

THE NEW GAMMA-RAY ASTRONOMY

Our understanding of the gamma-ray sky is being revolutionized. Seven years ago, gamma-ray astronomers knew of only a scattering of very bright sources. Now, thanks to two international observatories, the gamma-ray sky appears to be teeming with variety—unstable sources that change violently on short time scales, steady sources that glow radioactively and others whose nature we barely understand.

In the vanguard of this revolution are NASA's Compton Gamma Ray Observatory and the Russian–French mission known as Granat. Compton, which was launched in 1991, has four instruments on board that together span the energy range from 20 keV to 30 GeV. Launched in 1989, Granat has two instruments that image the sky from 3 keV to 1.3 MeV. The sensitivities and angular resolutions of these six instruments are an order of magnitude better than anything flown before. Just as important, because they operate simultaneously, the entire suite of instruments covers six decades in photon energy. This huge stretch of the electromagnetic spectrum equals, in logarithmic size, the entire ground-based regime from radio through ultraviolet.

The physical mechanisms that produce gamma rays in astronomical sites are quite different from those at work in other wavelength bands. Gamma rays come from the realm of nonthermal astrophysics, where particle acceleration and other far-from-equilibrium processes predominate. This is quite different from emission in infrared, optical, ultraviolet and x-ray wavebands, which is produced by mostly thermal processes. Ironically, the gamma-ray band's closest ties are to the wavelength band farthest from it—radio—where nonthermal emission also reigns. As in physics laboratories, astrophysical gamma rays are produced by nuclear de-excitation, matter–antimatter annihilation, particle collisions, cyclotron processes, bremsstrahlung and Compton upscattering.

The new findings from Compton and Granat cover many areas of Galactic and extragalactic astrophysics. Gamma rays from particle interactions in large solar flares have been found to last hours after the optical flare is over. New Galactic transients have been discovered with exotic properties such as jets, pulses, flares and positron annihilation. Gamma-ray lines from supernovae have been detected and used to map the sites of nucleosynthesis

Nucleosynthesis sites, Galactic black holes, gamma-ray bursters, blazars—all yield up secrets and surprises when observed with the latest gamma-ray detectors.

Neil Gehrels and Jacques Paul

in the Galaxy. A new kind of distant active galaxy has been discovered whose bright and variable gamma radiation presumably originates in jets flowing out from the galactic nucleus. The once utterly mysterious gamma-ray bursters have been found to be isotropic on the sky and, like solar flares, have long-duration after-

glows of 100 MeV gamma rays.

There are several overarching themes that not only tie these results together but also illustrate their significance to other areas of astrophysics. We concentrate on four of them that have particularly exciting new gamma-ray results—nucleosynthesis, Galactic black holes, gamma-ray bursts and active galactic nuclei. We also discuss prospects for future progress in gamma-ray astronomy.

More details on many of the results presented here can be found in the proceedings of the Fourth Compton Symposium.¹ And to get an idea of how far gamma-ray astronomy has come in the last 20 years, readers can compare our article here with Richard Lingenfelter and Reuven Ramaty's "Gamma-Ray Lines: A New Window to the Universe" (PHYSICS TODAY, March 1978, page 40).

Sites of nucleosynthesis

The modern era of theoretical nucleosynthesis sprang from a classic 1957 paper by Geoffrey Burbidge, Margaret Burbidge, William Fowler and Fred Hoyle.² These four astrophysicists set down the basis for the currently held belief that chemical elements derive their abundances from stellar evolution rather than the composition of primordial gas. Elements heavier than helium, we now believe, are the by-products of steady burning in stars, whereas some intermediate-mass elements and most elements heavier than iron are forged by explosive burning in supernovae and novae. (Exceptions are lithium, beryllium and boron, which are produced mostly by cosmic-ray interactions.)

Some of the isotopes produced in supernovae and novae are radioactive and emit gamma rays when they decay. Gamma-ray instruments can detect this radiation and determine the emitting isotope by its characteristic line spectrum. With this spectroscopic technique, abundances and matter distributions can be studied directly and, ultimately, the predictions of the theory of nucleosynthesis can be tested.

A partial list of lines important to gamma-ray astronomy is given in the table on page 27. The radioisotopes nickel-56, nickel-57, titanium-44 and aluminum-26 are particularly important since they are synthesized in supernovae and have a wide range of half-lives—from days to millions of years.

NEIL GEHRELS is an astrophysicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland, and is the project scientist for the Compton Gamma Ray Observatory. JACQUES PAUL is an astrophysicist at Saclay Nuclear Research Center in Gif-sur-Yvette, France.

