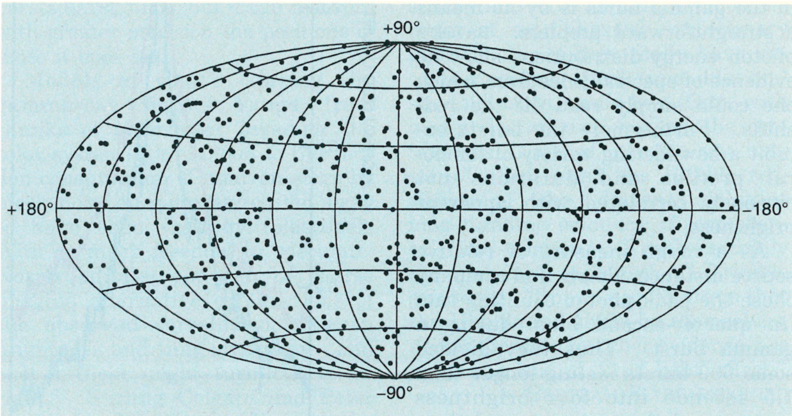
EVIDENCE OF TIME DILATION SUGGESTS GAMMA BURSTERS ARE VERY FAR AWAY

The 1 April issue of *The Astrophysical Journal* brings news of a provocative contribution to the continuing debate about gamma-ray bursters.[1] Astronomers have been looking at these celestial outbursts for three decades—ever since the US military convinced itself that they were not clandestine Soviet bomb tests. But we still don't know for sure whether the sources are local (in our Galaxy) or cosmological (billions of light-years away). Therefore our ignorance of their intrinsic luminosities spans at least 13 orders of magnitude. The *Astrophysical Journal* article is a novel analysis by Jay Norris and colleagues at the NASA Goddard Space Flight Center and the NASA Ames Research Center of data collected by the orbiting Compton Gamma Ray Observatory's Burst and Transient Source Experiment. Though this anlysis brings strong reinforcements to the cosmological camp, no one has as yet declared victory.

The gaping uncertainty over intrinsic luminosity makes it frustrating to speculate about what's causing these sporadic eruptions—typically half a minute long—of photons with energies ranging from tens of keV to MeV. It doesn't help that no one has as yet found long-lived counterparts to these transient events anywhere on the electromagnetic spectrum. Nor, it seems, do we see repeat bursts from the same source.

The question of "repeaters" has not yet been resolved to everyone's satisfaction. The issue is important: Neutron stars are favored source candidates in both the local and cosmological scenarios. But in the latter category, the speculation is about cataclysmic collisions that would generally—though not in all models—preclude the possibility of repetition.



Galactic angular coordinates of 743 gamma-ray bursts recorded by the BATSE detectors aboard the orbiting Compton Gamma Ray Observatory by the end of last year. The equator is the plane of the Galactic disk, with the Galactic center at the origin.

The BATSE data

The Burst and Transient Source Experiment aboard the Compton Gamma Ray Observatory is far more sensitive to faint bursts than any of its predecessors. BATSE, which is one of the GRO's four scientific detector systems, has harvested almost a thousand gamma-ray bursters since the observatory was launched into orbit in April 1991. By the end of that year the apparently isotropic distribution of about 200 bursters detected by BATSE had pretty well ruled out the plane of the Galaxy, or its central bulge, as the primary home of the bursters. (See PHYSICS TODAY, February 1992, page 21.)

With almost five times that many bursters now in hand, the BATSE team still sees no departure from isotropy. (See the figure above.) Most of those who still believe that the bursts are coming from neutron stars in or around the Milky Way have long since abandoned the Galactic disk for an imagined spherical halo enveloping the Galaxy. But because we're off to one side of the Galactic center, enough data from bursters in the halo must eventually show some anisotropy. The larger the halo, the smaller the anisotropy. As more and more data fail to show any discernible anisotropy, this putative Galactic halo is now becoming uncomfortably large.

In addition to the uniform angular distribution of bursts on the celestial sphere, another very important BATSE result has been the distribution of observed intensities. From the start, BATSE has been seeing significantly fewer faint bursts than one would expect from a homogeneous, unbounded distribution of sources in Euclidean space. This striking shortfall at low apparent brightness implies some sort of boundary within the range of observation.

