

Infrared Detectors for Astrophysics

Recent advances in materials, system architectures, and microfabrication have spawned a new generation of detectors that can image infrared sources at speeds and spatial resolutions orders of magnitude greater than was possible just a decade ago.

Paul L. Richards and Craig R. McCreight

Covering wavelengths between 1 micron and 1 millimeter, the IR region of the electromagnetic spectrum contains a wealth of astronomical information. That range covers the radiation from dust, protostellar regions, planets, and the cosmic microwave background (CMB), as well as the vibrational and rotational spectra of molecules and solids. Such sources can radiate at many different IR wavelengths.

Astronomical IR measurements provide a powerful way to extend our understanding of fundamental astrophysical problems. Broad spectral-band IR instruments measure the dominant mechanisms for radiant energy transfer in the universe and provide insights into the formation and structure of planets, stars, galaxies, and galactic clusters. They also measure the geometry, structure, and content of the early universe. In addition, narrow-band spectroscopic observations provide information about the composition, density, temperature, and velocity of many sources that emit in the IR.

Ground-based observations and major space missions are currently producing vast amounts of data from radiation in this rich part of the spectrum. Most observations are made with detectors that convert the oscillating photon field to a steady output signal, which is then amplified. Major industrial development efforts based on investments in military technology have produced mature arrays with ever larger numbers of detectors for astronomy at IR wavelengths shorter than 40 μm . Arrays produced for longer wavelengths—mainly from national laboratories or universities—are less developed, but improving rapidly. Because of advances at both shorter and longer wavelengths, the speed of many astronomical observations has increased by orders of magnitude. Much progress is also being made on the heterodyne mixers used to measure spectral lines. Those devices mix the frequency of the incident photons with a local oscillator to produce a difference frequency low enough to be amplified. A detector then produces a steady output voltage.

Paul Richards is a professor in the graduate school and a member of the department of physics at the University of California, Berkeley. **Craig McCreight** is chief of the project technology branch at NASA's Ames Research Center at Moffett Field, California.

To appreciate the amount of information that the IR band can now provide using modern-day detectors, see figure 1. The multiwavelength IR image from NASA's *Spitzer Space Telescope* tells a very interesting story, not revealed in the optical image taken at the Cerro Tololo Inter-American Observatory in Chile. Centarus A is an elliptical galaxy that has appar-

ently captured a smaller spiral galaxy. Simulations show that a disk of interstellar dust and gas freed from the spiral during the collision can become folded and twisted, so as to produce the parallelogram shape seen at the center. Extremely strong radio emission from the center of Centarus A indicates the presence of a supermassive black hole, which may be feeding on the remnants of the spiral. The IR image combines data at wavelengths from 3.6 to 24 μm to emphasize the emission from dust rather than from stars.

Techniques similar to those of optical astronomy find application throughout the IR. The spectral resolving power R , defined as the average wavelength divided by the wavelength interval, varies widely. Band-pass filters and arrays of directly illuminated, closely packed detectors are used on large telescopes to image thermal sources with R between 3 and 5. Gratings or interferometers are included for spectroscopic imaging with R from 10^3 to 10^4 . The goal is to make diffraction-limited observations, with many pixels and over a range of wavelengths, limited only by photon noise from the astronomical signal in the band of interest. Cooling the filters, spectrometers, and baffles to cryogenic temperatures minimizes the background signal from unwanted blackbody radiation.

At longer IR wavelengths, radio techniques are more common. Heterodyne down-converters followed by multi-channel RF filter banks are used for high-resolution spectroscopy (with R from 10^5 to 10^6) and for aperture-synthesis interferometry, in which the signals from a number of telescopes combine to create high spatial resolution.

Some properties of an array help produce high-quality images: a large number of high-sensitivity pixels, for high-speed mapping of signals from different regions of the sky; a precise registration of those pixels to simplify reconstruction of spatial images; and temporal stability, which allows astronomers to assess backgrounds accurately. Detector arrays are packaged into instruments—variously called cameras, photometers, spectrometers, or receivers—for use on telescopes. Such systems may be dedicated to single observations or available to the community in a user facility.

The scope of this article encompasses detectors for important astronomical instruments that are in use or under development. The developments of very new detector concepts are not reviewed here.^{1,2}



Figure 1. Colliding galaxies. Two views of the elliptical galaxy Centarus A as it swallows a smaller spiral galaxy. In the visible image (left), light from stars produces the dominant, bright halo. A dense band of foreground dust blocks the light from stars behind it. The IR image (right) reveals more complexity—it is the first picture of the interior structure of this galaxy. Different colors represent different spectral ranges: Emission near 4 μm from the stars is shown in blue; the green regions are associated with emission at 8 μm from complex organic molecules in the dust; and the red component, near 24 μm , is thermal radiation coming from the dust itself, warmed by starlight. The bands of dust within the image appear in yellow, as the red (dust) and green (organics) blend. Star-forming regions, where thermal emission from warm dust is dominant, appear as bright red dots within the disk. (Visible image courtesy of the National Optical Astronomy Observatory and Eric Peng, Herzberg Institute of Astrophysics/Dominion Astronomical Observatory); IR image courtesy of NASA/Jet Propulsion Laboratory and Jocelyn Keene, Caltech.)

