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.

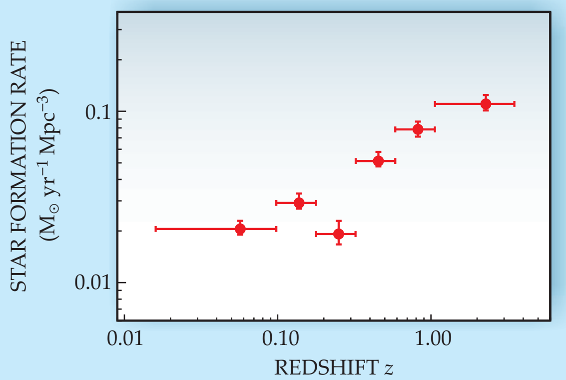

Figure 3. The steadily falling cosmic rate of star formation since redshift 3, about 2 billion years after the Big Bang, is deduced from the *BLAST* observations of galaxies luminous at submillimeter wavelengths and redshift (z) measurements of those galaxies at other wavelengths. The rates are plotted in solar masses per year per cubic megaparsec of comoving volume—that is, $(3.3 \times 10^6$ light-years$/[1 + z])^3$—in the expanding cosmos. (Adapted from ref. 3.)

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 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

1. M. J. Devlin et al., *Nature* **458**, 737 (2009).
2. G. Marsden et al., http://arxiv.org/abs/0904.1205v1.
3. E. Pascale et al., http://arxiv.org/abs/0904.1206v1.

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

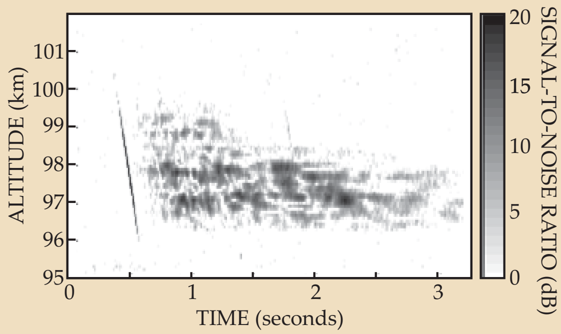

Figure 1. Collisions of a tiny meteor with thermospheric air leave a trail of electrons and ions whose evolution in space and time can be measured. Jicamarca Radio Observatory's large radar array at Earth's geomagnetic equator recorded 5000 reflections per second for each altitude bin. The thin streak represents the "head echo," the leading edge of the ionization front. Once it starts flowing, an initially smooth column of hot plasma (invisible to radar) becomes turbulent as instabilities in the plasma give rise to irregular clumps that align with the magnetic field. Note the appearance of a second, faint head echo 1.5 seconds after the first when another meteor flies through the beam. (Adapted from ref. 4.)

dust that can seed clouds lower down in the troposphere or otherwise influence atmospheric chemistry. Meteoric dust and ions are small enough to be blown about easily in the thin air of the thermosphere. The driving force comes from tidal oscillations—periodic fluctuations in density, pressure, and temperature lower down—and gravity waves (also known as buoyancy waves), which arise from vertical oscillations in stratified air as it flows over mountains, islands, or other topographic features. When the waves rise and break, they transfer energy and momentum to the upper atmosphere (see John Emmert's Quick Study in Physics Today, December 2008, page 70).

Indeed, winds throughout the thermosphere blow at hurricane speeds, up to 150 m/s. And differences in velocity of nearly that magnitude (around 100 m/s) between layers of air separated vertically by just a few kilometers create enormous wind shears. Those values are typical of what's been found from some 400 rocket-based experiments over the past half century. The rockets release luminescent tracers into the thermosphere for ground cameras to track as the tracers drift in the wind.[1]

Climate-circulation models fail to predict the wild swings in velocity from one altitude to another and the amount of momentum carried to the upper atmosphere. Moreover, the rocket experiments are expensive and the data anecdotal: Each launch costs $1 million to probe one wind profile for just a few minutes.

Meers Oppenheim and his colleagues from Boston University, Peru's Jicamarca Radio Observatory (JRO), and Los Alamos National Laboratory now offer an alternative approach[2] that has its origins in another 50-year-old technique. Free electrons produced in the plasma trails of incoming meteors make an ideal radar target. They also work well as wind tracers: The plasma preserves its charge neutrality such that the highly mobile electrons remain closely tied to heavy ions that are swept along in the neutral wind. For decades aeronomers have inferred wind speed based on the average Doppler shift they record from specular echoes, reflections from the trails when their paths lie normal to the radar beam. But those echoes give just one velocity component at one height at one time from each meteor. The averaging required to combine many meteor signals into a wind profile washes out the fine structure.