If the sources are local, that boundary might be the outer limit of the Galactic halo. If, on the other hand, they are at cosmological distances, the non-Euclidean character of general relativity provides an effective boundary: The observed shortfall is fitted nicely by a geometrical effect of relativistic cosmology *if* the most distant sources catalogued by BATSE have cosmological redshifts of about $z = 1$. (A value of 1 for the fractional wavelength shift z implies that the photons have been in transit for about half the age of the universe.)

Time dilation

Two years ago Bohdan Paczynski at Princeton and, independently, Zvi Piran at the Hebrew University in Jerusalem suggested that one should look for another relativistic effect at high redshift. If the faintest sources seen by BATSE do indeed have $z = 1$, they pointed out, then it's not just the photon wavelengths that are doubled. Cosmological time dilation should also stretch out the total burst duration and all temporal substructure within a gamma burst by the same factor of $z + 1 = 2$.

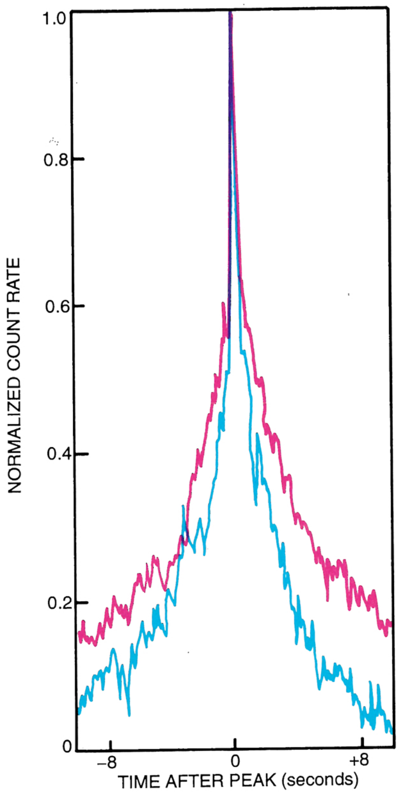
That's what Norris and his NASA Goddard colleagues Robert Nemiroff and Jerry Bonnell, working with Jeffrey Scargle from NASA Ames, set out to look for in the accumulated BATSE data, and that's what they appear to have found. The other authors of reference 1—Gerald Fishman, Chryssa Kouveliotou, Charles Meegan and William Paciesas—are from the BATSE team at the Marshall Space Flight Center that provided the data.

Finding evidence of time dilation in the gamma burts is by no means a straightforward problem. BATSE's photon energy distributions show no evidence of spectral lines from which one could simply read off the redshifts. Furthermore the bursts exhibit a bewildering variety of temporal profiles and durations not obviously correlated with apparent brightness.

As a rough measure of relative source distance, Norris and company chose the peak photon counting rate (in quarter-second bins) during a gamma burst. Thus they divided some 600 bursts lasting longer than 1.5 seconds into four brightness groups, and then concentrated their effort on comparing the 41 brightest bursts (with peak counting rates above 18 000 gammas per second) against the 46 dimmest bursts (with peak counting rates below 2400 gammas per second.) Having taken care to compensate for selection biases, Norris could assume, in the absence of some bizarre correlation between intrinsic brightness and distance, that these two groups were reasonable samples, respectively, of the nearest and farthest bursters accessible to BATSE.

Before they could compare these two extreme groups in detail, Norris and his colleagues had to compensate for the greater relative noise afflicting the fainter bursts. This they did by adding artificial noise to the bright bursts. Now they were ready to look for evidence of cosmological time dilation.

If $z = 1$ is a typical redshift for the bursters in the dimmest category, as suggested by the shape of the population shortfall with decreasing brightness, then the bursts in the brightest category should mostly have z much smaller than 1. Therefore, because cosmological time dilation goes like $z + 1$, the bright bursts should exhibit negligible time dilation, while the temporal features of the faint bursts should be stretched by about a factor of 2 on all time scales. If, on the other hand, the sources are at Galactic rather than cosmological distances, all redshifts will be much smaller than 1 and the most distant bursts should look the same as the closest.



