The Gamma-Ray Cosmos

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Gamma rays, the highest energy photons of electromagnetic radiation, are the signature of the most energetic events in the universe (*1*). At present, two satellites are in orbit mapping the gamma-ray sky. In April 1991 NASA launched the now highly successful Gamma-Ray Observatory, soon re-christened the Compton Observatory in honor of Arthur Holly Compton, who discovered a basic process by which gamma rays interact with matter. The Russian Granat satellite was launched in December 1989 carrying the French/Russian SIGMA, a new type of gamma-ray telescope. Both Compton and Granat, complemented by ground-based and balloon-borne observations, have produced an explosion of knowledge (Table 1) about the gamma-ray universe that is challenging physicists and astronomers for interpretations. Table 2 shows the properties of the gamma-ray telescopes.

The most energetic and distant objects in the universe are galaxies with small bright nuclei. These include radio-frequency sources such as quasars, Seyfert 1 and Seyfert 2 galaxies, BL Lacertae objects, and numerous others, all with different properties depending on the observing wavelength and the time of observation. These objects, which are referred to collectively as active galactic nuclei (AGN), are now found to be powerful emitters of gamma rays above 100 MeV. A popular (but by no means universally accepted) hypothesis is that all AGN have a common energy source or powerhouse that is a rotating black hole, with narrow outward-extending relativistic plasma jets whose direction may or may not intersect the line of sight to the Earth. Before Compton only the quasar 3C 273 was observed at gamma-ray energies (> 100 MeV) and the Seyfert Galaxy NGC 4151 at energies below 1 MeV. Compton's EGRET has observed the QSOs 3C 273, 3C 279, and 14 other AGN, and at lower energies Compton's COMPTEL has reported observations of 3C 273 and 3C 279 above 1 MeV. The Whipple Observatory in Arizona has observed the BL Lacertae object Markian 421 above 10^{12} eV (1 TeV). These AGN generally emit in quiescent and sporadic episodes of increased intensity apparently over the full electromagnetic spectrum. The current findings show that the power emitted reaches a maximum at gamma-ray energies (around 1 to 100 MeV). These new results force a severe constraint on the black hole jet model because a self-consistent explanation must now be found that accounts for high power transfer to the low and medium energy gamma rays and still explains observations at other photon energies (*2*).

The production of elements—nucleosynthesis—in "explosive events" such as supernovae can be studied by identifying characteristic gamma rays emitted by the resulting radioactivity. The first evidence that nucleosynthesis has occurred in our Galaxy was provided in 1979 by the gamma-ray spectrometer on the Third High Energy Astrophysics Observatory (HEAO 3) and subsequently confirmed by several balloon and satellite experiments. The gamma ray observed at 1.809 MeV is emitted from the million-year half-life radioactive isotope ^{26}Al. This isotope could be produced, at numerous sites throughout the Galaxy, over the course of several million years. Some potential nucleosynthetic sources are novae, supernovae, or massive star interiors. Because these explosive phenomena occur about every 100 years or less, the long-lived remnant radioactivity would be expected to be distributed throughout our Galaxy where the explosive events occurred. Therefore, in principle, the actual source of the ^{26}Al could be determined by comparing the intrinsic spatial distributions of these potential sources with an image of the ^{26}Al gamma-ray line intensity along the galactic plane. The COMPTEL telescope has now obtained a preliminary spatial image of the 1.809-MeV radiation, and it is hoped that as analysis progresses a true image of the ^{26}Al distribution will be obtained. Unfortunately, the distribution of the potential ^{26}Al sources in the Galaxy is only poorly known; thus, the solution to this important problem may not come easily.