Challenges and opportunities

Absorption and refraction by water vapor and other atmospheric gases restrict ground-based observations to certain wavelengths up to 30 μm and beyond 300 μm , using IR telescopes located at high, dry sites. Adaptive optics systems, which correct for atmospheric scintillation, are becoming important for short-wavelength measurements on large ground-based telescopes (see PHYSICS TODAY, February 2003, page 19). Thermal emission from measurement systems, though, is an important limitation. Space platforms using cooled optics are, by comparison, much more powerful.³

Many different materials and modes of operation are required to ensure that detectors are optimized for each wavelength range. As the signal wavelength of interest in-

creases, semiconducting arrays of photon detectors give way to semiconducting and superconducting arrays of thermal detectors. Similarly, semiconducting photon heterodyne mixers give way to superconducting thermal mixers and then superconducting junction mixers. Box 1 illustrates the sensitivity of various technologies to regions of the IR spectrum and the relevance of those materials to several dominant astronomical sources, from the visible to the microwave. Box 2 describes the physical mechanisms used to detect such sources.⁴ For the shorter-wavelength end of the IR spectrum, most instruments are based on photon detectors. At the longer-wavelength far-IR end, bolometers sensitive to the heating caused by photon absorption are used.

Photon detectors (1–200 μm)

Photovoltaic (PV) arrays of indium antimonide are now well developed to detect wavelengths out to 5 μm . Megapixel-class arrays have been used with great success on many ground-based telescopes, and arrays with 256×256 pixels are performing well on the *Spitzer Space Telescope*⁵ as shown in the table at left. These arrays have high quantum efficiency, low readout noise, and low dark current.

Laboratory tests on 2048×2048 pixel PV arrays of the ternary compound mercury cadmium telluride, $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, are yielding results that surpass even those on *Spitzer*.⁶ The cutoff wavelength depends on the composition fraction x . The HgCdTe arrays are produced by molecular beam epitaxy on lattice-matched cadmium zinc telluride substrates. The absorbing CdZnTe substrate is often removed afterward to extend the short-wavelength re-

Materials and Performance Levels for Detectors on the *Spitzer Space Telescope* and the *James Webb Space Telescope*

Array Type	Spectral Range (μm)	Pixel Count	Dark Current (e^-/s)	Temperature (K)	Noise (e^-)	Quantum Efficiency
<i>Spitzer</i> (2003)						
InSb	2.8–5	131 072	0.5	15	6.8*	0.86
Si:As IBC	5–26	180 224	2.4	6	6.6*	0.55
Si:Sb IBC	14–38	32 768	<40	4	30*	0.25
Ge:Ga	51–106	1024	156	1.5	92*	0.18
Stressed Ge:Ga	140–174	40	500	1.5	280*	0.15
<i>JWST</i> (2011)						
$\text{Hg}_{0.55}\text{Cd}_{0.45}\text{Te}$	0.6–2.3	46 137 344	<0.001	37	5†	0.95
$\text{Hg}_{0.70}\text{Cd}_{0.30}\text{Te}$	2.4–5	20 971 520	<0.001	37	5†	0.95
Si:As IBC	5–28	3 145 728	$\ll 0.1$	7	<19†	>0.7

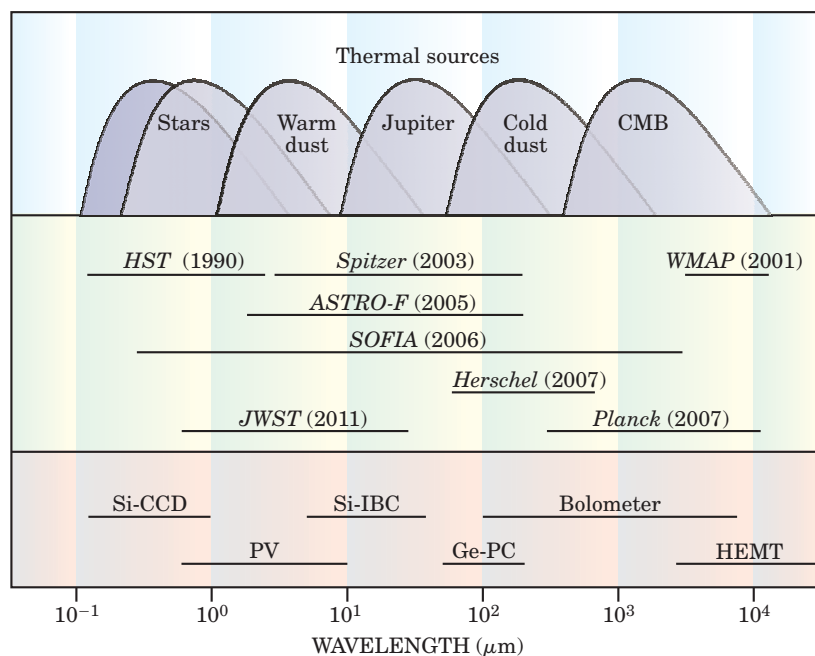
*Read noise only, integrations <200 s. †Total noise, integrations 1000 s.

