

Balloon-borne telescope resolves cosmic far-IR background into starburst galaxies

Their distribution of redshifts manifests the falling cosmic rate of star formation since its heyday some two billion years after the Big Bang.

In 1996 the *Cosmic Background Explorer* (COBE) revealed the existence of a diffuse cosmic far-IR background at wavelengths ranging from below $100\text{ }\mu\text{m}$ to beyond 1 mm . The FIRB is about 30 times fainter than the cosmic microwave background, which was the COBE's primary interest. "The FIRB was our most unexpected finding," recalls COBE team leader John Mather. "It suggested a very dusty universe some 2 or 3 billion years after the Big Bang." Nurseries crowded with newborn stars tend to be particularly dusty. So it was thought that much of the FIRB would eventually be accounted for by thermal radiation from dust heated by visible and UV light from bright young stars in so-called starburst galaxies experiencing high rates of star formation. Because the most massive and luminous stars die youngest, they are greatly overrepresented in newborn populations.

Peaking at about $200\text{ }\mu\text{m}$, the FIRB spectrum encompasses about as much radiant energy in the cosmos as does all the light that escapes galaxies at UV, visible, and near-IR wavelengths. The presumption in recent years has been that sufficiently sensitive telescopes would ultimately resolve the entire spectral range of the FIRB into discrete source galaxies. And indeed much of that task has already been accomplished at wavelengths below $100\text{ }\mu\text{m}$ and above $800\text{ }\mu\text{m}$. But in the intervening submillimeter spectral region, where the FIRB shines brightest, ground-based IR telescopes are largely defeated by atmospheric absorption and, until the launch of the European Space Agency's 3.5-m-diameter *Herschel* telescope on 14 May, no IR space telescope has had adequate imaging resolution above $100\text{ }\mu\text{m}$.

In December 2006, however, the 2-m *Balloon-borne Large Aperture Submillimeter Telescope* (BLAST), circling Antarctica at an altitude of 36 km, captured deep diffraction-limited exposures of significant patches of the extragalactic sky at wavelengths from 200 to $600\text{ }\mu\text{m}$. Now the US-UK-Canadian BLAST collaboration, led by Mark Devlin (University of Pennsylvania), has made public its submillimeter maps and reported its findings on submillimeter-luminous galaxies near and far—out to a redshift z of 3.5. That is, the light from the most dis-

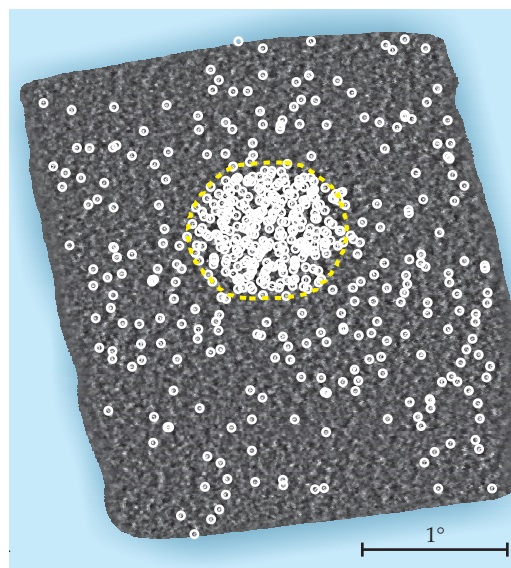


Figure 1. Map of the SNR (signal-to-noise ratio) measured by the *Balloon-borne Large Aperture Submillimeter Telescope* in a patch of sky near the galactic south pole reveals 514 galaxies (white circles) with SNR exceeding 5 at wavelengths from 200 to $600\text{ }\mu\text{m}$. Half of them were found by especially long exposures in the Great Observatories Origins Deep Survey-south field (demarcated by the yellow circle). Earlier deep surveys of the patch at other wavelengths make it possible to determine the redshifts of most of the galaxies found by BLAST. (Adapted from ref. 1.)

tant starburst galaxies identified by BLAST has been en route since just 2 billion years after the Big Bang.¹⁻³

