"It's hard to waste 10^8 dollars."
—Philip Morrison (1975)

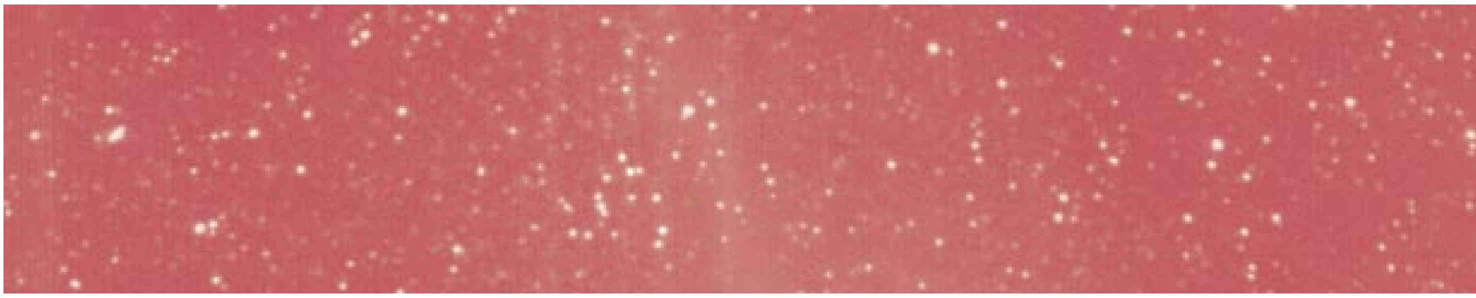
On Beyond X

by VIRGINIA TRIMBLE

Astrophysics in the Gamma Ray, Neutrino, and Gravitational Radiation Regimes

"But, unfortunately, no longer impossible."
—Virginia Trimble (1995)

X-RAY ASTRONOMY began in a blaze of glory with extra-solar-system sources brighter than anyone could rationally have expected. I except, of course, the pioneers, working with Bruno Rossi and Herbert Friedman, who built the first rockets—such people are necessarily irrational or nothing new would ever get done.



In contrast, the field of gamma ray astronomy saw generations of rationally-motivated detectors come and go before the photons outnumbered the people writing about them. The sagas of neutrino and gravitational radiation astronomy are even stranger.

I have tried elsewhere to draw some profound conclusion from these very different histories, and failed. Readers are therefore cordially invited to propose answers to the question "And the moral of that is?" provided they keep in mind that most of the founders of all four fields are likely to be out there surfing the net.

GAMMA RAY ASTRONOMY

Gamma rays were part of the astrophysical inventory from 1920 to 1929, because cosmic rays were erroneously so identified. Correlations with the earth's magnetic field cast early doubts, but the critical measurement was one of cosmic ray penetrating power. The paper, by Bothe and Kohlhorster, is still exciting reading, even (or perhaps especially) if you don't know German. The first sentence mentions "Gammastralung" and the last "Korpuskularstrahlen," and in between are three centimeters of plumbium. Limits on real cosmic gamma rays dropped to 1% of the particle flux in the post-war era of flights of V2 rockets and clones.

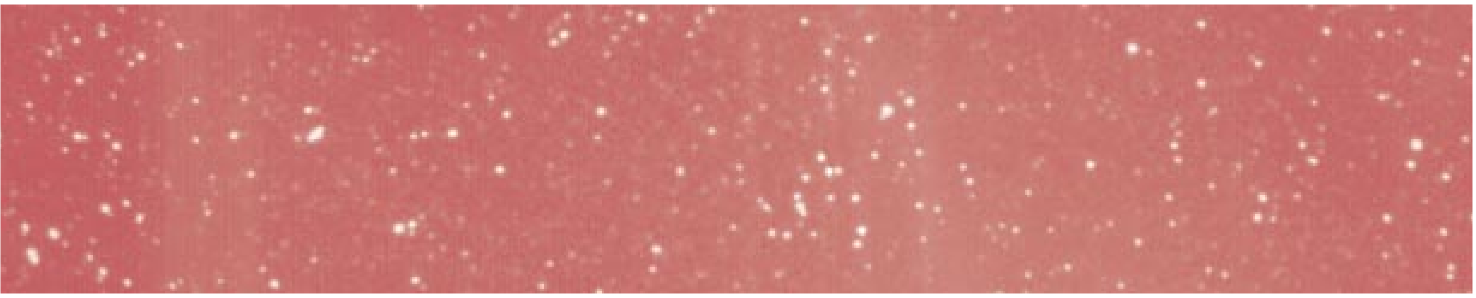
Theorists began advertising detectable sources in the 1950s—first, annihilation gamma rays that, according to Geoffrey Burbidge and Fred Hoyle, should be coming from the radio source Cygnus A if its energy source was the collision of a galaxy with an anti-galaxy; and second nuclear decay gamma ray lines expected from supernovae if their light curves were powered by the Californium-254 source advocated by Burbidge, Burbidge, Fowler, and Hoyle. The classic 1958 previews, written by Philip Morrison and Satio Hayakawa, popularized these and other, less exotic, potential sources. Promised fluxes ranged as high as $0.1–1\gamma/\text{cm}^2$–sec in the MeV range.