Box 1. Astronomical Sources, Space Missions, and Detectors

Panels in the figure shown here illustrate major types of astronomical sources that emit from the visible wavelengths to microwaves, current and future space missions designed to collect emission from those sources, and the different flavors of detectors, each sensitive to a different range of wavelengths.

In the top panel, Planck blackbody curves span a range of wavelengths calculated from the objects' representative temperatures. In the visible to near-IR range, stars are represented by blackbody curves for 5000 and 10 000 K; warm dust, in close proximity to stars, by 1000 K; planets, by Jupiter at 120 K; and interstellar dust, heated by starlight, by 20 K. Emission from all of these sources is redshifted to longer wavelengths when they are observed at cosmological distances. The cosmic microwave background, at 2.73 K, is viewed at only one redshift—it is the same in all directions.

Of the missions shown in the central panel, the *Hubble Space Telescope* (HST), the *Spitzer Space Telescope*, and the *Wilkinson Microwave Anisotropy Probe* (WMAP) are now in orbit. *ASTRO-F* is scheduled to launch later this year. The airborne *Stratospheric Observatory for Infrared Astronomy* (SOFIA), which will carry instruments with a wide range of wavelengths, begins flying in 2006. The *Herschel Space Observatory* and the *Planck Surveyor* are scheduled for launch together in 2007. The *James Webb Space Telescope* (JWST) is scheduled to launch in 2011. WMAP, *ASTRO-F*, and *Planck* will produce all-sky surveys. The other missions are designed for smaller surveys and pointed observations. The line below each name indicates the spectral range it is designed to measure. The bottom panel lists the spectral sensitivities of widely used detector technologies: silicon CCD arrays, photovoltaics, impurity-band photoconductors, conventional photoconductors, bolometers, and high-electron-mobility transistors.



sponse into the visible range. This detector technology has reached extraordinary levels of sensitivity, with dark current levels about 0.001 electrons per second and a total noise level of about 5 electrons, integrated over 1000 s. The near-IR instruments on the *James Webb Space Telescope* (JWST) will include 12 such arrays providing 67 million pixels for imaging and spectroscopy. More complete data are shown in the table on page 42, which illustrates the dramatic progress made between major space missions and the trends in array properties as a function of wavelength.

Many ground-based telescopes use megapixel arrays of both InSb and HgCdTe for observations as diverse as sky surveys, spectroscopic studies of star formation, and wide-field photometric imaging. Examples of array-based instruments⁷ are the

NIRC-2 on Keck, the GNIRS on Gemini, the CRILES on the VLT, and the FLITECAM for SOFIA. The image shown in figure 2, obtained using a 16-megapixel array on the University of Hawaii's 2.2-m telescope, illustrates the remarkable resolution achievable in deep, wide-field, near-IR imaging—the image is a single 30-minute exposure.⁸ The earliest generation of single-detector instruments would have required lifetimes to raster over the same area and register even a fraction of the information obtained here.