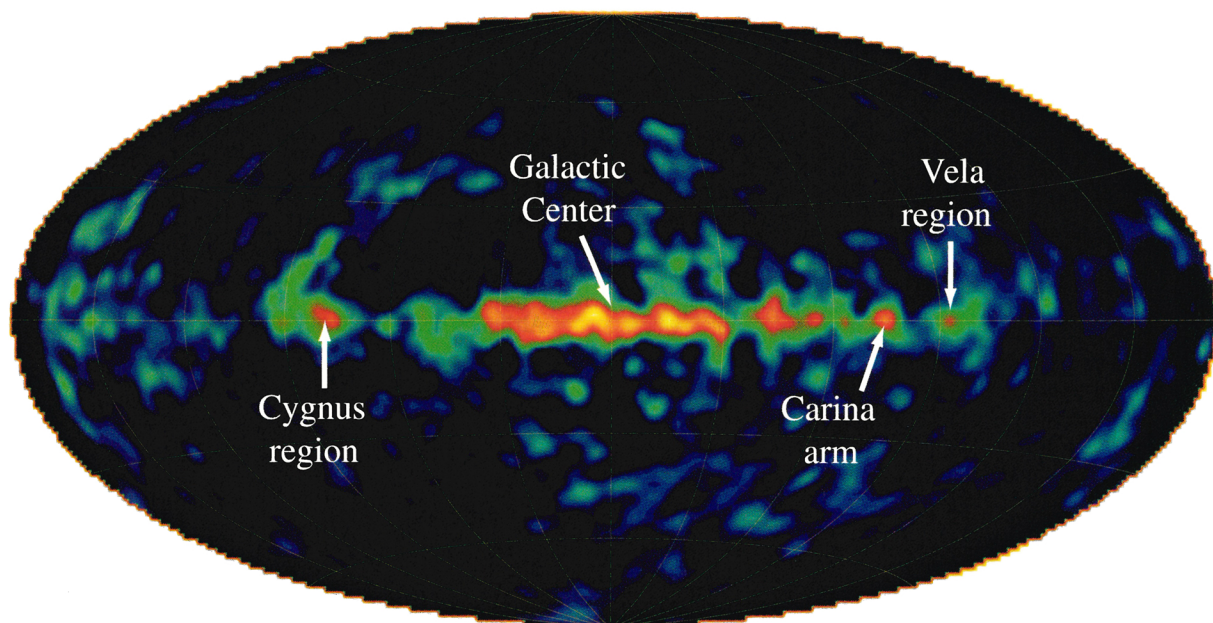


FIGURE 1. MAP OF THE GAMMA-RAY LINE EMISSION at 1809 keV from aluminum-26 decay as measured by the Compton Telescope (COMPTEL) instrument. The map is in Galactic coordinates, with the Galactic plane along the abscissa and the Galactic center at the origin. (Map courtesy of the COMPTEL team.)

In the first years after a supernova explosion, the lines from ^{56}Ni and cobalt-56 have high intensities due to the high abundance of synthesized nickel and the short half-lives of those isotopes. Models predict that two of Compton's instruments—Oriented Scintillation Spectrometer Experiment (OSSE) and the Compton Telescope (COMPTEL)—should be able to detect the ^{56}Co 847 keV and 1239 keV lines from extragalactic Type 1 supernovae out to a distance of about 10 megaparsecs. (1 Mpc $\approx 3 \times 10^6$ light-years.) No supernova as close as that has exploded since the launch of Compton, but, at a distance of 12 Mpc, SN 1991T does show faint 847 and 1239 keV lines in the COMPTEL data.

Type 1 supernovae are expected to be much brighter in those gamma-ray lines than Type 2 supernovae because the white dwarf progenitor in a Type 1 is almost all burned up in the explosion, whereas the exploding massive star in a Type 2 has thick absorbing layers of ejected gas that surround the inner burned shells. (See box 2 on page 29 for a description of the two supernova types.) Not surprisingly, Type 2 supernovae were seldom mentioned in gamma-ray line studies.

That changed when SN 1987A occurred in February

1987 at a distance of only 55 kpc in the Large Magellanic Cloud. That was before the Compton and Granat era, but balloon instruments and the solar gamma-ray detector on the Solar Maximum Mission did detect and study the ^{56}Co

Nucleosynthetic Radioactive Decay Lines

Process	Half-life	Line Energy (keV)	Branching Ratio (%)
$^{56}_{28}\text{Ni} + e^- \rightarrow ^{56}_{27}\text{Co} + \nu$	6.1 d	158.4 811.9	98.8 86.0
$^{56}_{27}\text{Co} \rightarrow ^{56}_{26}\text{Fe} + e^+ + \nu$	77 d	846.8	99.9
$^{56}_{27}\text{Co} + e^- \rightarrow ^{56}_{26}\text{Fe} + \nu$		1238.8	68.4
$^{57}_{27}\text{Co} + e^- \rightarrow ^{57}_{26}\text{Fe} + \nu$	272 d	122.1	85.5
$^{22}_{11}\text{Na} \rightarrow ^{22}_{10}\text{Ne} + e^+ + \nu$	2.6 y	1274.5	99.9
$^{22}_{11}\text{Na} + e^- \rightarrow ^{22}_{10}\text{Ne} + \nu$		511.0	89.4n
$^{44}_{22}\text{Ti} + e^- \rightarrow ^{44}_{21}\text{Sc} + \nu$	~ 60 y	67.9 78.4	91.0 96.6
$^{26}_{13}\text{Al} \rightarrow ^{26}_{12}\text{Mg} + e^+ + \nu$	7.1×10^5 y	1808.7	99.8
$^{26}_{13}\text{Al} + e^- \rightarrow ^{26}_{12}\text{Mg} + \nu$		511.0	82.1n
$^{60}_{26}\text{Fe} \rightarrow ^{60}_{27}\text{Co} + e^- + \bar{\nu}$	1.5×10^6 y	—	—
$^{60}_{27}\text{Co} \rightarrow ^{60}_{28}\text{Ni} + e^- + \bar{\nu}$	5.3 y	1332.5 1173.2	100.0 99.9

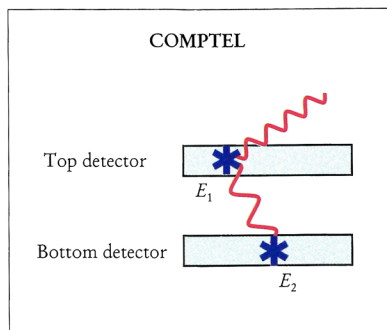
When two processes per decay are listed, it means that both processes put the nucleus into the same excited state. For the positron beta decays, $n = 2 - 1.5 f$, where f is the fraction of positron annihilation occurring through positronium formation.