An off-the-shelf nuclear emulsion stack, flown on an Italian balloon, quickly cut these numbers by 100. Thomas Cline built the first detector deliberately designed for astronomical gamma ray sources in 1961 and pushed the limits down to about $10^{-3}\gamma/\text{cm}^2$–sec. The extraordinary efforts required to beat down backgrounds and extract signals shine through the bland 1962 remark of Bill Kraushaar and George Clark that "the remaining 22 events, which come from a variety of directions in space, are gamma rays." Jim Arnold, piggy-backing on Ranger 3 in the same year, defined the diffuse background, while balloon and rocket-borne detectors pushed sources down to near $10^{-4}\gamma/\text{cm}^2$–sec, interrupted by one 1966 false alarm at about the same level, in the general direction of Cygnus. A 1967 review by Giovanni Fazio pointed out that the ratio of papers to confirmed extra-solar-system photons above 100 keV was still infinity (but his discussion of the likely radiation processes has held up well).

Gamma ray photons coming from the galactic center direction and from the Crab Nebula finally appeared in 1967–68. The Crab photons were pulsed and, having been collected in 1967 by Richard Haymes and his colleagues, provide the earliest measurement we have, or will ever have, of the pulsar period.

SAS2, the first satellite optimized for gamma rays, went up in 1972 and quickly increased the photon number count to 10^4 or so, though the number of identified sources hovered at a handful. COS B returned 2×10^5 photons in the 1970s, leading to a catalog of a couple dozen sources, nearly all unidentified. Balloons and rockets continued to fly, and it was a balloon package that first spotted the cobalt-56 decay line from supernova 1987A.

The modern era began with the spring 1991 launch of the Compton Gamma Ray Observatory (CGRO). The source inventory now includes pulsars, X-ray binaries and transients, supernova(e), the centers of many active galaxies and of the Milky Way, the interstellar medium (both diffuse and patchy), a diffuse isotropic background of somewhat uncertain origin, and, of course, the sun. All the processes advertised in the early reviews have been seen—nuclear decay lines (of aluminium-26,

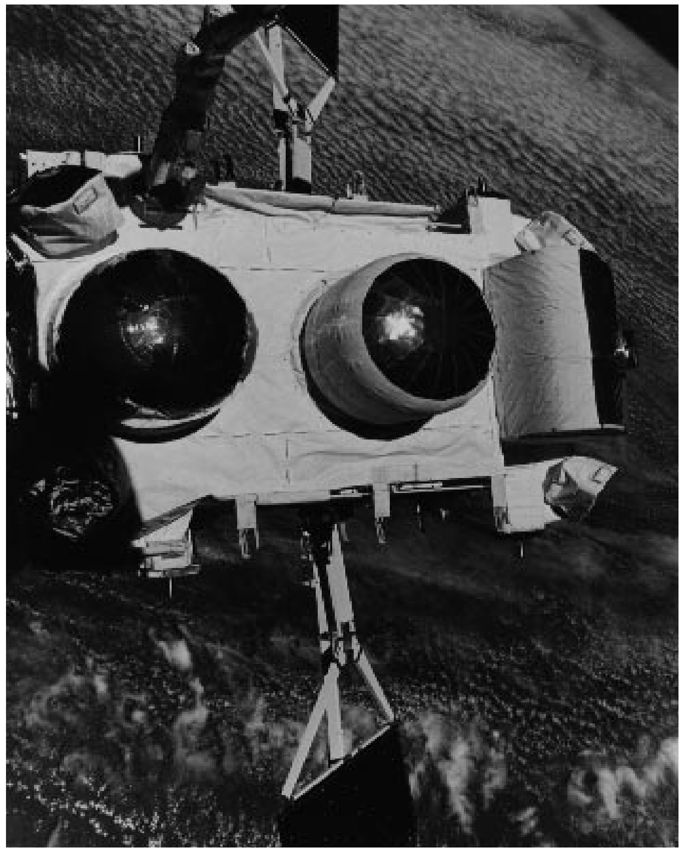


cobalt-56, cobalt-57, excited carbon and oxygen, but not californium-254!), electron-proton annihilation, pion decay, bremsstrahlung, inverse Compton scattering, and probably synchrotron radiation, though the experts are still sometimes arguing about which process goes with which source.

Most gamma ray astronomy has been done at energies of 0.5–100 MeV. One CGRO instrument(EGRET) records photons up to 30 GeV. There is then a decade or so nearly unprobed. By the time you reach TeV and PeV energies, a single photon entering the earth's atmosphere will give you a shower of relativistic particles sufficient to make a Cerenkov light flash or even an extensive air shower (EAS), happily distinguishable from that of a real cosmic ray.