Devlin and company conclude that the entire FIRB can indeed be accounted for by individual galaxies.^{1,2} But beyond simply showing that the background is a sum of discrete sources, one wants to know how the prevalence and fecundity of starburst galaxies have evolved over cosmological time. Documenting that evolution at the hitherto inaccessible wavelengths where the thermal radiation from star-nursery dust at high redshift is brightest should help theorists explain the "cosmic downsizing" puzzle: The aged star populations of the giant elliptical galaxies, the most massive known, seem to imply that they formed very early and suddenly in cosmic history. And IR-ultraluminous superstarburst galaxies (called ULIRGs) were far more prevalent in the early cosmos than they are now.

Dark-matter simulations of galaxy evolution have thus far been unable to reproduce those biggest-first observations. Theorists favor the gradual hierarchical accumulation—from small to big—of the dark-matter gravitational potential wells in which galaxies presumably form. "But the baryonic matter that makes the stars is much harder to simulate than the almost collisionless, nonradiating dark matter," says BLAST theorist Douglas Scott (University of British Columbia). "We hope that the submillimeter observations will tell us

how the giant ellipticals formed." The collaboration has already extracted from its deepest submillimeter map and complementary redshift measurements a history of the falling cosmic rate of star formation since $z = 3$, when the cosmos was $1/(z + 1) = 25\%$ of its present linear size.^{1,3}

Circling Antarctica

The balloon was kept aloft for 11 days, circumnavigating the continent on the steady westward high-stratosphere wind that prevails along the Antarctic Circle in nightless December. Orientation motors in the swaying gondola kept the telescope pointing in the desired directions by referencing guide stars and onboard gyroscopes. The submillimeter light collected by the telescope's primary mirror was separated by a sequence of wavelength-sensitive beamsplitters into three wavelength bins, centered at 250 , 350 , and $500\text{ }\mu\text{m}$. Each of the resultant beams was then focused on its own cryogenically cooled detector—a 300-mK array of heat-sensitive bolometers—to yield simultaneous views of the same 13-arcminute-wide patch of sky.

BLAST's bolometer arrays were prototypes of those developed for *Herschel*. "In keeping with the frugality of flying balloons instead of launching spacecraft, we've piggybacked on the development of submillimeter detectors and beam splitters for *Herschel* by our colleagues at Caltech and Cardiff University," says Devlin. "By way of recompense, our

quantitative results should help in refining *Herschel's* observing strategy."

BLAST spent fully 90 hours scanning and rescanning a 9-square-degree patch of sky, near the galactic south pole, in which an earlier survey by the orbiting 0.8-m *Spitzer* IR telescope had identified many thousands of galaxies glowing brightly at 24 μm . About half of that time was used to take especially long exposures of a circular, 1°-wide field at the center of the rectangular patch (see figure 1). That much-studied knothole through the disk of the Milky Way covers the so-called Great Observatories Origins Deep Survey-south field. The GOODS-south field had already been probed to great depths at x-ray, optical, near-IR, and radio frequencies.

Figure 1 maps the signal-to-noise ratio, combined over the three wavelength bins, of *BLAST's* submillimeter observation of the GOODS-south field and the surrounding wide field. The circles mark the 514 source galaxies detected with signal/noise exceeding 5. Fully half of them were found in the long-exposure deep field. Most of the 514 correspond to galaxies previously identified by *Spitzer* at 24 μm . The converse is not true. Only a small fraction of 24- μm sources are starburst galaxies luminous at submillimeter wavelengths. Some of the others are active