When two line energies per decay are listed, it means that the nucleus de-excites by emitting two gamma rays, one after the other.

The iron-60 decay does not produce interesting gamma-ray lines, but is listed because it is the starting point for cobalt-60 decay, which is observable, and because its half-life is the dominant one.

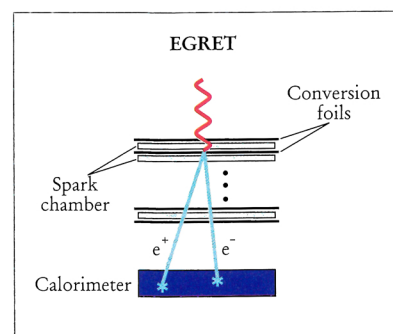
Box 1: Instrumentation

The instrumentation used for gamma-ray astronomy is similar to that found in the physics laboratory. Examples of three of the Compton and Granat instruments follow:



ter being Compton scattered (depositing energy E_1) in the top detector, incident photons are absorbed (at an energy E_2) in the bottom detector. By measuring the two energy deposits, the incident direction of each photon is determined to lie within a circle on the sky. For a point source, the circles for all photons overlap at one spot on the sky. Analysis techniques such as maximum entropy enable sky maps to be made.

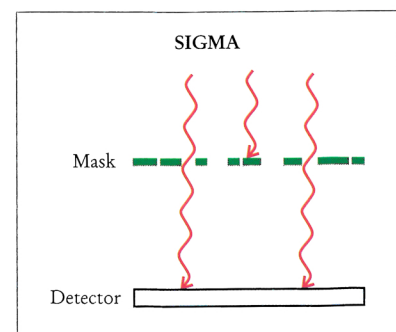
▷ Compton's Energetic Gamma Ray Experiment Telescope



(EGRET) relies on electron-positron pair production of the incident gamma ray in thin conversion foils made of tantalum. Then, the pair is tracked through a wire spark chamber to determine the photon arrival direction and is

finally absorbed in a thick sodium iodide scintillation detector. The foils are interleaved with the layers of the spark chamber. The thick bottom detector measures the total energy and is called the calorimeter. Upward-moving background events are rejected by a time-of-flight system.

▷ Granat's Sigma telescope images the low-energy gamma-ray sky with a coded mask. The mask is located 2.5 meters above the sodium iodide Anger camera detector and has 1-centimeter sized tungsten occulting elements. The detectors measure the shadow pattern of the incident gamma rays cast by the mask. This shadowgram is then processed



through an inversion algorithm based on the mask pattern to map the sky. The angular resolution of the telescope is 17 arcminutes.

lines from SN 1987A. A tremendous amount of information was learned from those observations.

The lines and scattered continuum x and gamma rays were detected earlier than predicted by the models of the day, which indicated that the inner layers of the ejecta containing the ^{56}Co had been mixed into the outer layers. Also, the gamma-ray lines were broader than expected and had more redshifted than blueshifted components. Therefore, more receding than approaching ejecta must have been produced. And the ejecta must have been clumpy, since a clear line of sight was required to see the receding ejecta at all.

Although the ^{56}Co lines from SN 1987A had died away by the time of Compton's launch, the OSSE instrument did detect the 122 keV line from the longer-lived ^{57}Co . Again, important things were learned about the supernova. The strength of the ^{57}Co line showed that the ratio of synthesized ^{57}Ni to ^{56}Ni was 1.5 ± 0.5 times the ratio of iron-57 to iron-56 in the Sun. Early claims of relatively bright infrared and optical emission from SN 1987A at late times had been thought to be due to reprocessed photons from the $^{57}\text{Ni} \rightarrow ^{57}\text{Co} \rightarrow ^{57}\text{Fe}$ decay chain, but that would have required a $^{57}\text{Ni} / ^{56}\text{Ni}$ ratio of about five times the ratio on the Sun—which is clearly ruled out by the gamma-ray line observations. The beauty of the gamma-ray observations is that they make possible the direct detection and location of the synthesized nuclei.

Moving up in half-life, the ^{44}Ti line provides a way of finding obscured supernovae that occurred in our Galaxy over the past several hundred years. By comparing our Galaxy with others, we know that its supernova rate should be about 2.5 per century. The reason that only two—or possibly three—have been seen by people over the past several hundred years (Tycho's supernova in 1572, Kepler's in 1604 and possibly Cassiopeia A in 1667) is that most occurred far enough away in the Galactic plane that interstellar gas and dust obscured the optical radiation. Gamma rays, by contrast, can easily penetrate the entire Galactic disk and should uncover these previously hidden events, which should still be glowing in the light of radioactive ^{44}Ti .