Larger radar, richer data

Fortunately, very sensitive radar or large enough meteors can free one from reliance on specular echoes. In either case, reflections from any angle that satisfies the Bragg condition will do. Four years ago, and again in 2007, Oppenheim and colleagues gained access to JRO. There, three 1.5-MW transmitters and an array of nearly 19 000 dipole antennas were trained on a narrow part of the sky. The combination is powerful enough to detect the nonspecular signals backscattered all along an ionization trail, including the rich heterogeneous structure that Oppenheim's earlier numerical simulations had predicted should emerge as the

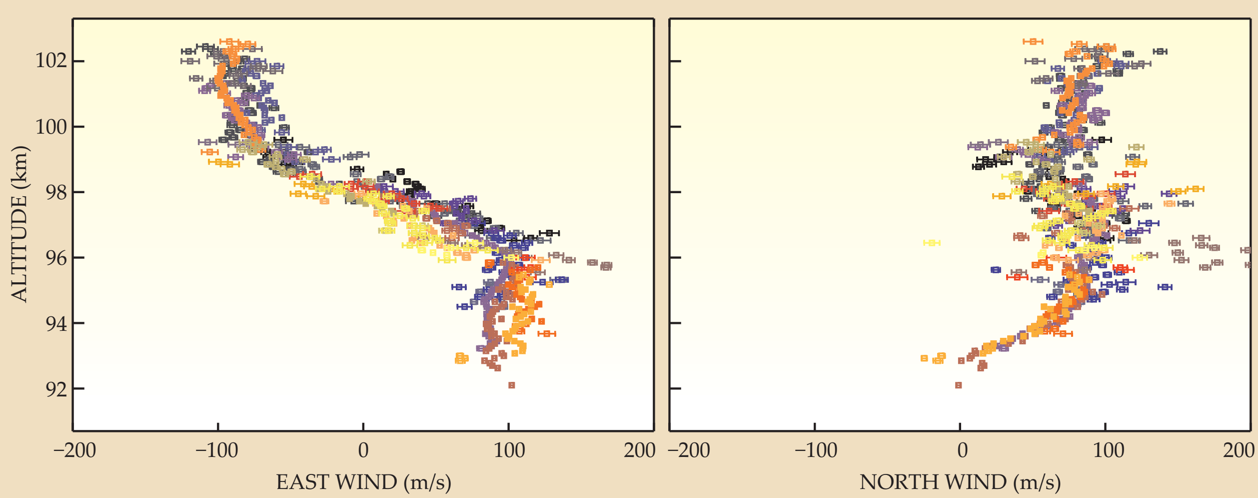

Figure 2. Wind-velocity profiles, compiled from the data of many meteors (each represented by a different color) whose plasma trails intersect the radar beam within minutes of each other. Using interferometry to keep track of the phase difference between different channels in the radar array, one can follow the position and bearing of each part of a meteor's trail over several seconds as it's swept up in the winds. The signals from some larger meteors can persist beyond 20 seconds. (Adapted from ref. 2.)

plasma disperses.[3,4]

Figure 1 captures the first few seconds in the evolution of a single trail detected 12 July 2005. The thin streak is the front edge of the plasma created during the few hundred milliseconds the meteor takes to plow through the lower thermosphere. Behind the ionization front, hot gas and electrons flow too smoothly for radio waves to coherently reflect changes in the dielectric constant, so the signal vanishes. But plasma instabilities driven by the density gradient and by complex electric fields set up between magnetized electrons and collisionally demagnetized ions quickly give rise to turbulence and irregular clumps of plasma that align along Earth's magnetic field.

Peru's JRO sits directly on the geomagnetic equator. Its radar points nearly perpendicular to the field lines, so the scattering cross section is optimal for detecting that blobby aftermath. Also important for observations, JRO's antennas can be partitioned into a phased array capable of interferometry. By beating the phase of one radar channel against another, the team measured not just the position of each part of a plasma trail over time but also its bearing. To get the velocities, they fit the slope of the phase differences between the channels as a function of time.

The interferometry measurements allowed the researchers to build a complete vector profile of the horizontal wind speeds at different altitudes with a spatial resolution less than a few hundred meters—comparable to that from rocket tracer experiments. The profile can also be derived repeatedly on a nearly continuous basis. During the hours before dawn when Earth runs headlong into meteors, JRO detects one every half second or so. Figure 2 shows the proof-of-principle plots of wind vectors constructed from data of many meteors intercepted over several minutes one night in 2005.