Another important gamma ray of discrete energy is produced by the annihilation of positrons with electrons, which gives a line at 511 keV. Balloon experiments in the 1960s suggested the existence of such a line, but it was only in 1977 and 1978 that gamma-ray telescopes on balloons launched from Australia definitively showed that celestial annihilation radiation was emanating from the central region of the Galaxy and possibly from the galactic plane. The galactic center line observed was narrow (<1 keV wide), because its width was not resolved by the spectrometer used. By 1980 balloon and satellite experiments showed that the narrow annihilation line was variable in intensity, and by 1981 it was not detectable from the galactic center direction! Conversely, analysis of data from the Solar Maximum Mission Satellite Gamma-Ray Spectrometer (SMM GRS) over a 9-year period from 1980 to 1989 showed that an annihilation line, steady in intensity, was observable. This seeming contradiction could be explained if there were two sources of the annihilation line, one a diffuse source that was always visible as seen by SMM, and another near the galactic center that was sporadic. Nevertheless, the 511-keV line presented an enigma.

It is easy to imagine the exhilaration when a 1988 balloon flight of the Goddard Space Center group's GRIS spectrometer revealed that the annihilation line had reappeared. Something ghostly existed in the core of our Galaxy, and it would not be long before a likely candidate for producing the ephemeral line was located. Hard x-ray sources in the central region of our

Table 1. The celestial objects that have been observed in gamma rays since 1988. Details of the experimental results are available in several publications (*2–7*).

Emitting Source or Radiation	Observations
Active galaxies	
3C 273	EGRET, COMPTEL, OSSE, SIGMA
3C 279	EGRET, COMPTEL
MK421	EGRET, WHIPPLE
13 additional	EGRET
The Milky Way Galaxy	
1.809 MeV (^{26}Al)	GRIS, HEXAGONE, COMPTEL
0.511 MeV	GRIS, HEXAGONE, SIGMA, OSSE
1E1740.7-2942	SIGMA, GRIP
Nova Musca	SIGMA
Crab Nebula/Pulsar	EGRET, COMPTEL, OSSE
Vela Pulsar	EGRET, COMPTEL
Geminga Pulsar (1E0630+178)	(ROSAT), EGRET, DURHAM
Pulsar 1706-44	EGRET
Pulsar 1509-58	BATSE
Other sources	
Gamma-ray bursts	BATSE, EGRET, COMPTEL
Transient *GRO* J0422+32	BATSE, OSSE
LMC	EGRET

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Galaxy were known to be variable in their output, and in 1988 a sophisticated telescope that could image gamma-rays, GRIP of the California Institute of Technology, pinpointed an x-ray source (1E1740.7-2942). This object, which was seen by the Einstein Observatory, had an unusually high flux of energetic photons above 200 keV. In 1990, the Granat SIGMA experiment, which like GRIP could pinpoint 1E1740.7-2942, found that the source was emitting a strong sporadic flux of the energetic photons with an intense broad line feature below the energy of the annihilation line. The SIGMA team has proposed that the broad feature is related to the variable galactic center annihilation line, but it remains to be proven that a narrow line is emitted as well. One current conjecture is that 1E1740.7-2942 is powered by a black hole that occasionally emits a burst of positrons that promptly annihilate in a surrounding hot, dense gas giving the broad feature. The narrow line arises from those positrons, which escape and annihilate in a more distant dense, cool molecular cloud as much as a year later.

Table 2. Celestial gamma-ray studies require large devices, typical of those used in nuclear physics laboratories, with modifications to produce an image of the radiation source of interest. Listed are the operating principles and effective energy range of the instruments. More detailed descriptions of these detectors may be found in recent publications (*8*).

Instrument	Technique	Energy Range
SIGMA	Coded Mask	0.035 to 1.3 MeV
EGRET	Spark Chamber e^+-e^- Pairs	30 MeV to 30 GeV
COMPTEL	Compton Scattering	1 to 30 MeV
OSSE	Collimator	0.1 to 10 MeV
BATSE	All Sky Monitor	0.05 to 30 MeV
GRIP	Coded Mask	0.03 to 5 MeV
GRIS	Collimator (germanium)	0.020 to 8 MeV
HEXAGONE	Collimator (germanium)	0.1 to 14 MeV
WHIPPLE VHE	Atmospheric Cerenkov	$> 5 \times 10^{11}$ eV
DURHAM VHE	Air Shower Cerenkov	$> 10^{12}$ eV