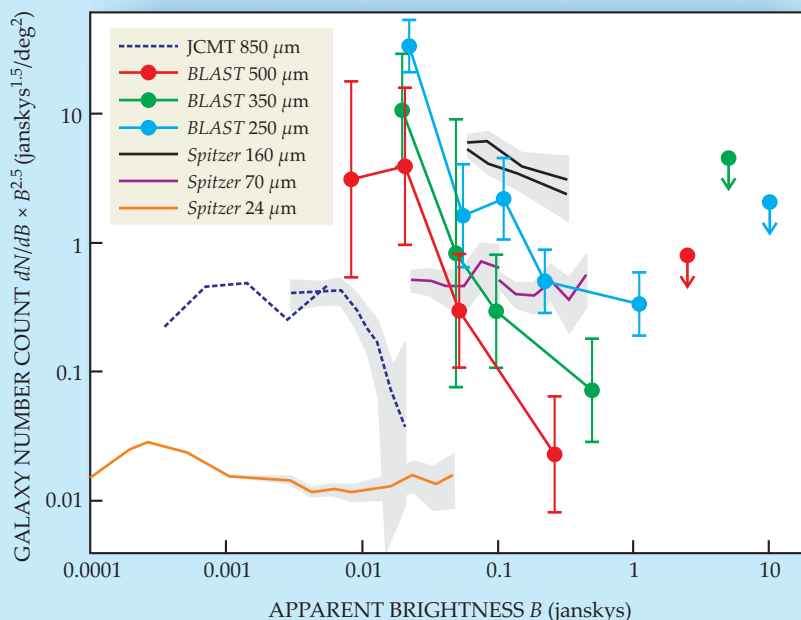


Figure 2. Dependence on apparent brightness B of the differential source count dN/dB of IR-luminous galaxies found (per unit solid angle of sky) by various telescopes at different IR wavelengths. (One jansky = $10^{-26} \text{W m}^{-2} \text{Hz}^{-1}$.) The trivial $B^{-2.5}$ falloff with increasing B expected just from Euclidean geometry and inverse-square dimming with distance is divided out so that local or nonevolving populations would show a flat dN/dB . The steep nontrivial falloffs with increasing B exhibited by the *BLAST* data and the brightest of the galaxies found by the James Clerk Maxwell Telescope imply a dwindling of the number of galaxies in starburst phase as the cosmos has been aging. (Adapted from ref. 1.)

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galactic nuclei with hot spots that glow at much higher temperatures than the 30 K typical of the dust that envelops thriving star nurseries.

From its wavelength-specific maps, the collaboration concludes that starburst galaxies account for just about the entire FIRB in *BLAST*'s submillimeter range. In a starburst galaxy's rest frame, the thermal radiation from the 20- to 40-K dust peaks at about 100 μm . But observed at long distance in the expanding cosmos, that peak wavelength is stretched by a factor of $z + 1$. The redshifts of almost all the galaxies *BLAST* found in and around the GOODS-south field are known from photometric *Spitzer* data or from spectroscopic records at optical or radio wavelengths.

Devlin and company conclude that already at 250 μm , more than half the intensity of the FIRB comes from galaxies with z greater than 1.2, which means epochs earlier than 5 billion years after the Big Bang. At wavelengths beyond 800 μm , the FIRB appears to come predominantly from ULIRGs at considerably higher z .

Probing history

Cosmological redshift is a direct measure of distance and therefore time. But a galaxy's apparent brightness B depends on both distance R and intrinsic luminosity L . The number distribution dN/dB of galaxies counted within the cosmic cone visible through a knothole on the sky can reveal much about galactic evolution. In a static, Euclidean cosmos in which the L distribution is independent of R , an infinitely sharp-eyed observer would find dN/dB decreasing like $B^{-2.5}$ with increasing apparent brightness. That falloff follows simply from geometry and the $1/R^2$ dependence of B .

