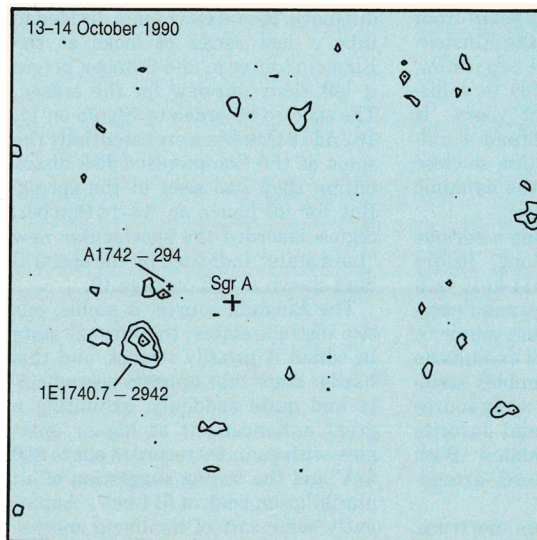


GAMMA TELESCOPE FINDS 'GREAT ANNIHILATOR' NEAR GALACTIC CENTER

For 20 years gamma-ray astronomers have been reporting intermittent evidence of positron-annihilation gammas coming from the vicinity of the center of our Galaxy. Much speculation about what's going on in the hidden heart of the Milky Way has been fueled by these sporadic sightings of 511-keV gammas. (When an electron-positron pair at rest annihilates into two photons, the result is a pair of back-to-back 511-keV gammas.) The most spectacular notion attributed the positrons to the workings of a monstrous black hole of some 10^6 solar masses, residing at the dynamical center of the Galaxy.

Now, it seems, we know for the first time where most, if not all, of the 511-keV gammas from the central region of the Galaxy originate. The newly identified annihilation source may be somewhat more prosaic than a million-solar-mass black hole, but it's quite spectacular nonetheless. In December, a Franco-Soviet collaboration reported that they had fingered an already known, compact x-ray source located some 45 arcminutes from the dynamical center of the Galaxy. For one day in October, while the Soviet orbiter GRANAT just happened to be looking its way, this otherwise respectable x-ray source with the unimaginative name 1E1740.7-2942 was spewing out 511-keV gammas at the rate of 10^{44} per second! That is to say, its energy output in annihilation radiation alone was fifty thousand times the luminosity of the Sun integrated over all wavelengths.

Therefore Marvin Leventhal (Bell Labs) suggests it be called "the Great Annihilator." When it's "on," it is certainly the most intense source of annihilation gammas we know of in the Galaxy. But, for the moment, most people are just calling it "the Einstein source," after the "E" in its name, which indicates its inclusion in the catalog of x-ray sources identified by the 1979 Einstein Observatory satellite. The 511-keV signal seen coming from the Einstein source on that one lucky day (13-14 October 1990) by GRANAT's Sigma telescope



Gamma-ray map of the Galactic center, recorded by GRANAT on the day the Great Annihilator (1E1740.7-2942) was active. The map covers $4.3^\circ \times 4.3^\circ$. The dynamical center of the Galaxy is marked by Sagittarius A. The Great Annihilator is separated from Sgr A by $45'$. The map records energies from 360 to 670 keV, and the contour lines delineate 2, 3, 4 and 5 standard deviations above background.

was intense enough to account, all by itself, for the reports of sporadic annihilation-gamma radiation from the general direction of the Galactic center over the past two decades.

Mapping gamma sources

The Sigma telescope, built by the French Saclay-Toulouse collaboration, is the first real imaging gamma telescope to fly in orbit. It is no easy matter to form an image out of gamma rays. Sigma can locate a compact source to within 1.5 arcminutes, compared with the typical 20-degree collimation of the earlier gamma detectors aboard satellites, balloons and rockets. It is therefore clear that the 511-keV outburst GRANAT witnessed last October came from 1E1740.7-2942, and *not* from the dynamic center of the Galaxy some 45 arcminutes away. (See figure above.) In fact, the Galactic center, marked by the intense radio source Sagittarius A, doesn't show up at all on maps of hard x-rays, not to speak of gammas.

The identification of the annihilation source was first reported at a symposium in Saclay early in December by Jacques Paul¹ (Saclay) and Evgeny Churazov² (Space Research

Institute, Moscow), and then a week later at the Texas-ESO-CERN Symposium on Relativistic Astrophysics, Cosmology and Fundamental Physics in Brighton, England, by Rashid Sunyaev, head of high-energy astrophysics at the Space Research Institute. Pierre Mandrou heads the contingent from the Centre d'Etude Spatiale des Rayonnements in Toulouse.