The discovery of pulsars by radio astronomers in 1967 revealed a new class of objects whose definite repetition period and eventual observation at other wavelengths permitted an accurate physical description of the dense end state of a stellar explosion, a neutron star. Similar to the flashing of a lighthouse beacon, a rotating neutron star emits pulses at radio, and sometimes at optical and x-ray, wavelengths. Pulsars have not been prolific sources of gamma rays, however, and above 100 MeV only two were known, prior to Compton: the famous Crab Nebula pulsar and the constellation Vela pulsar. The situation has somewhat improved with the launch of the Compton Observatory. Table 1 indicates the gamma-ray pulsars now observed. Besides the Crab and Vela pulsars, two additional pulsars are under study by EGRET, and one by BATSE. The discovery of the Geminga pulsar is particularly significant because it lays to rest a 20-year old gamma-ray mystery. In 1972 the gamma-ray satellite SAS-2 observed a strong steady gamma-ray source (>100 MeV), 2CG195+04 in the constellation Gemini, which was later seen by another gamma-ray satellite COS B and named Geminga—a word in the Milanese dialect of Italian for "it's not there." Except for a soft x-ray source 1E0630+178 found by the x-ray observatory Einstein some years later and a faint blue star, no other object could be associated with the mystery source. Although it was thought that the object was a pulsar, this was not confirmed until recently when the the German/U.S. ROSAT satellite x-ray detector found that 1E0630+178 was indeed a pulsar with a period of 0.237 s and possibly as close as 38 pc. The object appears to be an old pulsar and, with the period accurately known, the EGRET team, using their new Geminga data, readily verified that the source was the pulsar. Even the earlier SAS-2 and COS B data, when reanalyzed with the pulsar period derived from the known slowdown rate of 1E0630+178, confirmed this result. It is amazing that the Geminga pulsar has also been identified at photon energies above 10^{12} eV in archival data recorded by ground-based air shower and Cerenkov detectors operated by the University of Durham (United Kingdom).

The first major revelation from Compton was the startling finding from BATSE which showed that gamma-ray bursts (GRBs) are uniformly or isotropically distributed on the celestial sphere and with a seeming paucity of GRBs of small size. The GRBs have been an enigma for astronomers since their discovery in 1968 when U.S. satellites, monitoring the Nuclear Test Ban Treaty, detected many bursts, ranging in duration from hundreds of seconds down to several milliseconds, not from our then adversary in the cold war but from outside the solar system! Over the past 20 plus years observers have seen these transient phenomena but no celestial object has been identified as the source of the radiation. Depending on the size of the detecting instruments as many as two or three GRBs were detected on the average each month before 1991 but, with the large Compton BATSE, a burst is seen nearly every day. The lack of knowledge of the nature of the emitting objects has led to considerable speculation. Circumstantial evidence had suggested to many theorists that the bursts are associated with neutron stars, which are believed to have strong magnetic fields. This model received strong support from observations made by Japanese and Russian spacecraft that showed features in a few GRB gamma-ray energy spectra consistent with the belief that neutron stars in our Galaxy are the progenitors. However, BATSE observations are particularly perplexing because the new results do not match the spatial distribution of any objects known to populate the Galaxy. The results of subtle statistical tests of the new GRB properties imply that the sources are either very nearby, within about 100 pc of the Earth, in an extended galactic halo of radius 50 to 100 kpc, or at cosmological distances. At the moment there is an intense effort by observers to find a GRB radiating at radio, optical, or soft x-ray energies, thereby, hopefully, identifying a previously known object or leading to a discovery of a new object. This is no mean feat: by the time Compton instruments can locate the GRB's approximate position a day or more may have elapsed, and the elusive source may have ceased radiating at any other wavelengths, remaining forever invisible to man!