Astronomy at installations sensitive to these has a checkered history. Reports of positive TeV and PeV detections (of the Crab Nebula, Cygnus X-3, Hercules X-l, and several others) surfaced in the early 1980s. Most probably deserve the Scotch verdict of not proven. The exceptions are TeV fluxes from the Crab Nebula (unpulsed) and the nearby, BL Lac type active galaxy Markarian 421, both seen by the Cerenkov installation at the Whipple Observatory. Limits in the range 40 TeV to 1 PeV, even for the Crab, have been the main product so far of the Cygnus EAS array near Los Alamos. The next step in this direction will augment the Cygnus scintillation detectors with water Cerenkov detectors to produce an EAS array reaching down to about 1 TeV and to fluxes well below the current 10^{-11}/cm^2–sec limits. Will Milagro expand the source inventory beyond two? Will primordial black holes finally show up? Morrison's theorem says yes.

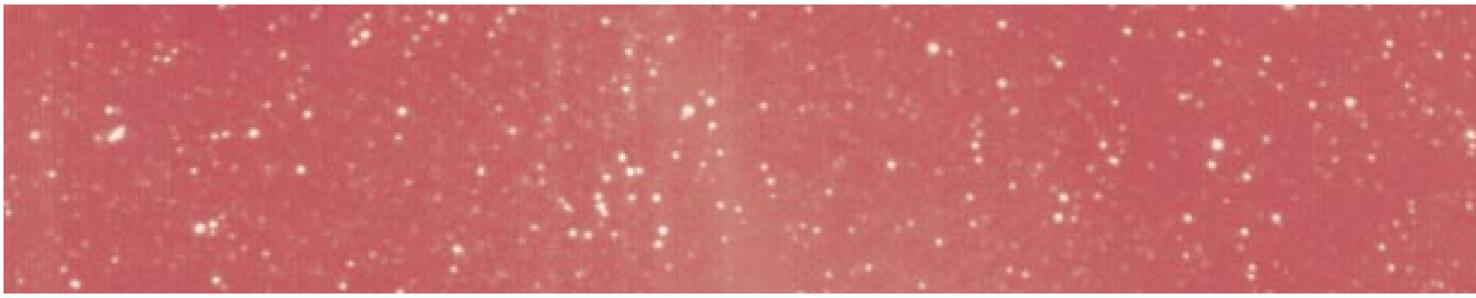
And then there are the gamma ray bursters. Two sorts were predicted (shock break out in supernovae triggered by the collapse of stellar cores to neutron stars; evaporation of mini black holes) and two sorts have been seen (many of one type and three soft gamma repeaters). But they are not the same sorts. Supernovae are no longer supposed to do this sort of thing, because the emerging shock is less explosive and radiates mostly ultraviolet, and the limits on black hole gamma rays are still not very constraining.



NASA

The Compton Gamma Ray Observatory, launched in April 1991, carries four instruments. Each of them provides some information about gamma ray arrival times, energies, and directions of travel. But EGRET specializes in the highest energies (to 30 GeV), while the others are most efficient around an MeV, and COMPTEL concentrates on locations and imaging, OSSE on spectral information, and BATSE on accurate arrival times, especially for bursts and variable sources.

The bursters we have were accidental discoveries, made in the data collected by the American Vela satellite series starting in 1969 and, at about the same time, by the Soviet Cosmos satellites, and announced in 1973–74. What the satellites were supposed to do was



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One of the VELA satellite series, originally launched to look for neutrons and gamma rays from terrestrial events (nuclear bombs). They began seeing celestial events (gamma ray bursters) in about 1969 and the data became generally available a few years later. The author has never even had a "company confidential" clearance and knows nothing whatever more about the satellites.

look for gamma rays from illegal atmospheric bomb tests carried out by "the other side." Neither series ever saw any illegal tests,* but they did discover the bursters. This is the context in which Morrison originally made the remark about the difficulty of wasting 10^8 dollars. His other example was the seismic array, aimed at illegal underground tests, whose primary discovery was the tracing out of tectonic plate boundaries by microseisms.

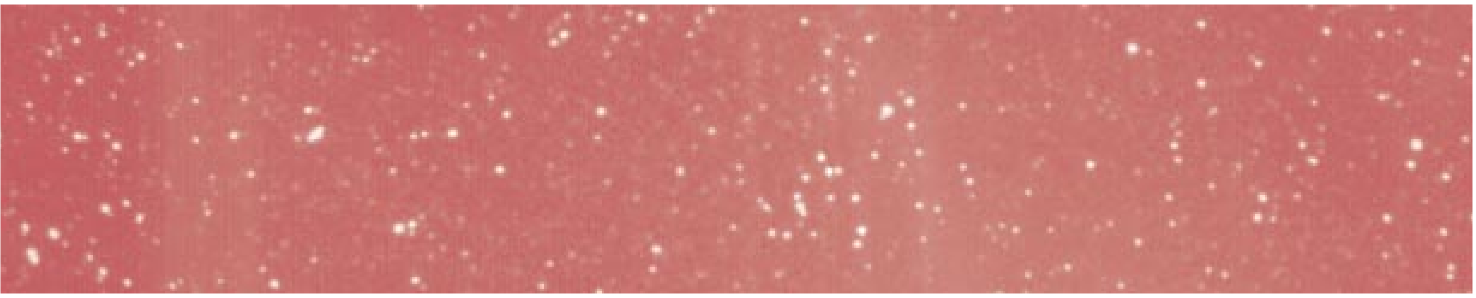
*A test by a country that has not signed the nuclear non-proliferation treaty cannot reasonably be called illegal!