Now that GRANAT has pinpointed the source of the annihilation gammas from the general direction of Sgr A, the quiescence of the Galactic center itself poses interesting questions. Radio and infrared observations tell us that gas clouds and stars near the center seem to be moving in Keplerian orbits as if under the pull of several million solar masses crowded within 1 or 2 light-years of Sgr A. This incredible mass concentration may very well be a black hole. If so, why isn't it contributing significantly to the positron population of the neighborhood, or even to its lower-energy gamma and x-ray output?

In the wake of the GRANAT observations, 1E1740.7-2942 has joined the exclusive club of the very best "stellar" black hole candidates in the Galaxy—that is to say, putative black

holes with masses ranging from a few solar masses to perhaps a hundred. If the accretion of surrounding material by so modest a black hole can generate plasma temperatures occasionally hot enough to bring forth bursts of positrons, why wouldn't a supermassive black hole at the Galactic center do at least as well?

There are several reasons for believing that the Einstein source is a stellar black hole. Why stellar rather than supermassive? Assuming that we are some 30 000 light-years from the Galactic center and the Einstein source, the 45-arcminute separation between them corresponds to a distance of about 300 light years. It would be hard to understand a million-solar-mass object sitting so close to, and yet so far from, the dynamic center of a spinning galaxy.

The Einstein source was a serious black-hole candidate long before GRANAT witnessed its 511-keV outburst last October. The gamma energy spectrum of the Einstein source in its "normal state," when it exhibits no bump at 511 keV, resembles strikingly the spectrum of the x-ray source Cygnus X-1, the perennial favorite among black hole candidates. Both spectra are unusually hard, extending out beyond 200 keV.

The shape of this gamma spectrum, for both Cygnus X-1 and the quiescent Einstein source, is well described by a "Comptonized disk" model: The source is presumed to be a stellar black hole steadily accreting material from a close, orbiting companion. The material falling down the black hole's very deep potential well forms itself into an "accretion disk" around the black hole, radiating x-rays and gammas as it accelerates and heats up. Many of these photons get kicked up to higher energy by Compton scattering, yielding the very hard Comptonized-disk spectrum that many astrophysicists have come to regard as a useful earmark of black holes.

In the case of Cygnus X-1 and a few other black hole candidates, there is dynamical as well as spectroscopic evidence. The time variation of Cygnus X-1 clearly indicates a binary pair whose compact member is about 8 times as massive as the Sun, well above the allowed maximum mass for a neutron star. GRANAT will be looking for similar evidence of periodicity from the Einstein source.

GRANAT was launched from Kazakhstan into a very high elliptical orbit in December 1989. When its Sigma telescope got its first look at 1E1740.7 – 2942 last spring, it saw the Comptonized-disk spectrum shown in blue in the figure on page 19.

The spectrum extended beyond 200 keV, but there was no evidence of a 511-keV annihilation peak. Nonetheless, the Einstein source, even in this quiescent state, was the most prominent source of high-energy gammas anywhere near the Galactic center. Sigma saw no other significant source of gammas above 100 keV within 4° of Sgr A.

The annihilator in action

By the good fortune that attends diligence, the GRANAT team decided to take a last series of looks at the Einstein source in mid-October, before it left their purview for the season. The spectra recorded by Sigma on 11, 16 and 19 October were essentially the same as the Comptonized-disk distribution they had seen in the spring. But for 20 hours on 13–14 October, Sigma recorded the spectacular new "hard state" indicated by the spectral data shown in red on page 19.

The Einstein source, it seems, has two distinct states: the normal state in which it usually resides, and this harder state that appears sporadically and quite suddenly, exhibiting a great enhancement at higher energies, with gammas recorded out to 800 keV and the strong suggestion of an annihilation peak at 511 keV. Apparently some sort of nonlinear mechanism occasionally makes the accretion plasma hot enough to radiate photons that can make electron-positron pairs when they collide with one another. This implies a plasma temperature in excess of 10^9 K, making it hotter than any other (nonexplosive) system we know of in the Galaxy.

The observation that the Einstein source can switch from one state to the other in a day or two tells us that the source is no larger than a couple of light-days. The betting is that it's a lot smaller than that. The wager would be settled by seeing the source vary on an even smaller time scale.