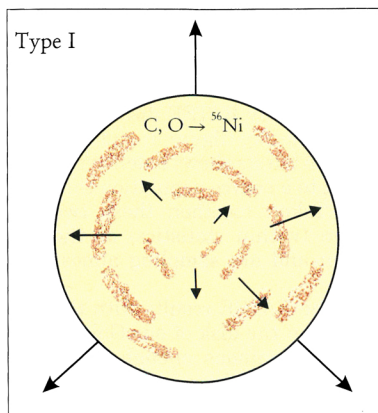
A favorable omen for this search is that COMPTEL has detected the 1.157 MeV ^{44}Ti line from Cas A. The flux in the line is about 4×10^{-5} photons $\text{cm}^{-2} \text{s}^{-1}$, which corresponds to a total mass of ejected ^{44}Ti of about $2 \times 10^{-4} M_{\odot}$, where $M_{\odot}$ is the Sun's mass. Though somewhat high, this yield is not inconsistent with theoretical calculations of ^{44}Ti nucleosynthesis through the explosive burning of silicon.

Finally, another gamma-ray line diagnostic is the 1.8 MeV line from the long-lived ^{26}Al radionuclide, which traces the sites of nucleosynthesis in the Galaxy over the past million years. Figure 1 shows the first all-sky map made in this line emission by COMPTEL. It confirms the Galactic nature of the emission, as the Galactic ridge dominates the emission. But instead of the smooth ridge of emission expected from steady nucleosynthesis in thousands of individual events, concentrations of emission appear in several specific regions—namely, the Cygnus region, the Vela region and a sharp feature along the Carina arm. There is also some emission at intermediate latitudes. In this light, the Galaxy's spiral arms disclose their presence, supporting the idea that massive stars and their supernovae are the major contributors to the ^{26}Al emission. Mapping the distribution of massive stars in the otherwise occulted inner regions of the Galaxy now seems possible.

Galactic black holes

One of the outstanding discoveries of space astronomy has

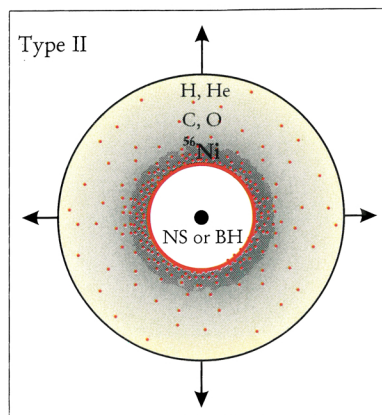
Box 2: Supernovae



Astronomers distinguish two classes of supernovae, Type I and Type II, based on the presence or lack, respectively, of hydrogen lines in their spectra. The following approximate characteristics pertain:

▷ **Type I Supernova.** Progenitor star: white dwarf accreting matter from a normal companion star. Progenitor mass: about $1 M_{\odot}$. Explosion mechanism: nuclear instability of white dwarf. Amount of radioactive material synthesized: $0.5\text{--}1.0 M_{\odot}$. Ejection velocities: $5000\text{--}10\,000 \text{ km s}^{-1}$.

▷ **Type II Supernova.** Progenitor star: supergiant star. Progenitor mass: greater than about $8 M_{\odot}$. Explosion mechanism: gravitational instability of inner core when nuclear fuel is exhausted. Amount of radioactive material synthesized: about $0.1 M_{\odot}$. Ejection velocities: about 1000 km s^{-1} .



been that closely separated binary stars release an enormous amount of energy (up to 10^6 times that of the Sun) in the form of x and gamma radiation. In those systems, a collapsed star (a neutron star or a black hole) accretes matter from its normal, less-evolved stellar companion.

The quest to understand such systems began in 1962, when rocket-borne instruments detected copious x rays from a source known as Scorpius X-1. Following more observations, it emerged that Sco X-1 is a nearby (about 1 kpc distant) binary system consisting of a neutron star and a normal star. Further, we now know that the accreting material forms a massive ring of plasma around the compact star (an accretion disk), which is heated to very high temperatures by frictional or magnetic dissipation in the disk. The inner part of the disk releases intense thermal radiation in the x-ray band. Gamma rays are thought to be produced by the Compton upscatter process in which hot—that is, fast-moving—electrons near the compact object scatter and kick the abundant x-ray and ultraviolet photons to higher energies.

The specific kind of compact star involved—whether it is a neutron star or a black hole—gives rise to an interesting difference in the gamma radiation. For a neutron star, low-energy x-ray emission from the star's surface cools the electron population in the accretion disk near the central, compact object. As a result, much of the gamma-ray production is impeded. For a black hole, no radiation escapes from the central object and Compton upscattering flourishes. Therefore, the presence of gamma rays that extend to high energies can be a signature of black holes.

Almost all the known black hole systems produce strong and variable gamma-ray emission. In systems with low-mass (about $1 M_{\odot}$) companion stars, huge outbursts called x-ray novae are observed. The physical mechanism for the outbursts is believed to be instabilities in the accretion disks that cause episodes of high mass accretion.

With its currently unique capability to produce arcminute images of the gamma-ray sky, Granat's Sigma telescope gives us the opportunity to find accreting stellar black holes and neutron stars by precisely locating them on the celestial sphere. Among the ten black holes detected by Sigma, seven are particularly interesting in that they feature transient temporal behavior.

Nova Muscae 1991 was the first of this new class of black hole novae whose soft gamma-ray emission was studied by Sigma. For one week, this object was the brightest source in the gamma-ray sky: On 20–21 Janu-

ary 1991, it underwent an eruptive episode that appeared in the form of a spectral feature centered around 500 keV. The proximity of this line to the electron-positron rest mass suggested that Nova Muscae 1991 was the site of an enormous positron annihilation event.