The first gamma ray burst paper reported 16 events over three years, each depositing something like 10^{-3} erg/cm^2 at the top of the atmosphere. Data from later astronomical satellites, some with purposeful burst detectors, others with active anti-coincidence shielding, increased the inventory to a hundred or so, picked up fluxes down to 10^{-5} erg/cm^2, and revealed spectral features suggestive of cyclotron resonances in magnetic fields of about 10^{12} gauss, the same as ordinary pulsar fields.

We spent whole meetings assuring each other that this was all perfectly explicable in terms of hiccups in nearby, old neutron stars. The "nearby" part was needed to account for isotropy of the events over the sky and the relationship between numbers and fluxes that implied homogeneous distribution in space. All participants firmly expected that, with lower flux limits, we would begin to see both the edges of the galactic plane and the concentration of bursts within it.

Notoriously, this is not what happened. CGRO has increased the burst inventory to well above 1000 (growing at the rate of about one per day) and lowered the detectable fluxes to about 10^{-7} erg/cm^2. Sure enough, we are now seeing the edge of the distribution (in the form of a relative sparcity of the faintest detectable events). But the distribution on the sky remains isotropic. Somehow, we are in the middle of the source population, but we see the edge, and this has not been a popular astronomical position since the time of Copernicus.

Although a tiny subset of three sources (soft gamma repeaters) now seem to belong to neutron stars in young supernova remnants, the theoretical situation is otherwise A Mess. Potential for sorting it out with additional statistics or more detailed gamma ray spectra and light curves seems limited. What we need is optical or radio counterparts that last more than a second or so, which may well not exist at brightnesses we can see. Meanwhile, a follow-on gamma ray satellite called



INTEGRAL is rapidly pushing the 10^9 dollar barrier in its estimates.

NEUTRINO ASTRONOMY

And the Lord spoke to Pauli and said, "Speak unto the children of Rutherford and tell them that, wherever a proton is converted to a neutron or a neutron to a proton, there also shalt thou have a neutrino (or antineutrino) to make the spins and energies come out even." This illustrates that the Lord, who may indeed be an engineer, a biologist, and a mathematician, is primarily a bookkeeper. As with any other sort of particles, you can also make them pairwise, neutrino plus anti-neutrino, under appropriate (hot, dense) conditions.

Suitable environments for neutrino production occur in bombs, reactors, the early universe, and stars. For two of the four, the products have not yet been seen. Fredrick Reines and Clyde Cowan originally proposed their experiment as a way to "see the neutrinos coming out of a bomb," but applied it to reactors (successfully, of course). Detecting the cosmological sea of neutrinos that ought to correspond to the 2.7K sea of photons (cosmic background radiation) remains the sort of problem that experimental physicists dream about solving on their way to Stockholm.

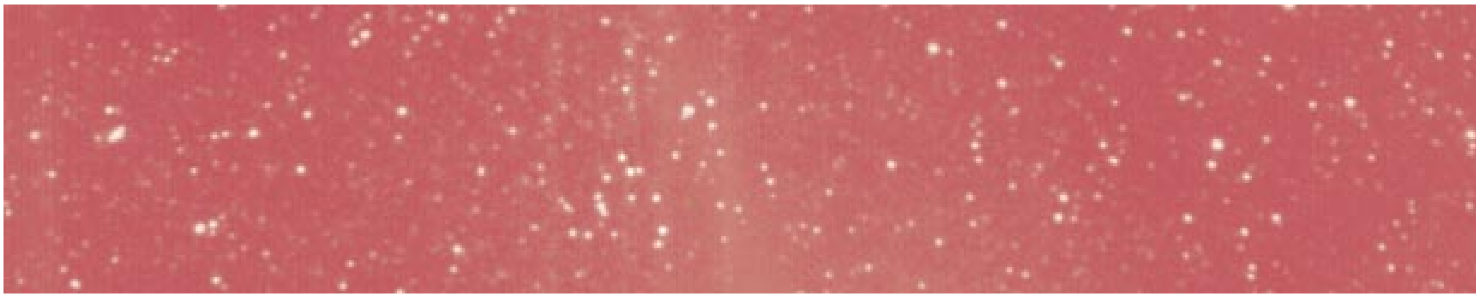
This leaves us with stars. Neutrino radiation by the sun and other hydrogen fusers is implicit in the reactions for the proton-proton chain and CN cycle as written down by Hans Bethe in 1938–39, though he himself did not actually show them in the reaction equations. Counting this particular sort of bean obviously did not seem so important in those days when the neutrino was thought probably to be its own antiparticle, the way the photon is. Soon after, Gamow and Schoenberg pointed out that much more copious neutrino emission might occur in evolved, denser stars, both from one-way conversion of $p + e$ to $n + \nu$ en route to neutron-rich conditions ("deleptonization" is the modern word) and from cycling between p's and n's, with energy loss at each cycle (the Urca process, named by them for the Rio de Janiero casino where money similarly vanishes at every exchange).