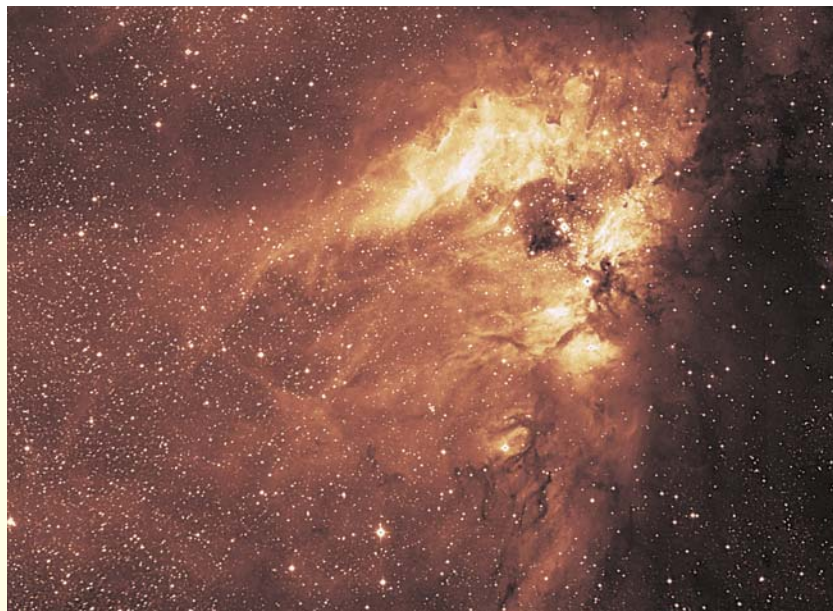


Figure 2. This near-IR image of a region in the nebula M17, dominated by dust and singly ionized hydrogen, was obtained using the University of Hawaii's 2.2-m telescope through the 1.1–1.4 μm transmission window in Earth's atmosphere. Hydrogen recombination lines and starlight scattered by dust make up the dominant radiation sources in this region of the sky. The image shows young dust-embedded stars not readily apparent at visible wavelengths. The 16-megapixel mercury cadmium telluride array is a prototype for the near-IR arrays on the *James Webb Space Telescope*, scheduled to launch in 2011.⁷ (Courtesy Donald Hall, University of Hawaii.)

Box 2. Physical Principles of IR Detectors

Intrinsic (bandgap) photoconductors. In a photon detector, photons with energy larger than a characteristic electronic binding energy create mobile charge carriers that move in a bias field and generate a measurable current in an external circuit. The bandgap of the material sets the maximum detectable wavelength—the long-wavelength cutoff. Shot noise that arises from the dark current due to thermally excited carriers sets a maximum operating temperature. In an intrinsic photoconductor, photo-generated holes in the valence band and electrons in the conduction band create output current until they recombine. This effect is the basis of the extremely important silicon CCD, a detector much used in the visible spectrum but less so in the IR.

Photovoltaic devices. These semiconductor IR detectors are made using p–n junctions. A double layer of charge develops close to the junction to satisfy the requirement that the Fermi energy have the same value everywhere. Photons generate electron–hole pairs that diffuse from a thin absorbing layer toward the field generated by the charge layers. This mechanism is used in solar cells, for instance. Astronomical PV arrays are back-biased to increase the well depth of the pixel and thereby increase its ability to store charge. Arrays made from indium antimonide cut off at a wavelength of $5\text{ }\mu\text{m}$, and mercury cadmium telluride detector arrays perform well out to about $10\text{ }\mu\text{m}$.

Extrinsic (impurity) photoconductors. In a doped semiconductor, photons with energies larger than impurity-atom ionization energies excite either electrons into the conduction band or holes into the valence band. At the high doping densities that are necessary for devices to absorb IR efficiently in thin epitaxial layers, however, the impurity states interact by the Stark effect and form an impurity band. Nominally, a detector using this band would be noisy due to a temperature-independent dark current. In doped silicon photoconductors, though, it is possible to introduce an intrinsic layer of very pure silicon beneath one of the electrodes. This layer blocks the impurity band current yet allows electrons excited to the conduction band to be collected as signal.

When these so-called impurity-band conduction devices are doped with arsenic, they produce excellent arrays for wavelengths between 5 and $28\text{ }\mu\text{m}$. The less well-developed antimony-doped arrays are used out to $40\text{ }\mu\text{m}$. Extrinsic germanium detectors are used at still longer wavelengths, although impurity-band blocking is not well developed in germanium. Astrophysical arrays made from bulk gallium-doped germanium are sensitive out to $110\text{ }\mu\text{m}$. When a uniaxial stress is applied to germanium, it lifts the valence-band degeneracy caused by cubic symmetry and extends the cutoff wavelength to $200\text{ }\mu\text{m}$.

Longer-wavelength photon detectors. Detector physicists are currently exploring extrinsic photoconductivity in epitaxial layers of gallium arsenide to extend photon detectors past $200\text{ }\mu\text{m}$ without having to apply stress. Indications suggest that impurity-band blocking might be easier to implement in GaAs than in Ge. Moreover, several promising developments exploit the even smaller energy bandgaps in superconducting metal films to extend detector photo-response to millimeter wavelengths.²

Extrinsic photon detectors with blocked impurity bands (impurity-band photoconductors or IBCs) are used for wavelengths beyond $5\text{ }\mu\text{m}$. *Spitzer* is producing excellent results from 256×256 and 128×128 pixel arrays of arsenic-doped silicon for wavelengths from 5 to $26\text{ }\mu\text{m}$, and 128×128 pixel antimony-doped silicon arrays for wavelengths from 14 to $38\text{ }\mu\text{m}$.^{5,9,10} Tests of larger (1024×1024) format Si:As arrays planned for the mid-IR instrument on the *JWST* are now under way.