In the following months, after having faded below the Sigma detection threshold, the source was studied extensively in the optical waveband. In quiescence, it became possible to observe the low-mass stellar companion and to detect the orbital Doppler shift of its spectral lines. A lower mass limit of $3.1 M_{\odot}$ was established for the unseen compact component. Since neutron stars with masses greater than about $2.5 M_{\odot}$ cannot withstand gravitational collapse, this $3.1 M_{\odot}$ lower limit suggests the presence of a black hole. More such novae have been observed by Sigma and Compton, and they all bear the signatures of accreting stellar-mass black holes.

From 1990 until 1996, Sigma performed a deep survey of the central region of the Galaxy, which led to the identification of fifteen sources active above 35 keV. Five of them are classified as black hole candidates on the basis of their spectral behavior. Except for Nova Ophiuchi 1993, a bright foreground black hole nova, the other four black hole candidates actually belong to the Galactic bulge, a spherical concentration of stars in the central core of the Galaxy. Because of their transient behavior, two of them are thought to be black hole novae. (See figure 2.) The peak luminosities of these two Galactic bulge novae were observed to be quite similar.

Another interesting source detected by Sigma in the Galactic bulge is the famous black hole candidate 1E 1740.7–2942. (See PHYSICS TODAY, March 1991, page 17.) Thanks to correlated observations performed with Sigma and the ground-based Very Large Array (at radio wavelengths), this source was identified with a peculiar radio source that features a double-sided jet structure emanating from a compact core.³ Since it exhibits two basic properties of quasars—black holes and radio jets—1E 1740.7–2942 is sometimes referred to as a microquasar.

Several other Galactic black hole gamma-ray sources have now been found to have jets in the radio waveband. Recent analysis of x-ray and gamma-ray spectra of these objects suggests that sources with jets could be those in which a black hole is rapidly spinning.⁴ As the result of observations performed at the two extremes of the electromagnetic spectrum, astrophysicists have found celestial bodies in which they can investigate two of the most intriguing manifestations of Einstein's relativity: gravita-

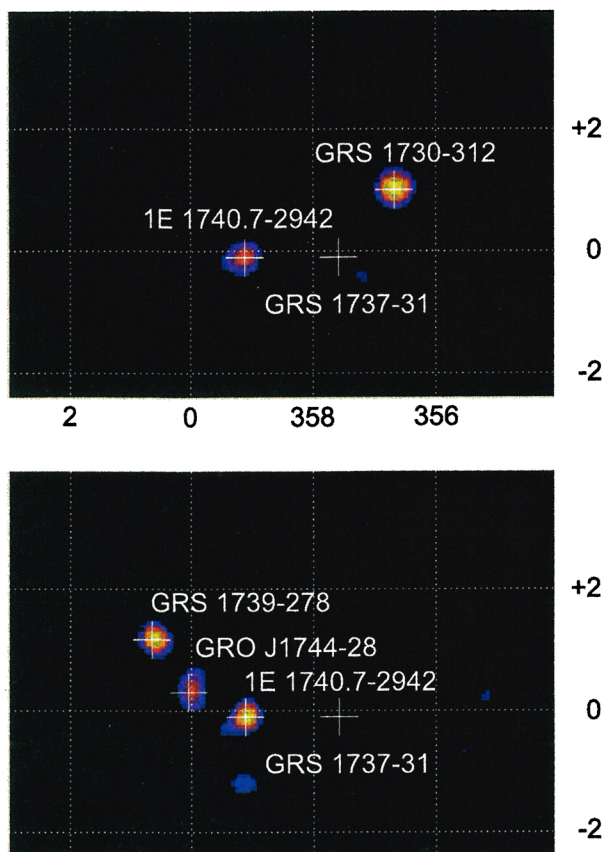


FIGURE 2. SIGMA MAPS IN THE 40–150 KEV BAND of the Galactic bulge field, constructed from data collected 22–26 September 1994 (upper map) and from 13–31 March 1995 (lower map). Colors (blue to white) represent the detection confidence level. Galactic longitude, l , increases from right to left; Galactic latitude, b , increases from bottom to top. The persistent accreting black hole identified with 1E 1740.7–2942 is visible in both maps at $l = 359$ and $b = 0$. The upper map illustrates the discovery of the black hole nova GRS 1730–312 (also known as Nova Scorpii 1994b) and the lower one that of GRS 1739–278 (Nova Ophiuchi 1996). Both maps also show the position of GRS 1737–31, a new Galactic bulge black hole nova discovered in March 1997 by Sigma.

tional singularities and relativistic particle flows.

Gamma-ray bursters

Gamma-ray bursters have mystified us since their discovery by the Vela satellites in 1968. These flashes of gamma rays (and x rays) appear throughout the sky about once a day and last from less than a second to several minutes. Peak fluxes in the 50–300 keV band can be higher than 100 photons $\text{cm}^{-2} \text{s}^{-1}$, which greatly exceeds even the brightest steady gamma-ray sources in the sky, such as the Crab nebula, whose flux is 0.1 photons $\text{cm}^{-2} \text{s}^{-1}$. Burst light curves are often erratic, with sharp irregular pulses, although smooth profiles are also observed. In fact, the light curves are amazingly diverse, with each burst having a unique fingerprint.