AMANDA is the Antarctic Muon and Neutrino Detector Array. It makes use of the extreme clarity of polar ice (from which bubbles have been squeezed by the weight of ice above). Thus flashes of Cerenkov light from high-speed particles passing hundreds of meters away can be seen by the widely-spaced phototube detectors.

Calculations of the various pair production processes (bremsstrahlung, synchrotron, plasmon, Compton, and annihilation neutrinos) followed hard upon the description by Feynman and Gell-Mann of the universal Fermi interaction which revealed their possibility. The recognition of neutral currents, permitting the production of mu and tau neutrinos (pairwise) under stellar conditions, triggered a third round of calculations in the 1970s. Round four, invoking rotations or oscillations among the neutrino types, is by no means over, the knock-out punch necessarily awaiting further experimental/observational results.*

The first experiments were gedanken ones. Bruno Pontecorvo and Luis Alvarez wondered in the 1940s what would happen if you exposed a sufficiently large quantity of some substance with a large cross-section

Baby astronomers are taught to call themselves observers; baby physicists experimenters. The distinction blurs most thoroughly in cases like gamma rays, neutrinos, and gravitational radiation, where you have no idea whether your telescope/detector will see anything at all until you have built and debugged it. Galileo never had this problem.



The interior of the Kamiokande detector. (Courtesy Yoji Totsuka, University of Tokyo).

for induced beta or inverse beta decay to the sun. Their answer was "nothing." Solar neutrinos would not be energetic enough. Rather, they proposed chlorine-37 as a trapper of reactor (anti) neutrinos, still believing the particle and anti-particle to be the same.

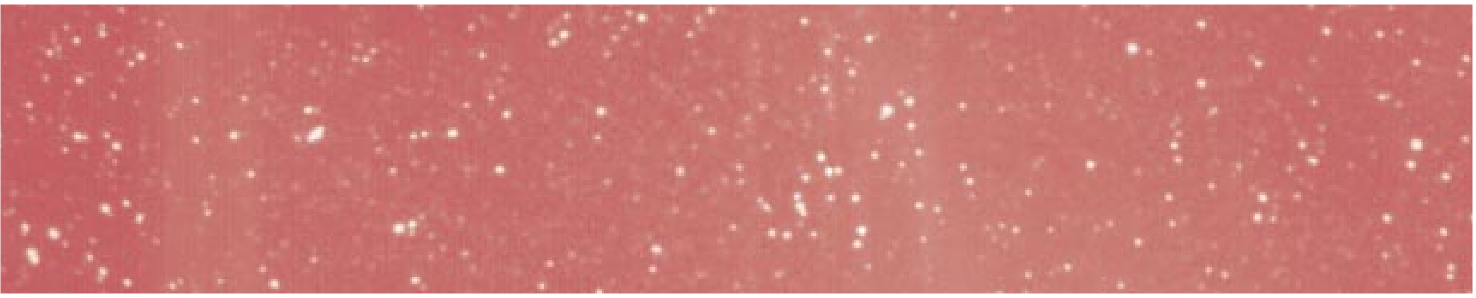
It is against this historical background that Raymond Davis, Jr. buried his first chlorine tank in the ground near Brookhaven in 1954, though he also took the trouble to report a solar upper limit (about 10^4 times the current best value). Incidentally, Ray assures us that he does not have a middle initial. The journal habit of name inversions (so that he appears in references lists as Davis, R., Jr.) is responsible for the ghost R.J. Davis. Similar practices have produced ghost papers by Einstein & Preuss, Einstein & Silbst, etc.

The solar experiment came to seem possible in 1958, with a large increase in the laboratory cross section for $He^3 + He^4$ producing Be^7, which would, in turn, capture either a proton or an electron, with a beta-unstable product above the energy threshhold for transformation of Cl^{37} to A^{37}. Davis began serious search for a mine deep enough and large enough to contain a 100,000 gallon tank of C_2Cl_4 (perchlorethylene, or cleaning fluid) in 1963. Even as theorists continued to throw scurrilous SNUs (solar neutrino units) at each other, the tank was built, filled, and instrumented, and data collected.