To couple the signal collected from IR-sensitive detector material to silicon-based electronics, physicists assem-

Bolometers. In a bolometer, the electron excitations caused by absorbed photons produce a temperature rise that can be detected by a resistive thermometer. Bolometers are currently used for astronomy at wavelengths beyond about $100\text{ }\mu\text{m}$. The components of a typical bolometric detector—a metal film to absorb radiation and a thermometer to measure the temperature rise, both supported by a dielectric membrane—are in strong thermal contact with each other and weakly coupled to a heat sink. Bolometric detectors can have high absorption efficiencies and produce a well-behaved linear response, but they require operating temperatures of 0.1 – 0.3 K to reduce the thermodynamic noise (Johnson noise and energy fluctuation noise) below the photon noise limit for photometry. Bolometers are potentially very useful for long-wavelength spectroscopy, but existing versions are too noisy for ideal performance.

Bolometers have traditionally been made using doped Si or Ge resistive thermometers, each with an individual junction field-effect transistor (JFET) amplifier operated near 100 K . But hand assembly, thermal complexity, a small amplifier noise margin, and an inability to multiplex the output signal make the construction of high-performance systems a challenge. The voltage-biased superconducting transition-edge sensor (TES), which can be produced by lithography, is becoming the technology of choice for many bolometer systems. The resistance R of a superconducting thermometer increases rapidly with temperature at the transition. Consequently, when a fixed bias voltage V is placed across the TES, the bias power V^2/R produces a strong negative electrothermal feedback. The negative feedback dramatically improves linearity and bandwidth, and immunizes the detector's response to changes in external parameters such as the absorbed optical power and the temperature of the heat sink. Researchers are developing multiplexed readouts for TES arrays using superconducting quantum interference devices (SQUIDs) that dissipate little power and have a large noise margin.

Heterodyne mixers. These devices mix the electromagnetic field of an incoming photon with a local oscillating field to produce a signal at the difference, or beat, frequency. Such mixing, or heterodyne down-conversion, shifts the signal to a frequency easier to amplify and preserves the phase information. After amplification, a multichannel filter bank, or correlator, capable of multiplexing thousands of frequency channels, detects the intermediate frequency signal.

Photon mixers with fast recombination times are used at IR wavelengths. Superconducting hot-electron bolometer mixers² are used to detect far-IR wavelengths out to $300\text{ }\mu\text{m}$. Superconductor–insulator–superconductor (SIS) tunnel junctions² are very useful as heterodyne down-converters at wavelengths beyond $300\text{ }\mu\text{m}$. High-electron-mobility transistor (HEMT) amplifiers are used at the front ends of both diode detectors and heterodyne receivers at wavelengths longer than about 3 mm . The amplifier gain reduces the importance of noise from subsequent signal processing. Heterodyne down-converters and HEMT amplifiers, like other phase-conserving linear photon amplifiers, are limited by quantum noise, which becomes increasingly important at shorter wavelengths, where the photon energy is larger.

ble both the PV and IBC detector arrays into hybrid detector packages that contain a low-noise multiplexing electronic readout (see figure 3). This microlithography-based approach allows developers to build detectors with large numbers of pixels in a device that survives repeated cycles to low temperature. Electrical contacts in the form of indium “bump bonds” channel the photogenerated charge from each pixel on the detector wafer to the gate of a dedicated MOSFET on the readout wafer. A simple integrating circuit with three to seven transistors per unit cell provides low-noise signal processing with little power

dissipation. The circuit typically samples the signal many times to average down readout noise. At the end of an integration period, a reset pulse applied to the integrating MOSFET repeats the cycle. The pixels integrate charge while isolated from the output amplifier, thus avoiding Johnson noise, which only enters during the reset period. This direct-pixel access differs from the lateral charge-transfer multiplexing common in CCDs.

Extrinsic germanium photoconductors doped with gallium or antimony are sensitive to wavelengths beyond $40\text{ }\mu\text{m}$. A 32×32 Ge:Ga array with a band centered at $70\text{ }\mu\text{m}$ on *Spitzer* is producing large amounts of data.¹¹ The PACS instrument on the *Herschel Space Observatory* will have a similar number of pixels. In the absence of IBC structures, these germanium arrays must be assembled by hand from bulk material. In the *Spitzer* array, bars of gallium-doped germanium, arranged in a 1×32 detector format, individually connect to a co-planar, 32-channel, low-temperature multiplexing readout chip. Stacking those components on top of each other creates a two-dimensional array. *Spitzer* also uses an array of stressed gallium-doped germanium detectors to detect a band centered at $160\text{ }\mu\text{m}$. These detectors are assembled into a 2×20 pixel format, with individual spring clamps to apply uniform, well-controlled stress.¹¹ The *Spitzer* gallium-doped germanium detectors represent a major advance in a difficult technology. To work around problems with hysteresis and sensitivity to ionizing radiation, astronomers have developed special observing techniques. Despite the challenges, designers of space systems often select these detectors over the bolometric alternative because the required operating temperatures are so much easier to achieve.

