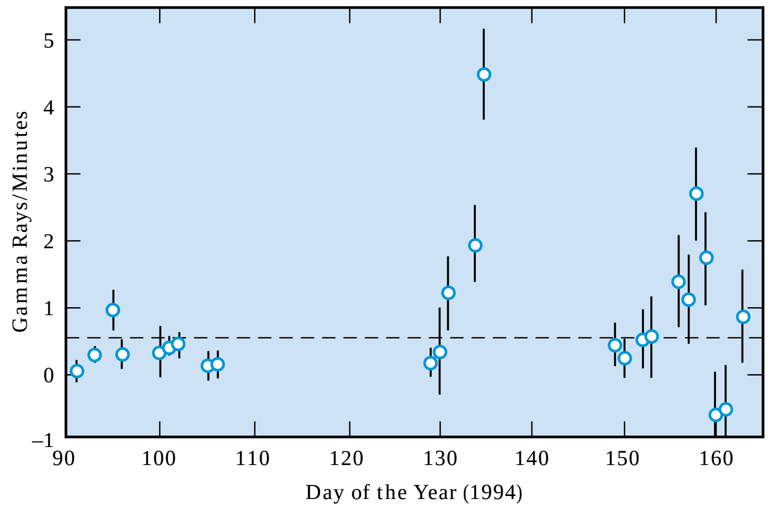
The Compton Gamma Ray Observatory, an enormously productive mission, still yielding valuable information about stellar, galactic, and other sources of radiation at energies lower than the ones addressed in this set of articles.



BLAZARS

Blazars are a subset of active galaxies, along with radio galaxies and quasars, quasi-stellar objects (not radio sources), several types of Seyfert galaxies, and so forth. The term is a sort of portmanteau, incorporating both the idea of blazing and the name of the prototype object, BL Lacertae (meaning that it was once thought to be a variable star in our own galaxy). Blazars are the ones with not much stray gas around to get in the way of narrow, beamed cones of relativistic stuff, that are somehow collimated by a magnetized accretion disk around a supermassive black hole, and aimed by chance more-or-less straight at us. Signatures include weakness or absence of emission lines, rapid variability in flux and in polarization of visible light, X-ray emission, and compact radio emission with a flat spectrum and a core-jet structure that changes fast enough to be called "superluminal motion" (meaning that if you forget to include special relativity correctly in your calculation, you will end up thinking that the source violates the $v \leq c$ speed limit).

The 1994 flare of blazar Mrk 421 as seen by the Whipple Observatory. An X-ray high state occurred twenty-seven hours later. (Courtesy Whipple Observatory)



The first eighteen months of discoveries from the Compton Gamma Ray Observatory included probable EGRET detections of about fourteen blazars at $E \geq 100$ MeV, and the number has increased to fifty or more (though a few are probably chance coincidences). Most are variable, and some are quite distant. Theorists immediately beefed up their beams to make gamma rays as well as X rays. This tended to mean that both the largest energies of individual particles in the beam and its bulk velocity had to get bigger.

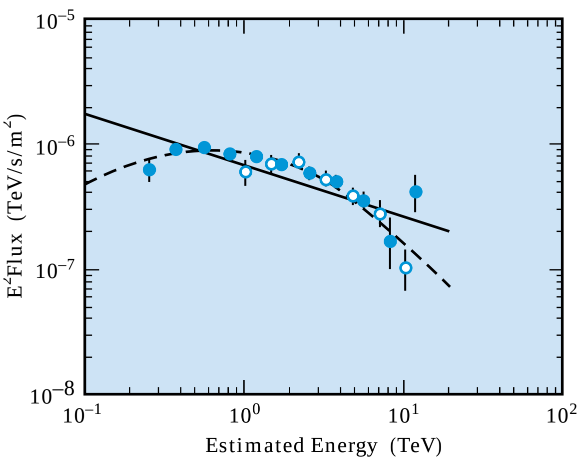
What is the beam made of? One school of theorists favors electrons that Compton up-scatter X-rays and other lower-energy photons, as in the gamma-ray supernova remnants. The alternative is a mostly hadronic beam, with the gamma rays coming from secondary pion production. In fact, relativistic tomatoes will work about as well as anything else, if you can figure out how to accelerate them (a point noted many years ago by Franco Pacini). If the bulk motion has $\gamma = (1 - v^2/c^2)^{-1/2} = 10$ or more (needed anyhow for the superluminal motions and so forth) then the maximum energy of photons coming out depends primarily on the energies of the individual particles in the beam.