The GRANAT collaboration has done a preliminary fit (the red curve) to the hard-state spectrum with a model comprising three components: the Comptonized-disk spectrum of the normal state, a narrow annihilation peak at 511 keV, and a continuum that rises to an abrupt high-energy cutoff at 511 keV. This last component corresponds to the three-photon annihilation of the spin-triplet state of positronium. If the electrons and positrons are indeed annihilating one another only from bound positronium states, the statistical predominance of the spin-triplet state should yield a 9:2 preponderance of three-photon annihilations over the two-photon mode. It is the latter annihilation

mode, which can only come from the singlet state, that contributes the monoenergetic 511-keV peak.

This fit is by no means unique. Although the sodium iodide Sigma telescope provides unprecedented spatial resolution, its energy resolution in this range is about 50 keV, much too wide to verify unambiguously the presence of the intrinsically very narrow 511-keV annihilation peak. The fit has to fold in the instrument's energy resolution. Furthermore, not everyone agrees that the low-energy tail of the 511-keV peak should be attributed to positronium. In particular, if the tail is due entirely to 3γ positronium annihilation, one can argue that the 511-keV bump ought to be more prominent than Sigma finds it.

The 511-keV annihilation line had been seen much more unambiguously by germanium detectors looking in the general direction of the Galactic center. The Ge detectors offer much finer energy resolution than NaI, but no one has yet flown a Ge imaging telescope that could specify this annihilation peak's direction of origin with a precision better than 4°.

An encouraging result of the GRANAT observation of 13–14 October is the line flux of 511-keV gammas. The fit yields a flux of 1.4×10^{-3} annihilation gammas per second per cm^2 of detector surface. That agrees very well with the flux of 511-keV gammas observed from the general vicinity of the Galactic center by nonimaging Ge detectors at intervals in 1977, 1979 and 1988 when that region was most active at 511 keV. All this is consistent with the hypothesis that 1E1740.7 – 2942, in its spectacular hard state, is the sole source of annihilation gammas in the neighborhood of the Galactic center, producing 10^{44} annihilation gammas per second.

The fine energy resolution of the Ge observations also tells us that the 511-keV line is neither Doppler shifted nor broadened by more than a part in a thousand. This implies not only that the source is not moving very fast along the line of sight but also that the actual positron-electron annihilations occur some distance from the source of the positrons, where it's cooler and the gravitational field produces no significant redshift. Ge detectors have given some evidence that Cygnus X-1, far from the Galactic center, also sends out sporadic bursts of annihilation gammas.

Twenty years of looking

The search for gamma spectral lines from the Galactic center began in 1970 with Robert Haymes's group at

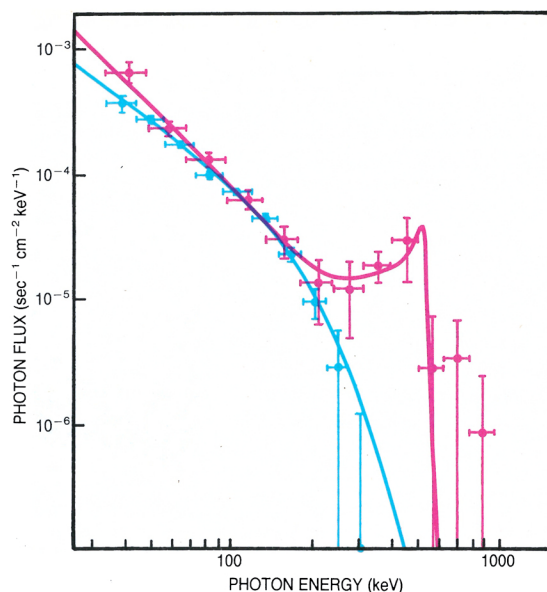
Rice University. They sent up a balloon from Argentina with a non-imaging NaI detector that had a 24° field of view. (The Southern Hemisphere is preferred for such balloon flights because the Galactic center sits at 29° south latitude, as in the full name of the Einstein source.) The Rice group reported seeing a gamma line at 476 ± 24 keV from the direction of the Galactic center. At this point Leventhal got into the business by pointing out that this might well be the 511-keV peak downshifted by the contribution of the three-photon continuum from spin-triplet positronium annihilation and the 90-keV spectral resolution of the Rice detector. With so broad a resolution, the line in question rose only $3\frac{1}{2}$ standard deviations above background.