Spitzer builds on international experience from earlier missions. Launched in 2003, *Spitzer* is returning enormous amounts of data from arrays of photon detectors that operate in spectroscopic and photometric bands from 3.6 to $160\text{ }\mu\text{m}$.¹² Many of the first scientific observations are surveys made over a wide range of wavelengths designed to identify and characterize populations of IR sources. Focused scientific programs are beginning and include investigations of the formation and evolution of planetary systems and identification of the sources responsible for the cosmic IR background. *Spitzer* will help address an enormous number of detailed questions as astronomical researchers gain access to telescope time. The mission lifetime, limited by the store of liquid helium cryogen, is expected to extend a bit beyond 5 years.

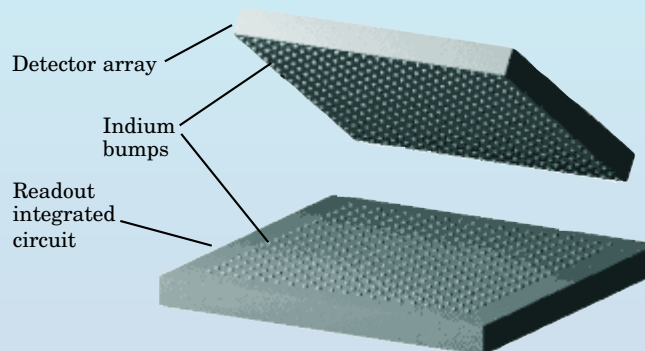
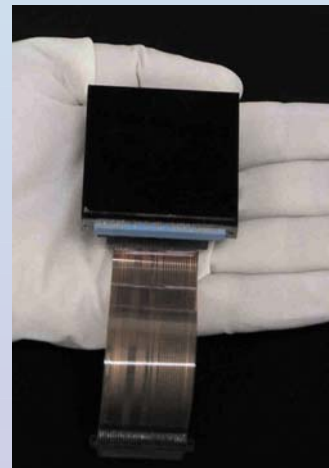


Figure 3. This hybrid array consists of a detector wafer attached to a silicon MOSFET readout multiplexer wafer by an array of indium bump bonds that electrically connects them. Each conducting bump transfers the charge collected from one pixel of the detector to its dedicated amplifier on the readout wafer. That architecture is now standard for IR wavelengths shorter than $40\text{ }\mu\text{m}$. In the mercury cadmium telluride hybrid package shown, the complete 2048×2048 array device is about 40 mm square. (Photo courtesy of Rockwell Scientific Co.)



Bolometers ($100\text{ }\mu\text{m}$ – 1 mm)

Radical new technologies are paving the way for a new crop of bolometric arrays for far-IR and submillimeter-wavelength measurements from ground-based, airborne, and space telescopes. These arrays usually have directly illuminated, close-packed pixels. The field is rapidly evolving. Semiconducting technology with individual amplifiers is used for arrays containing several hundred pixels (SHARC-II on the Caltech Submillimeter Observatory telescope and HAWC on *SOFIA*) and multiplexed semiconducting technology is used with 2048 pixels (PACS on *Herschel*). Multiplexed superconducting transition-edge sensor (TES) technology is being assembled with 5120 pixels (SCUBA-2 on the James Clerk Maxwell Telescope). Scientific goals of these instruments include measuring the emission from cool dust,