The theorists were still hard at work shocking the beams and each other to reach beyond 100 MeV when Markarian (Mrk) 421 was recorded as a TeV source at the Whipple Observatory in 1991. Confirmation by the HEGRA installation in the Canary Islands followed in due course. Mrk 421, at $z = 0.0308$, is the closest of all the superluminal sources. As a result, not only is $1/r^2$ in our favor, but the probability of photons being wiped out by gamma-gamma interactions and pair production en route to us is much reduced. The TeV gamma rays flared spectacularly a couple of years after their discovery, but the source is detectable the rest of the time at a flux level about one--quarter that of the Crab Nebula. Apparent correlations of TeV and X-ray flares slightly favor the Compton up-scattering models.

Next came Mrk 501, just a little further away and just a little fainter, again seen first at the Whipple Observatory and then at HEGRA (just before the summer 1997 fire there knocked it out).

At this point, one knew one needed theorists for two things: since there are closer, non-blazar active galactic nuclei (AGN) not detected, somebody has to work on the details of the beam; and since there are slightly more distant, but brighter, blazars also not detected, somebody has to work on the details of how far TeV gamma rays can travel though the photon sea of intergalactic space.

This second point wouldn't be very interesting except that the cross section for pair production is largest when $E(\gamma_1) \times E(\gamma_2) \approx 2\,(m_e c^2)^2$. In other words, photons with wavelengths of 20–50 μm are the most damaging, and we know practically nothing about the intergalactic background in that band.



The slightly sagging TeV spectrum of Mkn 501. The upper power law is what should be radiated by inverse Compton scattering (given the electron and photon energies one knows from the optical emission). The lower one is what we see, and the sources should disappear completely both at slightly higher energies and at slightly larger distances. (Courtesy Whipple Gamma Ray Collaboration)

Approaching the problem from the other, observational, side, we can say that both Mrk 421 and Mrk 501 have spectra that are beginning to droop below a power law at 10 TeV, which could be a signature of incipient pair production (or, of course, of a droopy beam). Helpfully, the third Whipplet which rejoices in the name 1ES 2344+514 and was published in summer 1998, has a slightly larger redshift of 0.044 and a spectrum that may not continue above about 1 TeV. It has been seen only when flaring.

When upcoming projects push Cerenkov techniques to slightly lower energies, we ought to be able to map out the mid-infrared background using the sagging sub-TeV spectra of additional blazars, and perhaps even verify that the background is the same in different directions. Yuri Neshpov and his Crimean colleagues have also reported TeV emission from the radio source 3C 66A. It is not an EGRET source, but then neither are Mrk 501 and 1ES 2344+514, while Mrk 421 is, so there are real differences in intrinsic spectra as well as in propagation effects.

GAMMA-RAY BURSTERS

The optical identification of several of these with entities at redshifts $\gtrsim 1$ means that photons of TeV and higher energies will have a very difficult time getting to us, though they might well be produced at otherwise detectable fluxes. The same applies to very high-energy protons that might otherwise contribute to the cosmic ray background. But neutrinos of 10^{14} eV and more should be co-produced and are unlikely to be scattered or degraded along the way.

COSMIC RAYS

We come at last to a territory where the papers do not outnumber the detections. A 10^{12} eV or even a 10^{15} eV cosmic ray is hardly worth mentioning, they are so common. At some point, though, we should stop calling them "galactic cosmic rays," on the grounds that they can leak both in and out of the galactic micro-Gauss magnetic field, and so need not have been accelerated here or have a higher energy density inside galaxies than outside.