Davis's 1968 upper limit of about a third of the expected high-energy neutrino flux eventually became a detection at about the same level, and there things have sat for 27 years. Kamiokande (a water Cerenkov device that began life as the Kamioka Nucleon Decay Experiment and matured into the Kamioka Neutrino Detection Experiment) has recorded the very highest energy neutrinos at about half the expected rate and shown that they indeed come from the direction of the sun. SAGE and GALLEX (where gallium transmuting to germanium signals the passage of even quite low energy neutrinos) report that the flux of neutrinos from $p + p$ making deuterium + positron + neutrino (the main solar reaction) is about half of what standard models predict. And we are not going to reconcile the various discrepancies in this paragraph!

The tale of Supernova 1987A is more coherent, according to most tale-tellers. On February 22/23, 1987, there were operating at least four detectors with possible sensitivity to supernova neutrinos above thresholds of 5–18 MeV. Two were large volumes of liquid scintillator (in the Mt. Blanc tunnel and in the Soviet Baksan Neutrino Observatory) and had been deliberately constructed to look for explosive astronomical events. The other two were large water Cerenkov counters (IMB in the Morton salt mine and Kamiokande, mentioned above) and had been constructed—also, of course deliberately, but to look for proton decay, as predicted by some grand unified theories of particle physics.

The Mt. Blanc group were monitoring their data in real time and quickly became aware of a cluster of five above-threshold events within a time interval of a few seconds, the largest such grouping in 2.5 years of operation. They promptly issued an IAU telegram and circular, reporting that a burst of neutrinos had arrived eight hours before the first photons from the supernova. This report sent the Kamioka group rootling in their data to find, eventually, 12 above-threshold events within 12.4 seconds, but 4.7 hours later than the Mt. Blanc ones. The



IMB group, who had previously supposed that their energy threshold was too high for supernova neutrinos with kT ≈ 5 MeV to produce visible flashes, then examined their data, finding 8 events above 19 MeV within a six-second period, less than a minute or two from the Kamioka event time. Finally, Baksan weighed in with five events also within a few seconds, not more than a few minutes apart in time from the IMB and Kamioka clusters. Only IMB and Mt. Blanc were using accurate clocks, and none of the other groups has ever reported anything above their thresholds at the time of the Mt. Blanc event.

The majority of reviewers have dealt with this by believing in the IMB and Kamioka neutrinos and their simultaneity, disbelieving the Mt. Blanc ones, and ignoring the Baksan ones. Then they can say that the flux, temperature, time scale, and so forth were just what should have come from a core-collapse (type II) supernova, and that there is no evidence for neutrinos having unexpectedly large mass, magnetic moment, coupling constants, or any other anomalies.

The Baksan and Mt. Blanc experimenters have, both independently and in collaboration, found correlations among the "below threshold" data streams of all four detectors during a two hour period around the time of the Mt. Blanc burst. Signals recorded by the two gravitational radiation antennas operating at the time also show statistically significant correlations with each other and with the neutrino detector data streams during this period. The results have been reported in several journals and at least four conference proceedings, but remain essentially unnoticed by the community.

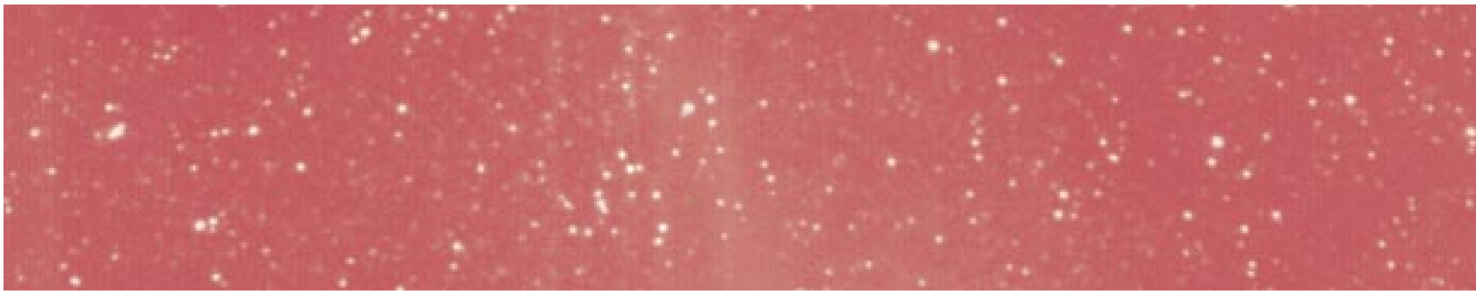
Looking ahead, designs, proposals, and some preliminary data exist for an assortment of detectors and arrays focused on higher energy neutrinos and lower flux events from astrophysical sources. In addition to supernovae and merging neutron-star pairs, plausible sources include the annihilation or decay of dark matter particles in the galactic halo and production in association with very high energy cosmic rays in active galaxies or elsewhere. The active substances to be used include water (e.g., Superkamiokande), deuterated water (Sudbury Neutrino Detector), and ice (Antarctic Muon And Neutrino Detector). All seem to be in the 10^8 dollar class, and at least the ones just mentioned are going forward more or less as planned. Keep your window cleaner handy!