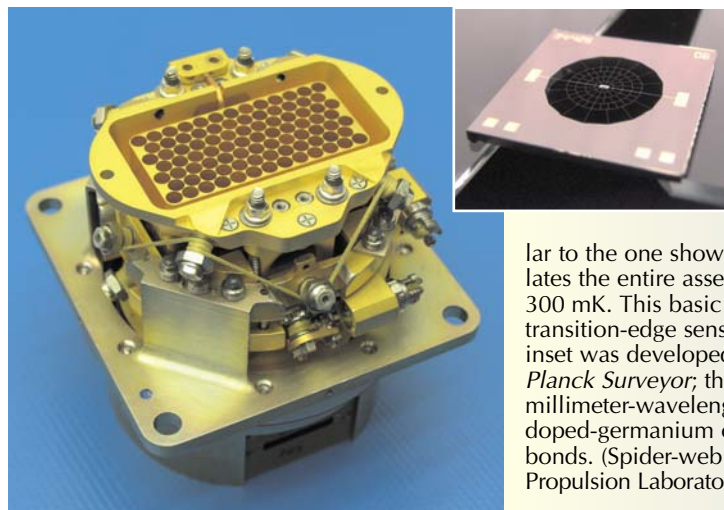


Figure 4. Bolometric focal plane assembly for the SPIRE instrument on the *Herschel Space Observatory*. The band-pass filter has been removed to show an array of horns that channel light onto a planar array of bolometers similar to the one shown in the inset. A support made of Kevlar braids thermally isolates the entire assembly—filter, horns, and bolometers—so that it can operate at 300 mK . This basic approach is now being scaled to arrays of 10^3 spider-web transition-edge sensor (TES) bolometers. The spider-web bolometer shown in the inset was developed for cosmic microwave background observations on the *Planck Surveyor*; the 3.4-mm -diameter web of metallized silicon nitride absorbs millimeter-wavelength photons but has a small cross section for cosmic rays. The doped-germanium chip thermometer at its center is attached by indium bump bonds. (Spider-web image courtesy of Minhee Yun and Anthony Turner, Jet Propulsion Laboratory; assembly image courtesy of Turner and Mark Weilert, JPL.)

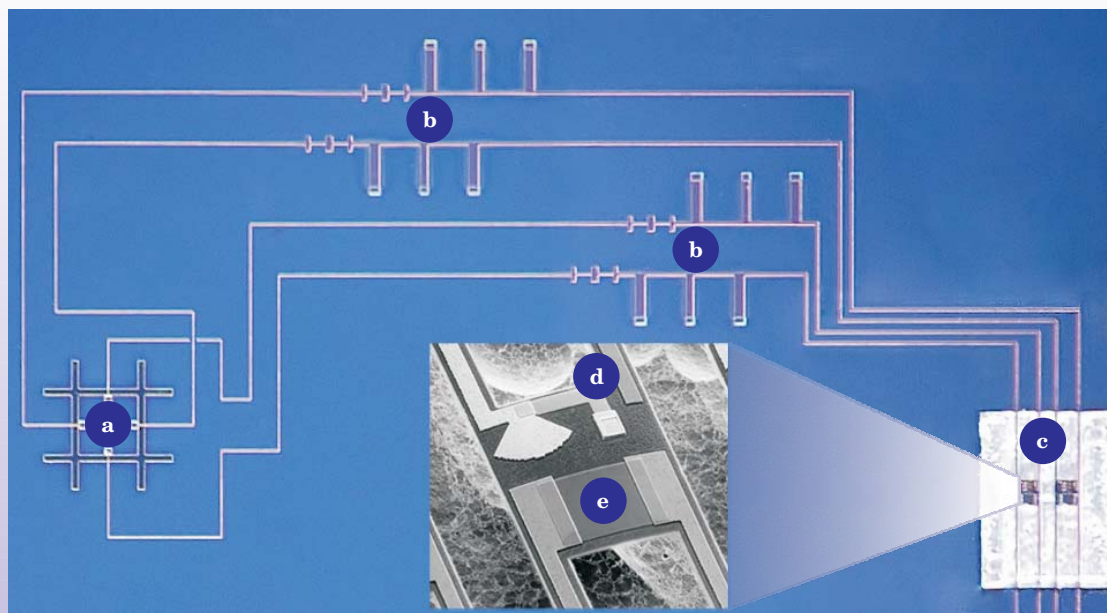


Figure 5. Transition-edge sensor bolometers, designed to measure the polarization anisotropy of the cosmic microwave background. Long used for far-IR heterodyne mixers, superconducting integrated circuits are being developed for arrays of detectors. Etched into the superconducting ground plane, two orthogonal dipole antennas (**a**) are connected by superconducting microstrip lines through band-pass filters (**b**) to two TES bolometers (**c**). In the detailed view of one bolometer, the microstrip lines enter at the top and terminate in a matched resistor (**d**); leads to the TES thermometer (**e**) exit along the bolometer legs. (Courtesy of Mike Myers, University of California, Berkeley.)

especially at large redshifts, and studying the rate and mechanism of star formation. Such sources radiate more energy at far-IR wavelengths than is directly observed at UV or visible wavelengths.