Two episodes of discovery have tremendously stimulated the field of gamma-ray bursters, which has been one of the hottest in astrophysics for the past six years. The first episode, initiated by Compton, has been playing out

since 1991. The second episode began in January 1997 and is primarily due to the Italian–Dutch BeppoSAX mission. We start first with the Compton discoveries.⁵

The most comprehensive list ever of detected gamma-ray bursts has been compiled by Compton's Burst and Transient Source Experiment (BATSE). So far, more than 2000 bursts have been seen. The key BATSE discoveries are that bursts are isotropic on the sky (figure 3) and that the brightness distribution of the bursts shows a deficiency of weak bursts when compared to a source population that homogeneously fills space. Taken together, these two findings indicate that we are (within statistics) at the center of the burst population and are sampling almost to the edge of the population.

It is difficult to reconcile the BATSE results with the notion that the bursts originate in the disk of our Galaxy. For, if the burst sources were luminous enough to be visible throughout the Galaxy, we would see a concentration along the Galactic plane. And if BATSE is detecting only the nearby sources, then the deficit of weak bursters would be hard to explain without invoking an improvised source density enhancement around the Sun.

The two most popular explanations of the BATSE results have been Galactic halo models in which sources are typically 100 kpc away and release 10^{42} ergs of energy per burst, and cosmological models in which the sources are 2 Gpc (equivalent to a redshift, z , of 1 for a Hubble constant of $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and release 10^{52} ergs per burst. The source objects for the halo models could be high-speed neutron stars that have broken free from the Galaxy's gravitational potential and are flying outward. For the cosmological models, the source objects could be colliding binary neutron stars or other compact stars.

Some support for the extragalactic models comes from studying the spectra and durations of bursts with BATSE. These data show evidence for redshifts and time dilations that are consistent with a cosmological origin.

Another important result from Compton is that some bursts have strong gamma-ray emission that lasts for an hour or more after the main burst is over. In particular, from GRB 940217, Compton's Energetic Gamma Ray Experiment Telescope (EGRET) detected 100 MeV emission for more than 90 minutes. This emission has important implications for the physics of the source: Some mechanism seems to be accelerating or storing high energy particles (to make gamma rays) for long periods after the burst.

New results this year from BeppoSAX have hugely excited the astrophysics community. (See PHYSICS TODAY, June 1997, page 17, and July 1997, page 17.) BeppoSAX is currently the only mission that can locate bursts on the sky with a gamma-ray burst monitor and wide-field x-ray camera and then maneuver the spacecraft to point sensitive x-ray telescopes at the position of the burst. Because the repointings are not immediate (the fastest possible response is five hours), the high-resolution x-ray measurements are delayed, but they are much more sensitive than any rapid x-ray observations to date.

BeppoSAX's great discovery is that bursts can have x-ray emission that lasts for hours and days after the burst and slowly fades away. The fading is critically important because it allows the x-ray detections to be confidently associated with the bursts. So far, fading x-ray afterglows have been found in seven out of about eight bursts examined. Two of these x-ray afterglows were not found by BeppoSAX, but by the proportional counter instrument on the Rossi X-Ray Timing Explorer after being triggered by BATSE.

Following the detection of x rays, the next step is to obtain accurate burst positions (typically with arcminute

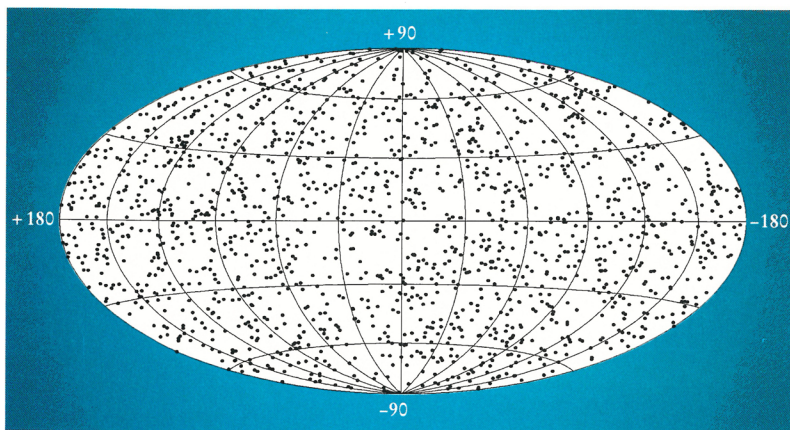


FIGURE 3. BATSE MAP IN GALACTIC COORDINATES of the 1636 bursts detected between April 1991 and August 1996. Each dot corresponds to a single gamma-ray burst. The distribution is consistent with an isotropic burst population. (Map courtesy of BATSE team.)

precision) by analyzing the images from the x-ray telescopes. Counterparts in the optical and radio wavebands can then be sought. Of the eight bursts examined so far, three have definite optical counterparts, one of which also has a radio counterpart.

In this rapidly unfolding story of discovery, most news circulates through International Astronomical Union (IAU) circulars and e-mail. At this point, the preliminary results are as follows.

▷ The first confidently identified optical counterpart was for GRB 970228, which was observed with a ground-based telescope on La Palma, one of the Canary Islands. A faint optical source (21st magnitude in the visible) was found to fade over a period of a week. Observations of the same position by the Hubble Space Telescope found diffuse emission surrounding the counterpart that could be a distant galaxy. No spectra were obtained, however.