GRAVITATIONAL RADIATION ASTRONOMY

Gravitational radiation comes from wiggling massive particles in much the same way as electromagnetic radiation comes from wiggling charged particles. And you can detect them because they, in turn, will wiggle other particles with mass or charge. Why then are the production and detection of gravitational radiation still challenges when we have been radiating infrared and seeing optical photons since the time of the coelenterata or thereabouts? Mostly (as you know perfectly well) because gravitation is the weaker force. Thus, even for entitities moving at (nearly) the speed of light, the ratio of radiated powers is $GM^2/q^2 \approx 10^{-36}$, where G is G, M is mass, and q is electric charge (in God's units or cgs).

To make things worse, the lowest non-zero order of radiation is a dipole for the electromagnetic case and a quadrupole for the gravitational case. This happens because the former force is carried by a spin one particle (photon) and the latter by a spin two particle (graviton).* It costs you two extra powers of (v/c) for systems in slow motion. As a result, the earth in its orbit will lose more energy in 31.7 nHz electromagnetic radiation than in 63.7 nHz gravitational radiation if there is as much as a tenth of a Coulomb of excess charge hanging around. The corresponding ratio for orbiting neutron stars or black holes with $v \approx c$ is one electron per Teragram, and the radiated frequencies will be kilohertz (the range in which most detectors are designed to operate). And, other things being equal, whatever sort of detector you might think of constructing is correspondingly more sensitive to electromagnetic than to gravitational disturbances, not to mention acoustic noise, microseisms, changes in local g, and massive visitors tilting the floor. That the moon overhead raises tides rather

**The connection has been explained to me on a number of occasions in ways that seemed to make perfect sense at the time.*



Joe Weber with aluminum cylinder gravitational antenna. (Courtesy Joe Weber)

than hair is only because it (like most macroscopic objects) is so nearly electrically neutral.

As if all this weren't sufficiently offputting, for about 30 years (1925–55) many general relativists doubted whether gravitational radiation had any physical reality at all. Their doubts came from defective choices of viewpoint and sign errors (in odd numbers of places) and surely delayed serious consideration of this window on the universe.

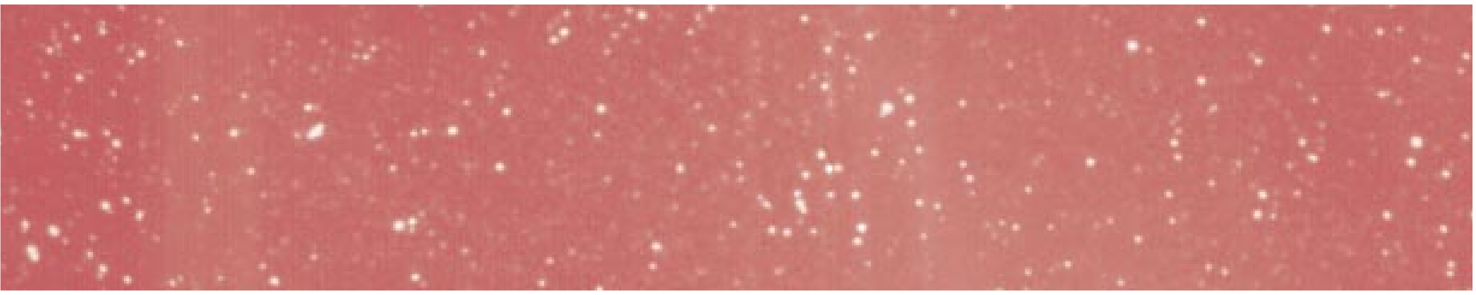
Joe Weber, the one man who was apparently not discouraged, combined a background in radio engineering and electronic countermeasures with a knowledge of general relativity gained in late night reading to design (before 1960) and build (by 1965) a detector for gravitational radiation. Initial calculations by Freeman Dyson and John A. Wheeler of the radiation expected from binary neutron stars and supernovae date from the same period. Weber's first antenna used multi-ton aluminum bars as the energy collectors and piezoelectric crystals glued at their centers to turn mechanical energy of the oscillating bar into varying electrical currents of the sort radio amateurs had been amplifying and filtering for decades. At least one antenna of this design has been operating nearly continuously at the University of Maryland ever since. When supernova 1987A exploded, the only detectors on line were two Maryland bars and a similar one at the University of Rome. If supernova 1995N (or thereabouts) goes off, similarly close to us, as I write this, the same situation is quite likely to obtain.

Not that others haven't tried. The five years after the 1969 publication of the first positive results from Maryland saw about 10 room-temperature, single-mass detectors built, instrumented, and operated (as a rule only very briefly) by as many different groups. None was a precise copy of the Weber bars, and negative results outnumbered positive ones in the literature by so large a factor that most people in the field remain unaware of the latter.