Remarkably, Oppenheim's team waited nearly four years before analyzing its interferometry data. "Plasma instabilities were on my mind, not winds," Oppenheim confesses. "I never guessed that the changes in phase from what is mostly turbulence would be as clean as they turned out to be."

Mark Wilson

References

1. M. F. Larsen, *J. Geophys. Res.* **107**, 1215 (2002), doi:10.1029/2001JA000218.
2. M. M. Oppenheim, G. Sugar, N. O. Slowey, E. Bass, J. L. Chau, S. Close, *Geophys. Res. Lett.* **36**, L09817 (2009), doi:10.1029/2009GL037353.
3. M. M. Oppenheim, L. P. Dyrud, A. F. vom Endt, *J. Geophys. Res.* **108**, 1064 (2003), doi:10.1029/2002JA009549.
4. M. M. Oppenheim, G. Sugar, E. Bass, Y. S. Dimant, J. Chau, *Geophys. Res. Lett.* **35**, L03102 (2008), doi:10.1029/2007GL032347.

Resonant radio waves rotate tokamak plasma

An experiment at MIT's Alcator tokamak has demonstrated a technique that could make fusion plasma easier to confine.

In its original and still-unrealized conception, a tokamak traps steadily fusing plasma within a helical magnetic field that winds around, and delimits, a bagel-shaped confinement vessel nested inside a metal chamber.

Two components create the helical field: a toroidal component, which arises from ring-shaped magnets positioned at regular intervals around the chamber, and a poloidal component, which arises from the circulation of the plasma's fast electrons and slower ions.

Confinement can never be perfect because Coulomb collisions cause electrons and ions to drift across magnetic field lines.

In the mid-1990s, plasma physicists began to realize that a range of instabilities could be mitigated if the current-carrying plasma were made to rotate inside the chamber. The stabilization would be more effective if the rotation had shear, for then it could tear apart nascent eddies before they grew to burst-out size.

Experiments at various tokamaks around the world found that plasmas rotate in response to the various methods used to heat them. That finding is not perhaps surprising. At tokamaks, fusion temperatures are reached by irradiating the plasma with energetic beams of neutral particles or with radio waves.

Without any deliberate rotation-inducing intervention, Alcator plasmas rotate at speeds of about 10 km/s. Now, a team from MIT led by Yijun Lin and John Rice has demonstrated a method for spinning a plasma twice as fast.[1] The method relies on transferring momentum from VHF radio waves via a resonance to minority helium-3 ions seeded in the plasma.

Exactly how the waves rotate the plasma is unclear. Nor do the MIT researchers know how much stability the waves bestow. Even so, the method looks promising for helping to stabilize ITER, which in a few years' time will become the world's biggest tokamak.

Heating plasma

An operational run at a current research tokamak or a future tokamak-based power station begins with the injection of fuel at high vacuum into the chamber. Because of its favorable cross section, a mixture of deuterium and tritium is the likely choice for tokamak reactors. For tokamak experiments, deuterium is typically used.

Despite starting off at room temperature, the fuel contains a modest fraction of free electrons. When a huge electromagnet at the center of the chamber is switched on, the free electrons in the plasma respond like the conduction electrons in the secondary coil of a transformer: They flow. The magnetic field corrals the electrons well enough that they slam into neutral ions, setting off an avalanche of ionization and setting up the so-called plasma current, which gives rise to the poloidal confinement field.

The collisions that ionize the plasma also heat it—to about 10 million K. At that temperature, the plasma's electrical conductivity is about the same as copper's. Attempts to further heat the plasma stall because the plasma's conductance rises with temperature as $T^{3/2}$.

That dependence is unfortunate, because an additional order of magnitude in temperature is needed to ignite the fuel and sustain fusion. To supply the extra heat, two principal methods are employed. The first is to fire into the plasma a high-energy beam of neutral atoms. Being neutral, the atoms are not deflected by the confining magnetic field. But once they penetrate the plasma, they collide with electrons, become ionized, and give up their energy. It was with neutral-beam injection that two tokamaks—JET outside Oxford, England, and TFTR outside Princeton, New Jersey—achieved fusion temperatures in the 1990s.

The other method is to irradiate the plasma with radio or microwaves. Energy transfer occurs at one of three principal resonant bands: ion cyclotron