▷ Another burst, GRB 970508, also had a weak, fading optical counterpart. For that burst, spectral lines were detected by the Keck II telescope in Hawaii with a redshift of 0.8. If these are lines from gas in a galaxy where the burst source resides, they imply a distance of 1.8 Gpc to the burster.

The new evidence strongly supports a cosmological origin for the bursts.

Active galactic nuclei

It is now widely accepted that the highly luminous (10^{40} – 10^{46} ergs $^{-1}$) emission from the central cores of quasars and other active galactic nuclei (AGN) is produced by the accretion of gas onto a massive (10^6 – $10^9 M_{\odot}$) black hole. The origins of this idea can be traced to suggestions made in the early 1960s by Fred Hoyle and William Fowler⁶ and Edwin Salpeter⁷ of supermassive objects powering quasars and to the work in the late 1960s and early 1970s of Donald Lynden-Bell⁸ and Martin Rees,⁹ who developed the framework of the current AGN paradigm. Results from Granat and Compton give additional support to this picture.

The new gamma-ray data show that there are two distinct classes of AGN defined by their redshift and luminosity distributions and their gamma-ray spectral properties. Sources in the first class, which are generally associated with AGNs classified in other wavelength ranges as Seyfert galaxies, have redshifts of less than 0.06 and 50–150 keV luminosities in the range of 10^{41} – 10^{44} ergs $^{-1}$. As first discovered by Sigma in the case of NGC 4151, these sources display spectral steepening at energies around 60 keV. Their gamma-ray emission is thought to come from the inner accretion disk around the

black hole, and the spectra are quite similar in shape to those of Galactic black holes such as Cyg X-1.

The second class of gamma-ray AGN consists of those associated with blazars—quasars with strong radio emission and flat radio spectra. With redshifts as large as 2.3, these objects have gamma-ray luminosities—assuming isotropic emission—as high as 10^{49} ergs $^{-1}$. In fact, the gamma-ray luminosity of these objects from 20 MeV to 30 GeV is often much higher than their luminosity at other wavelengths.

The discovery of the gamma-ray blazars was made by EGRET in 1991. To date, more than 60 gamma-ray blazars have been identified. Almost all of them vary strongly and flare for periods of days to weeks. A full-sky map of the gamma-ray sky as viewed by EGRET is shown in figure 4. The sources seen off the Galactic plane are the blazars.

Blazars are thought to be AGNs whose orientations are such that we observe them nearly along the axis of relativistic particle jets that emanate from a central black hole. The emission is strongly beamed, which implies that we see only a small proportion (10%) of all systems, and that the actual luminosities are significantly lower than the 10^{49} ergs $^{-1}$ quoted above.

The future

The rapid development of gamma-ray astronomy that has occurred since the launches of Granat and Compton is likely to continue into the future as these missions observe more and as other approved and planned missions get under way. Granat is nearing the end of its life, but will be able to make a few more observations toward the center of our Galaxy over the coming years. Compton's onboard thrusters have recently been fired to raise its orbit enough to keep it in space until at least 2005. All four of the Compton instruments are working and have indefinite lifetimes, except for EGRET, which will run out of gas for its spark chamber in about two years.

Beyond Compton and Granat, there are two major missions being planned. The first is the International Gamma Ray Astrophysics Laboratory—INTEGRAL for short—which is an approved mission of the European Space Agency (ESA) with the participation of Russia and the US.¹¹ Its launch is scheduled for 2001. INTEGRAL's selected payload consists of two main instruments—an imager and a spectrometer—both of which are coded-aperture telescopes similar to Sigma but with improved detector technology.

Making use of cadmium telluride semiconductor detectors and cesium iodide scintillation detectors, INTE-