Average temporal profiles of 46 dimmest gamma bursts (red) and 41 brightest bursts (blue). For this comparison, all bursts are normalized to a peak counting rate of unity and shifted in time so that their peaks line up. The plot shows that in the vicinity of the peaks the dimmest bursts are, on average, about twice as wide as the brightest. (Adapted from ref. 1.)

Three tests

To compare the temporal structures of the brightest and faintest bursts on various time scales in search of cosmological time dilation, Norris and company applied three tests:

▷ As a measure of total burst duration they divided the "fluence" (total number of gammas counted above background during the burst) by the peak counting rate (also with background subtracted). This fluence-to-flux ratio, which has the dimensions of time, serves as an "equivalent burst duration." The average equivalent duration for the group of 41 brightest bursts turned out to be 3.2 seconds. For the group of the 46 faintest bursts, the average equivalent duration was 6.6 seconds, just about twice as long! The difference, we are told, is a 3.5-standard-deviation effect.

▷ To investigate structure over a range of time scales, Norris and his colleagues then did a "wavelet transform" analysis, a currently fashionable alternative to Fourier analysis that is particularly useful for compact, aperiodic bursts. In effect, as a measure of the variability of a particular burst on a given time scale, they divided its temporal profile into bins of that size and averaged the absolute values of the count differences between consecutive bins. This they did for eight bin sizes, ranging in octaves from ¼ second to 32 seconds, to produce a "wavelet-amplitude spectrum," the analog of a Fourier transform, for the event. Then they averaged these spectra over all events in a given brightness group and compared the results from the brightest and dimmest groups.

It turned out that the dimmest group showed significantly larger wavelet amplitudes for bin widths from 4 to 32 seconds. To clarify how well this result supports the idea that BATSE is seeing cosmological time dilation, Norris and company compared these averaged wavelet-amplitude spectra with the results of a Monte Carlo simulation in which the faint-burst profiles were created simply by stretching out the bright-burst profiles in time by a factor of 2. And indeed these Monte Carlo spectra with imposed time dilation look very much like the real thing.

▷ To examine structure on time scales shorter than 4 seconds, where the wavelet-spectrum test is largely defeated by noise, the Norris group devised a third, less noise-sensitive means of comparing the brightest bursts with the faintest: After applying various noise-reducing tricks to the data, they normalized all the time profiles to a peak intensity of 1. Then they shifted these normalized profiles in time so that all the maximum counting peaks lined up. Finally they created an average of all the normalized, aligned profiles in a given brightness group.

The figure above shows the result for about 10 seconds on either side of the counting peak. The average profile for the dimmest group (red) is about twice as wide as the profile for the brightest group (blue). As they had done with the wavelet test results, the authors compared this result with the same analysis applied to a Monte Carlo data set with simulated twofold time dilation. Once again the Monte Carlo bursts gave much the same result as the real BATSE data.

Spectral hardness

If the dimmest bursts seem to show time dilation by about a factor of 2 on all macroscopic time scales, the obvious next order of business is to look for the corresponding redshift in the energy spectra. If a gamma from a dim burst has been redshifted by $z = 1$, its energy will be half of what it started out with several billion years ago.

At the January meeting of the American Astronomical Society near Washington, Norris and company showed preliminary spectral data indicating that the energy distribution from the dimmest group of bursters is significantly "softer" (shifted toward lower gamma energies) than that of the brightest group. A detailed paper on the evidence for spectral redshifting consistent with $z = 1$ in the BATSE data is now in preparation.

So the evidence for cosmological time dilation in the dimmest gamma-ray bursters now extends all the way from minutes down to 10^{-20} seconds, the period of a 300-keV gamma. "When Paczynski predicted all this, I was skeptical," Norris told us. "My earlier work had been on models of what might be happening to neutron stars in the Galactic halo to make them emit gamma bursts. So my initial motivation for this work was to prove that gamma bursters are local by *not* finding cosmological time dilation."