The list of gamma-ray mysteries would not be complete without mentioning the latest enigma: "the gamma-ray burst that would not go away." On 5 August 1992, BATSE detected a strong rise in intensity of low-energy gamma rays for several days, which since then has been decreasing in intensity with an exponential decay time of about 75 days. The discovery of the source, known as GRO J0422+32, led the investigators to immediatly reorient Compton, so its full array of telescopes could study the source's emission. Within several days of the first sighting, the source was identified at optical and ultraviolet wavelengths. At gamma-ray energies no photons above 500 keV have been observed, but its spectrum and time behavior recall that of Nova Muscae, an x-ray Nova, studied at gamma-ray energies by the Granat instruments. Such objects are conjectured by some to consist of a black hole and a dwarf companion.

Mention should be made of the EGRET observations of gamma rays (>100 MeV) from a nearby galaxy, the large Magellanic Cloud (LMC) (*3*). Closer to home, sporadic gamma-ray sources, solar flares, are providing copious data for the instruments on Compton, Granat, and the Japanese Yohkoh satellite. The most dramatic flare observation was made by the EGRET (*4*) on 11 June 1991, when a large solar flare produced intense (> 100 MeV) gamma-ray emission that lasted for several hours.

The Compton and Granat observatories have revealed an exciting and at times perplexing view of the universe, and many more discoveries are likely. But what about the future, where do we go from here? A desirable approach would be to launch new instruments on several smaller, long-lived satellites, each carrying a detector tailored for optimum observations in a portion of the broad x- and gamma-ray energy range. Without doubt the lunar surface will be the ultimate platform for gamma-ray telescopes, but many modest programs in the next few years could make significant gains in knowledge and maintain the interest of younger scientists in solving some of the intriguing mysteries before us. For now, the astrophysics community can rejoice in the continuous flow of the exciting insights about the gamma-ray sky provided by Compton and Granat.

REFERENCES AND NOTES

1. With few exceptions gamma rays are photons with energies above 100 keV [extending to $>10^{15}$ eV (1 PeV)], which are produced by the interactions of high-energy charged particles with matter and fields. Since they have no charge, they are undeflected by electric and magnetic fields and therefore they directly probe high-energy phenomena in the gamma-ray source.
2. C. D. Dermer and R. Schlickeiser, *Science* **257**, 1642 (1992).
3. P. Sreekumar *et al.*, *Astrophys. J.* **400**, L67 (1992).
4. G. Kanbach *et al.*, *Astron. Astrophys. Suppl. Ser.*, in press.
5. *Proceedings of the Conference on Recent Advances in High Energy Astronomy*, Toulouse, *Astronomy and Astrophysics Supplement Series*, (Springer Verlag, Heidelberg, in press).
6. P. Durouchoux and N. Prantzos, Eds., *Gamma-Ray Line Astrophysics, AIP Conference Proceedings No. 232* (American Institute of Physics, New York, 1991).
7. Central Bureau for Astronomical Telegrams, International Astronomical Union, Smithsonian Astrophysical Observatory, Cambridge, MA 02138.
8. W. N. Johnson, Ed., *Proceedings of Gamma Ray Observatory (GRO) Science Workshop* (Goddard Space Flight Center, Greenbelt, MD, 1989); C. R. Schrader, N. Gehrels, B. Dennis, Eds., *Proceedings of Compton Observatory Science Workshop (NASA Conf. Pub. 3137*, NASA, Greenbelt, MD, 1992).

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Frosted Flies

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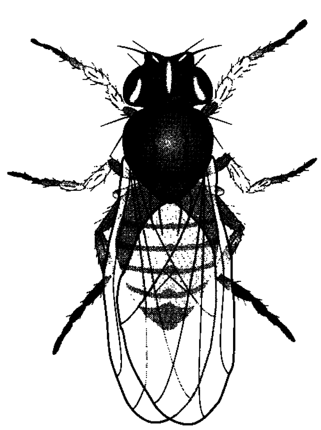
Drosophila—the geneticist's fruit fly—are easy to freeze, 'tis the waking 'em up that's the hard part. But no longer. Peter Mazur and colleagues show in a paper in this week's issue of *Science* (p. 1932) that FlyCryo Inc. is now a reality. *Drosophila* embryos can be frozen in liquid nitrogen and then thawed to develop into viable and fertile adult flies. This is the breakthrough that the *Drosophila* community has been waiting for.