Recognizing that ordinary thermal noise was a fundamental limitation, Weber's group cooled one of their bars to liquid helium temperatures in 1972. Others followed gradually (in Rome, Stanford, Western Australia, Louisiana State University, Japan and elsewhere). Efforts in this direction continue, using either aluminum or niobium (because it is a superconductor) bars, with a goal of operating or noise temperatures in the millikelvin range. The installations, like the first one, are so complicated that, so far, more has been learned from them about cryogenics than about relativity.

Present high-profile plans for the detection of gravitational radiation, like LIGO (the Laser Interferometer Gravity Wave Observatory) and its European counterpart Virgo, use a very different design. Two or more masses are suspended in isolation far apart and the distance between them monitored using laser light. The first device of this type collected data briefly at Hughes Research Laboratory in 1971. The builder was Robert L. Forward, who had been Weber's graduate student and says that at least the germ of the idea came from his teacher. Forward provided a stable base for his masses by mounting them at the ends of a large granite slab. Such slabs are more often used as raw materials for gravestones, which may be trying to tell us something.

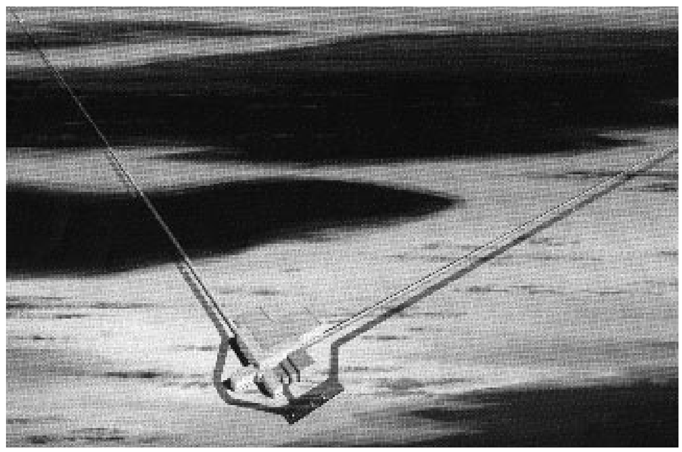
The cost of such an installation with a baseline of 3 km, rather than 3 m, has predictably escalated from 1980s estimates of \$60–\$80 million to three or more times as much. Construction is underway for the two LIGO detectors, with initial operation expected in this



decade and sensitivity to known sources to be reached with an upgrade in the next.

Meanwhile, the existence and properties of gravitational radiation are being explored in a very different way, from its effects on the orbital evolution of known pairs of neutron stars (binary pulsars). For a couple of the pairs, the radiation is sufficient that the stars will merge in less than 10^8 years. Such events, in distant galaxies, are a leading candidate to produce gamma ray bursts, thereby taking us back to the first section.

So far, there has never been a counterexample to the cliches that "whenever you open a new window you see a new scene," and "it's hard to waste 10^8 dollars." Gamma ray astronomy has already passed through this stage, and the discovery of supernova neutrinos with the two installations looking for proton decay probably also qualifies. The conservative bet is, I suppose, that the clichés will continue to be true for the still more expensive gamma ray, neutrino, and gravitational radiation projects now on the drawing boards and in the tunnels. This may be the only context in which I am not an unmitigated conservative!



An artist's conception of one of the two LIGO sites. The two perpindicular arms of the site extend four kilometers to end buildings. LIGO will measure gravitational waves by sensing very small motions (on the order of 10^{-18} meters) of suspended mirrors at the ends of the two arms. Light from a stable laser in the building at the vertex of the two arms is split and sent down the two arms through vacuum pipes to the end mirrors. The end mirrors reflect the light beams back to the vertex where it is recombined and compared. (Courtesy of the LIGO project, the California Institute of Technology and the Massachusetts Institute of Technology.)

~For Further Reading~

What else to read?

Gamma ray astronomy: The current situation is described in recent conference proceedings—**The Second Compton Symposium** ed. C.E. Fichtel, N. Gehrels, and J.P. Norris, AIP Conf. Proc. **304**, 1994 (which also has a bit more of the history), and the **Third Compton Symposium**, to appear in 1995 also in the AIP series.

Neutrino astronomy: The history and accomplishments up to 1988 are elegantly described by J.N. Bahcall in his **Neutrino Astrophysics**, Cambridge Univ. Press, 1989. Additional 1987A results and future detector plans appear in several volumes of proceedings of **Texas Symposia on Relativistic Astrophysics** (Annals of the NY Academy of Sciences), especially the 14th, ed. E.J. Fenyves. And for the latest word on solar neutrinos, see John Bahcall's fine article in the Fall/Winter 1994 *Beam Line,* Vol. 24, No. 3.

Gravitational radiation detection: Not even a short history that would be regarded as correct by all participants has yet been written, including this one.