Holdout

For University of Chicago theorist Don Lamb it was somewhat the other way around. Nowadays he holds out for gamma-ray bursters very close by—in the Galactic disk itself.[2] But when he and Chicago colleague Jean Quashnock set out last year to take a careful look at the publicly available BATSE data catalog, "we came at it from a decidedly cosmological perspective," Lamb recalls. "We had written a paper suggesting the use of bursters as probes of the large-scale structure of the universe. So it was a shocker for us to find that previously unnoticed correlations in the angular-distribution data indicated repeaters and that bursts of intermediate brightness favored the Galactic plane."

Both of these effects, if true, strongly support the idea that the bursters are local. But Meegan, a senior member of the BATSE team, tells us that a recently completed analysis of a much larger data sample finds no evidence of repeaters or excess events in the plane of the Galactic disk. Lamb, however, remains unconvinced. Disputes of this kind are not uncommon in big science when outsiders who, in the short run, have only limited access to the data find themselves in interpretive disagreement with those who took the data.

A 12 March astronomical telegram[3] from the group that runs the COMPTEL imaging gamma-ray telescope aboard the Compton Observatory adds new grist to the repeater question. The group reports that a burst COMPTEL recorded on 1 March has an angular position so close to that of a burst it recorded last 4 July that it could well be a repeater. COMPTEL is able to see only a small fraction of the gamma bursts BATSE finds, but it can measure with greater precision the positions of those it does see.

Models of what's causing the gamma-ray bursts range from chunks of antimatter invading the solar system's Oort Cloud to the sudden consumption of neutron stars by black holes in galaxies too far away to have been seen by telescopes. With so much freedom to speculate, Norris admits, one can of course imagine alternative explanations of the observed correlation between brightness and time structure—"and one of them might turn out to be right." Stirling Colgate and Peter Leonard at Los Alamos, for example, have recently proposed a model that attributes the gamma bursts to planetoids falling onto neutron stars in the Galaxy.[4] That scenario, Colgate told us, might account for what Norris and company have found in terms of a correlation between evolutionary effects and distance from us. But it's not easy, Norris argues, to find an alternative explanation that gives roughly the same dilation factor on all time scales and also reproduces the isotropy and brightness distribution of the BATSE data.

"Even if the bursters are at cosmological distances," Norris concedes, "it's entirely possible that what we're seeing is complicated by evolutionary effects." (Those would be on a significantly longer time scale than the local evolutionary effects Colgate is talking about.) Virginia Trimble (University of Maryland and University of California, Irvine) recently pointed out that previous attempts to observe the cosmological expansion of space–time have all foundered on the rocks of astrophysical evolutionary effects.[5] "So if they really have unearthed cosmological time dilation," she told us, "it would be a 'first,' with a significance well beyond the contentious issue of gamma-ray bursters." But aren't the Hubble redshifts of the distant galaxies long-standing evidence of cosmological time dilation? "That's certainly the standard explanation," Trimble answered. "But one could argue that the Hubble red shifts by themselves, uncorroborated by other evidence, are just some sort of 'tired light' effect."

—BERTRAM SCHWARZSCHILD

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THE VERY LONG BASELINE ARRAY OPENS ITS EYES

One might expect a compound eye 5000 miles wide to have extraordinary vision, but also to open rather slowly. So it is with the Very Long Baseline Array, a continent-wide interferometer completed last May.

Built and administered by the National Radio Astronomy Observatory, the VLBA is a collection of ten identical radio telescopes (see box) that took seven years to build and cost $85 million. The VLBA, a national facility available to astronomers worldwide, is capable of carrying out very long baseline interferometry in both spectral-line and continuum emissions. The VLBI technique, first applied in 1967,[1] combines recordings of simultaneous observations made at widely separated telescopes as though each observation came from a different part of the same telescope. This single "effective" telescope has an aperture equivalent to the largest separation (longest baseline) between any two of the telescopes. The longest baseline is most sensitive to the smallest structures in the radio source and thus determines the highest resolution for a given wavelength. With additional telescopes on different baselines, the effective telescope becomes sensitive to a range of size scales in the source, and the structure of the source can be determined and mapped. Such maps have been reliably made since about 1980.[2] The VLBA can make VLBI maps with 0.2