TeV and PeV cosmic rays don't even present any particular theoretical problem, in the sense that they are seen to be a mix of protons and heavier nuclei (the mix varying somewhat with energy) and that they can be accelerated in shocks and magnetic fields around supernovae, neutron stars, AGNs and so forth. They come to us isotropically and cannot be associated with any particular sources. Individual supernovae may, however, contribute a large fraction of the flux at particular times. The evidence for this is apparent changes in the average local GCR density as measured from cosmic-ray tracks in meteorites.

The first three cosmic ray events above 10^{20} eV (one each from the Yakutsk, Fly's Eye, and AGASA experiments) were consistent with an isotropic distribution, and none seemed to be coming from the direction of any interesting source, like a nearby Seyfert or radio galaxy.

With increasing numbers, more elaborate statistical analysis has become possible. This has naturally resulted in some authorities concluding that the arrival directions are paired or clustered or associated with the supergalactic plane, and others concluding that the arrival directions are random. Larger numbers of events will inevitably resolve the issue (though students of gamma ray bursters were still having a very similar argument when the number approached 2000).

The difficulties start as soon as you ask what the primary particles are. If this is phrased as, "Are they mostly protons or heavier nuclei?" then even the answer "yes" would be helpful.* The troubles with either of these candidates are that (a) they are not very easy to accelerate to 10^{20} eV (and tomatoes are no easier), and (b) they cannot travel more than about 100 Megaparsecs through the intergalactic photon bath. The main enemy is the cosmic microwave background, because that is where most of the photons are. At least we know how many with some precision, so the calculation is a straightforward one. A distance of 100 Mpc corresponds to a redshift of only 0.017 to 0.033, and barely carries us to the nearest blazar (which is not, anyhow, in any of the arrival directions).

**Readers may recall other questions where something similar applies, for instance "Is it a boy or a girl?" when asked about an infant member of the Addams family, and "Is the Universe open or closed?" as a test of whether the standard, hot big bang covers all the likely alternatives.*

One theoretical camp nevertheless remains reasonably comfortable with a scenario in which protons are pushed to 10^{20} eV in the relativistic jets of radio sources, meaning the ones associated with massive black holes in galactic centers, but perhaps also the ones associated with stellar-mass black holes in the two known "mini-quasars" or superluminal sources in the Milky Way (though again neither of these is in a useful direction).

The other camp has put forward more exotic scenarios, in which, for instance, topological defects like monopoles and cosmic strings, left from phase transitions in the very early, hot universe, decay to some sort of supermassive X-particles, which then decay to ordinary baryons at very high energies. Because the decays are not strongly confined to galaxies, their products can come to us from any direction, and need not have traveled very far. The processes must not, of course, be allowed to mess up anything else we see, like the products of big bang nucleosynthesis or the diffuse gamma-ray background. This probably rules out superconducting strings as the initial defect. On the other hand, you can use the same X-particle to account for the baryon excess of the Universe. A slight variant invokes decaying dark matter particles that are specifically confined to the extended halo of the Milky Way and which therefore yield high energy particles that seem roughly isotropic and have hardly any distance to travel.

CONCLUSION

The highest energies you can think of, for photons, neutrinos, and other particles, are one of the windows to the Universe that is still fairly opaque. Opening it will undoubtedly reveal some unfamiliar scenery. The same can be said for the lowest radio frequencies (less than a few MHz), the vacuum ultraviolet (where there has never been an all-sky survey), and the band around 10 GeV, where photons are too few to be caught in space and too feeble to be seen from the ground.

HONEY, I SHRUNK THE SUN

Even before I had seen the summer 1998 issue of *Beam Line*, readers were emailing to point out that the correct ratio of the mass of the Sun to that of Earth is about 300,000, not 300. This is unquestionably true! I had simply copied Newton's and Encke's and modern numbers from a table in a standard history of solar physics, where the author did not emphasize that he was tabulating "milli-somethings." My apologies to Newton, anyone who strained his back trying to lift the sun as a result of the misinformation, and all others concerned.