To clarify the issues raised by Haymes's tantalizing observations, Leventhal organized a Bell Labs-Sandia collaboration in 1977 to fly a high-spectral-resolution Ge spectrometer aboard a balloon from Alice Springs, in central Australia. The result was a 6-standard-deviation spectral peak at 511 keV—right on the money. Without imaging one could only say that there was an annihilation source somewhere within 7° of the Galactic center. But the line flux they measured, $1.2 \times 10^{-3} \text{ sec}^{-1} \text{ cm}^{-2}$, was very close to what GRANAT would see 13 years later from the compact Einstein source. The low-energy tail of the 511-keV peak seen by the Bell-Sandia detector convinced Leventhal, but not everyone, that he had been right in guessing that most of the annihilating occurs in the bound positronium states.

In the spring of 1980 the picture became even more interesting. The Jet Propulsion Laboratory's Ge detector aboard NASA's HEAO-3 satellite, which had seen the gamma source near the Galactic center at full strength a few months earlier, now saw its spectacular intensity diminished by a factor of three. This was the first clear evidence that the source was fairly compact.

At this point theorists Richard Lingensfelter and Reuven Ramaty pointed out that the argument for a compact source was strengthened by the surprisingly large ratio of the 511-keV line flux to the gamma flux observed at higher energies. This also led them to conclude that the positrons were made primarily by $\gamma\gamma$ collisions. Two years earlier they had argued that there was only a diffuse positron source, attributable to β^+ decay of supernova debris.

As the decade progressed, the source became even more fickle. All



GRANAT's spectra of the source 1E1740.7 – 2942 show two different states. The normal spectrum (blue curve) fits well to the Comptonized-disk model (blue curve) of a stellar black hole. The red data are from the one day (13–14 October 1990) GRANAT saw the source in its "hard," Great Annihilator state. The red curve is a fit that includes a 511-keV positron annihilation line and a 3γ positronium annihilation continuum as well as the Comptonized-disk spectrum.

the gamma-detector balloon flights from 1981 through 1984 saw nothing at all from the neighborhood of the Galactic center. Four years later the annihilation source was on again. In 1988 Leventhal joined forces with Bonnard Teegarden's group at NASA's Goddard Space Flight Center. The Goddard group had built a powerful new multicrystal Ge detector called the Gamma Ray Imaging Spectrometer. (Its *imaging* potential has still to be exploited.) GRIS was flown from Alice Springs in the spring and fall of 1988. In the May flight the 511-keV line appeared at about half its 1977 intensity, and in October it was on again full blast. In May 1989 the Alice Springs ballooners flew another multicrystal Ge spectrometer called Hexagone, built by Jim Matteson's group at the University of California, San Diego, in collaboration with the Saclay-Toulouse group. Hexagone found the annihilation source once again on the wane.

Dicke's trick

With all this mysterious waxing and waning, it was high time to pin down the spatial position and extent of the annihilation source. But how does one image gamma rays? Lenses or mirrors won't do at these photon energies. Robert Dicke at Princeton suggested the solution more than 30 years ago, and the Saclay-Toulouse group has been working on its implementation for a decade.

If one shielded an NaI or Ge detector with a mask having a single small aperture, one would have an image-forming pinhole camera. But, like all pinhole cameras, it would let in too

few photons. Dicke's idea was to let in more photons by putting many holes in the mask in a random pattern. One would then use this pattern to perform a computer deconvolution of the resulting superposition of pinhole-camera images on the detector surface. GRANAT's Sigma telescope is the first realization of this "coded mask" scheme in orbit. The obvious next step is to combine the spatial resolution of coded masks with the energy resolution of germanium crystals. That's the plan for GRIS. Next time, it too will fly with a coded mask.

GRANAT, with its high, four-day orbit, is particularly well suited for looking at gammas from the Galactic center. Leventhal is concerned that the Soviets will have to shut GRANAT off for lack of funds. At the Saclay symposium in December he circulated a petition to keep it going. Leventhal is also negotiating for a Soviet-American satellite collaboration with an imaging Ge telescope.

Next month should finally see the shuttle launch of the NASA's much-delayed Gamma Ray Observatory. Although the OSSE spectrometer aboard the GRO is not an imaging telescope, its high sensitivity and year-round access to the Galactic center should make it a valuable monitor of the inconstant behavior of the Great Annihilator.

—BERTRAM SCHWARZSCHILD

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