Why is the cryogenic preservation of *Drosophila* so important? First, a little history and a moral tale. The genetic analysis of *Drosophila melanogaster* began in Thomas Hunt Morgan's laboratory at Columbia University just over 80 years ago. There are many factors that have contributed to the success of this fly as an experimental organism. Some of them are intrinsic—its short (10-day) life cycle, its relative ease of laboratory culture, its small chromosome number (and its relatively small genome size), its giant chromosomes at the larval stage—to mention but a few. These factors would have been of little importance had Morgan, and his brilliant students, C. B. Bridges, H. J. Muller, and A. H. Sturtevant, not proselytized, actively encouraging other biologists to work with their favorite fruit fly. As the Columbia school discovered more and more mutations and constructed more and more genetically marked strains, they freely gave these to colleagues for both research and teaching. As more mutations and genetically characterized strains accumulated, so the use of *Drosophila* as a research organism grew. There is a limit to the degree of sophistication in genetic analysis of a species with only one or a few mutations and no special chromosomes. However, with several thousand genes marked by mutant alleles and with the construction of thousands of strains with special chromosomes that allow, for example, the trivial maintenance of recessive lethal mutations, our ability to ask increasingly difficult questions of *Drosophila* increases.

The generosity of Morgan's group in sending their precious strains to colleagues began a tradition in research that continues to this day. It is this tradition that has fueled the recent explosion in our knowledge of many fundamental biological problems that has come from *Drosophila* research. There is, however, a heavy price to pay for this. The price is the maintenance of thousands of different stocks of *Drosophila* by the expensive, time-consuming, and precarious process of culture. A reasonably large *Drosophila* research laboratory might keep 2000 different stocks. At any one time only a fraction of these, perhaps 20%, will be in active use. The others will be kept either because they represent an essential living archive of research "completed" or because they may be of use for future work, either by the laboratory itself or by others. Since the 1930s, the *Drosophila* community has been in the habit of publishing its stock lists in its house journal, *Drosophila Information Service*. But even in the 1930s the need for centralized stock centers was realized. First at the California Institute of Technology (Caltech) (to which the Morgan group migrated in the late 1920s), then at Cold Spring Harbor, and then in Bloomington, Indiana (under Herman Muller), *Drosophila* stock centers were established to maintain in perpetuity stocks for researchers. Today there are three such stock centers, two in the United States (supported by the Natural Science Research Council) and one in Europe (supported by the Swedish Natural Science Research Council). The Caltech collection is now in Bloomington and carries well over 5000 stocks; the original Bloomington collection of Muller is now at Bowling Green, Ohio, and is only slightly smaller; the European Stock Center (about 1600 stocks) is in Umeå. Each of these centers publishes stock lists and all of their stocks are freely available to anyone. In 1985, Dan Lindsley estimated that there were at least 15,000 different stocks of *D. melanogaster* being maintained. Since then there has been a dramatic growth, particularly in stocks carrying marked P-elements and transformed DNA sequences. In addition, there is a collection of stocks of other species of *Drosophila*, originally at Austin, Texas, but now at Bowling Green; this carries about 1300 stocks.



For many years *Drosophila* geneticists have been jealous of their colleagues who work with mice or even *Caenorhabditis elegans*, for they can maintain their stocks by the "simple" expedient of freezing in liquid nitrogen. The *C. elegans* stock center in Missouri maintains all of its stocks by slow freezing of larvae. Major centers for mouse stocks, such as that at the Jackson Laboratory in Bar Harbor, Maine, are in the process of freezing eight-cell embryos of their stocks. Once frozen, of course, the stocks require relatively little care. Just as important, the genotypes of these stocks will not change with time, which will inevitably occur if they are kept from generation to generation by live culture. This is an important point. Natural selection does not stop

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