Therefore in figure 2, which compares the dependence of dN/dB on B from the *BLAST* maps with other observations, the trivial $B^{-2.5}$ dependence is divided out. Thus dN/dB would appear flat for a local or nonevolving population of galaxies. And indeed that's what

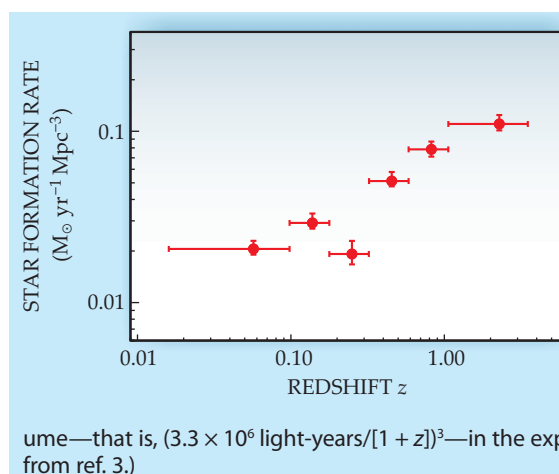


Figure 3. The steadily falling cosmic rate of star formation since redshift 3, about 2 billion years after the Big Bang, is deduced from the *BLAST* observations of galaxies luminous at submillimeter wavelengths and redshift (z) measurements of those galaxies at other wavelengths. The rates are plotted in solar masses per year per cubic megaparsec of comoving volume—

that is, $(3.3 \times 10^6 \text{ light-years}/[1 + z])^3$ —in the expanding cosmos. (Adapted from ref. 3.)

the figure shows for most of the galaxies detected by *Spitzer* at 24 and 70 μm and for the faintest galaxies detected at 850 μm by the James Clerk Maxwell Telescope on Mauna Kea in Hawaii. Devlin presumes them to be local populations seen over a cosmological time span too short to manifest evolution.

But the brighter JCMT galaxies and the *BLAST* galaxies show steep B falloffs that are steepest for the longest-wavelength observations. The pattern suggests that as one looks back in time to higher and higher redshifts, one finds increasingly more and stronger starburst galaxies.

Figure 3 makes more explicit *BLAST*'s history of decreasing star formation rates since the cosmos was 2 billion years old. The falloff is even starker than it looks at first glance. What's plotted is star-formation rate per unit "comoving volume" in the cosmic expansion. At $z = 3$, a given comoving volume was $(z + 1)^3 = 64$ times smaller than it is now.

The Milky Way produces about four new stars a year. In the GOODS-south field one finds far more quiescent galaxies like ours than submillimeter-luminous starburst galaxies. "That tells us that galaxies spend only a small portion of their lives in starburst phases, forming hundreds or thousands of stars a year," says Devlin. To elucidate the

history of profuse star formation and the mechanisms—such as collisions between galaxies—that instigate it, one wants to identify a large number of starburst galaxies for which one can also get redshift data.

British astronomer William Herschel discovered IR radiation in 1800, at age 61, by moving a thermometer around a spectrum of dispersed sunlight. Though the 3.5-m primary mirror of the new IR telescope that bears his name is the largest mirror ever launched into space, it has only three times the collecting area of *BLAST*'s. But the primary mirrors of both telescopes, unlike their cryogenically cooled detector arrays, are exposed to the ambient temperature.

In the environs of the Lagrange point L2 toward which *Herschel* is headed, 1.5 million kilometers behind Earth's night side, its primary mirror can be passively cooled to 80 K. That's even colder than the Antarctic stratosphere. So *Herschel*, in carrying on the search for IR-luminous galaxies, will be much more sensitive than its pioneering predecessor.

Bertram Schwarzschild

References

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Meteor trails track upper atmospheric winds

An old technique gets a makeover using radar that combines high power and interferometry.

At an altitude of 100 km, the density of air is less than a millionth of that on Earth's surface—thin enough that the mean free path of each molecule is on the scale of a meter. The density of ions and electrons is a million times smaller still. Those rarefied conditions make the lower reaches of Earth's thermosphere,

between 85 km and 110 km, a no man's land, inaccessible to the highest research balloons and the lowest orbiting satellites and difficult to probe with radars.

Yet that layer of the atmosphere is transformative. It buffers lower layers against solar x rays and UV; it marks the

transition from diffusive interactions above 100 km to turbulent mixing below it; and it is substantial enough to vaporize billions of meteors—most smaller than a grain of sand—that intersect Earth's orbit every day.

Every year, kilotons of material ablated from those meteors coagulate into