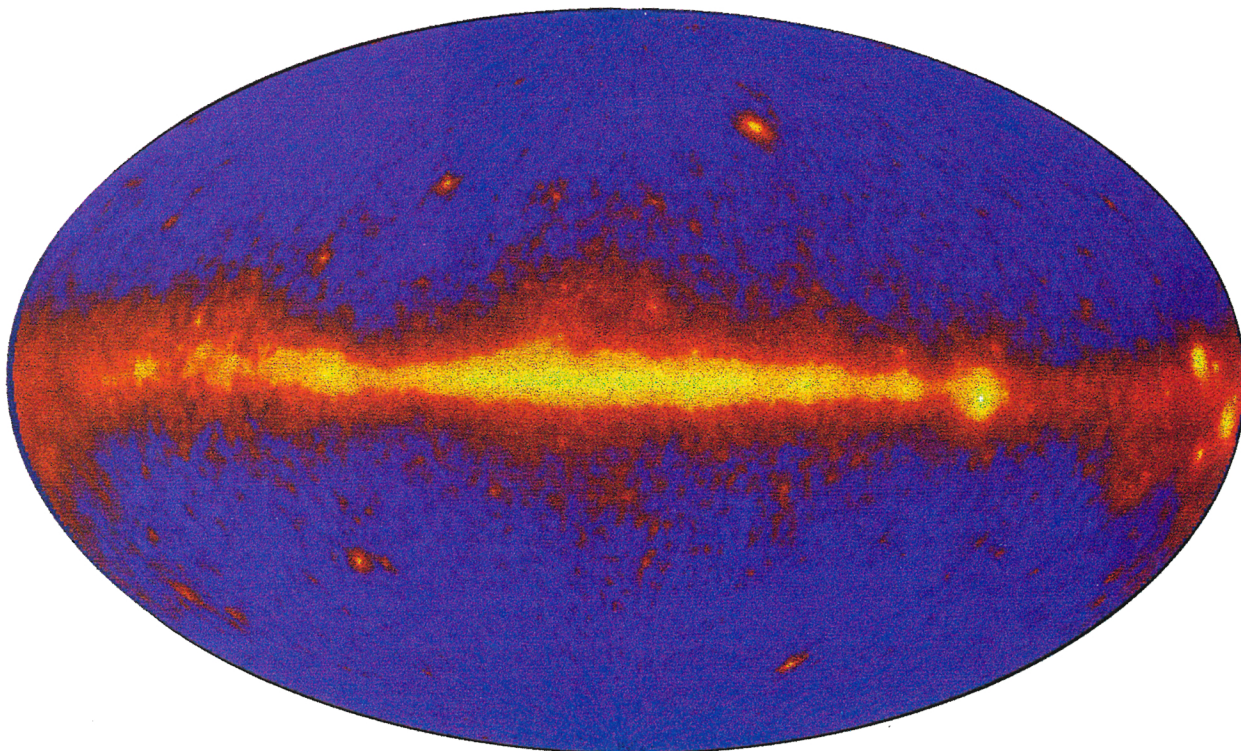


FIGURE 4. EGRET ALL-SKY MAP of the gamma-ray sky at energies greater than 100 MeV. The emission along the Galactic plane is due predominantly to gamma rays from cosmic rays that interact with interstellar gas. Bright sources along the plane include gamma-ray pulsars such as the Crab and Vela. At high Galactic latitude, gamma-ray blazars are seen, as well as a diffuse gamma-ray background glow of unknown origin. In addition to the identified sources in the map, there are more than 150 sources or concentrations of emission that have not yet been identified with known astronomical objects.

GRAL's imager will observe the sky in the 15 keV to 5 MeV band with an angular accuracy close to Sigma's but with much better sensitivity. The spectrometer has an array of cooled germanium detectors operating in the 20 keV to 8 MeV band whose spectral resolving power and line sensitivity are both an order of magnitude better than those achieved by the OSSE spectrometer for narrow-line discrete sources.

The other major future mission is the Gamma-Ray Large Area Space Telescope (GLAST), which is being planned by NASA and the US Department of Energy and will include significant Japanese and European participation. The objective of GLAST will be to build on the successes of Compton's EGRET by observing the high-energy gamma-ray sky from 10 MeV to 300 GeV with high angular resolution and sensitivity.

GLAST's baseline instrument concept features an array of 25 units, each to be made of 12 layers of silicon semiconductor strip detectors. With unprecedented accuracy, these detectors will locate electron-positron pairs produced when high-energy cosmic gamma rays interact with thin metal foils placed between them. A thick array of scintillator detectors will be located directly below the trackers to measure the energy carried by the pair. GLAST will observe over a very wide field of view (45% of the celestial sphere) with a sensitivity that is 50 times better than EGRET's. GLAST has not yet been approved, but would be launched in 2004 according to current NASA planning.

Two smaller missions are also under development. One is the second High Energy Transient Explorer (HETE-2), which is intended to make gamma-ray and x-ray

observations of gamma-ray bursts. The other is the Japanese-US Astro-E, which has a hard x-ray instrument on board covering the 10–700 keV energy range.

With Compton's and Granat's discoveries, gamma-ray astronomy has made a giant leap forward. These new missions promise that the next step will be just as great—maybe even greater.

We gratefully acknowledge comments and assistance from Dave Bertsch, Wan Chen, Roland Diehl, Gerald Fishman, Marat Gilfanov, James Kurfess, Kim Pollock, James Ryan, Volker Schönfelder and Marielle Vargas.

References

1. *Proceedings of the Fourth Compton Symposium*, C. D. Dermer, M. S. Strickman, J. D. Kurfess, eds., AIP Proceedings vol. 410, AIP Press, Woodbury, N.Y. (1997).
2. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, R. Hoyle, *Rev. Mod. Phys.* **29**, 597 (1957).
3. I. F. Mirabel, L. F. Rodriguez, B. Cordier, J. Paul, F. Lebrun, *Nature* **358**, 215 (1992).
4. S. N. Zhang, W. Cui, W. Chen, *Astrophys. J.* **482**, L155 (1997).
5. For results on gamma-ray bursters from BATSE, see C. Kouveliotou, M. F. Briggs, G. F. Fishman, eds., in *Gamma-Ray Bursts: Third Huntsville Symp.*, AIP Conf. Proc. 384, AIP Press, Woodbury, N.Y. (1996), and in two "Search and Discovery" articles in *PHYSICS TODAY*: February 1992, p. 24, and April 1994, p. 17.
6. F. Hoyle, W. A. Fowler, in *Quasi-Stellar Sources and Gravitational Collapse*, I. Robinson, A. Schild, E. L. Schucking, eds., U. Chicago P., Chicago (1965), p. 17.
7. E. E. Salpeter, *Astrophys. J.* **140**, 796 (1964).
8. D. Lynden-Bell, *Nature* **223**, 610 (1969).
9. M. J. Rees, *Nature* **229**, 312 (1971).
10. C. Winkler, *Astron. Astrophys. Supp.* **120**, 637 (1996). ■