Multiple-wavelength focal planes of horn-coupled spider-web bolometers with doped-germanium resistive thermometers and junction field-effect transistor (JFET) amplifiers were used to measure the CMB using high-altitude balloon-based experiments, such as BOOMERANG, MAXIMA, and Archeops, and the ground-based ACBAR project, which were important scientific precursors of the *Wilkinson Microwave Anisotropy Probe* (WMAP) spacecraft. Horns are cones of metal that collect input radiation and channel it to the detector; the thin web structure on the bolometer minimizes its thermal load. The High Frequency Instrument on the *Planck* mission will use 24 spider-web bolometers and 12 polarization-sensitive bolometer pairs,¹³ all operated at 0.1 K, to measure both the temperature and polarization anisotropy of the CMB. Powerful ground-based bolometric polarization anisotropy experiments, now under development, will use many hundreds to thousands of TES bolometers. Measurements of the CMB have shown that the geometry of the universe is Euclidean (space is flat). These measurements provide accurate values for many cosmological parameters and offer strong support for an inflation-motivated cosmological model of the universe dominated by dark energy. Scientists expect measurements of the polarization anisotropy to yield information about the production of gravity waves at the time of inflation.

The two very different examples in figures 4 and 5 illustrate the diversity of bolometric detectors for long wavelengths. Figure 4 shows an 88-pixel, horn-coupled focal-plane assembly developed for the SPIRE instrument on *Herschel*,¹⁴ along with a typical spider-web bolometer. At long wavelengths, it is difficult to cool baffles sufficiently to control their thermal emission, a problem that horn-coupled focal planes minimize. These focal planes

typically have many fewer detectors, but nearly comparable mapping speeds. The system in figure 5, designed to measure the polarization of the CMB, shows an antenna-coupled bolometer with microstrip bandpass filters.¹⁵ Such bolometer circuits promise dual polarization and multi-color detection in each pixel of a large-format array.

By implementing novel output multiplexing ideas, physicists have increased by an order of magnitude the number of pixels in bolometric arrays now under construction compared to those made just a few years ago. Bolometers being prepared for the PACS instrument on *Herschel* use very-high-impedance, ion-implanted silicon resistive thermometers coupled to a MOSFET multiplexer, similar to those found in photon detectors. Superconducting quantum interference device-based multiplexers, together with TES bolometers, achieve better noise performance. NIST has developed a time-division multiplexer¹⁶ that uses SQUIDs both for the switches and the output amplifier. In a frequency-division multiplexer being developed by groups at the University of California, Berkeley,¹⁷ and elsewhere, the TES bolometers are biased at different frequencies and the bolometer currents summed at the input of a SQUID amplifier. A lock-in demodulator extracts the signal from each pixel.

Dramatic developments in materials, system architectures, and microfabrication have led to IR detector arrays with far larger pixel numbers. Such arrays map regions of the sky more quickly and accurately than could have been imagined even a decade ago. Although individual pixels are beginning to reach the fundamental limits set by photon noise, further improvements in the pixel numbers and operating characteristics are possible and likely to prove very useful.

References

1. For more detail on specific detectors, projects, and detector design concepts, see the many articles in J. C. Mather, ed., *Optical, Infrared, and Millimeter Space Telescopes*, Proc.

SPIE, vol. 5487; J. Zmuidzinas ed., *Millimeter and Submillimeter Detectors for Astronomy II*, Proc. SPIE, vol. 5498; and J. D. Garnett ed., *Optical and Infrared Detectors for Astronomy*, Proc. SPIE, vol. 5499. All published in 2004 by SPIE, Bellingham, WA.

2. For a recent review of superconducting detectors and mixers, see J. Zmuidzinas, P. L. Richards, *Proc. IEEE* **92**, 1597 (2004).
3. Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, *Astronomy and Astrophysics in the New Millennium*, National Research Council, National Academies Press, Washington, DC (2001). Available at <http://www.nap.edu/books/0309070317/html>.
4. G. H. Rieke, *Detection of Light from the Ultraviolet to the Submillimeter*, 2nd ed., Cambridge U. Press, New York (2002).
5. G. G. Fazio et al., *Astrophys. J., Suppl. Ser.* **154**, 10 (2004).
6. J. D. Garnett et al., in *Scientific Detectors for Astronomy*, P. Amico, J. W. Beletic, J. E. Beletic, eds., Kluwer Academic, Boston (2004), p. 59.
7. See A. F. M. Moorwood ed., *Ground-based Instrumentation for Astronomy*, Proc. SPIE, vol. 5492, SPIE, Bellingham, WA (2004).
8. For more about the image and instrumentation used to obtain it, see <http://uh88.ifa.hawaii.edu/ULB4K>.
9. J. Huffman et al., *J. Appl. Phys.* **2**, 275 (1992).
10. J. R. Houck et al., *Astrophys. J., Suppl. Ser.* **154**, 18 (2004).
11. G. H. Rieke et al., *Astrophys. J., Suppl. Ser.* **154**, 25 (2004).
12. Special issue on the *Spitzer Space Telescope*, *Astrophys. J., Suppl. Ser.* **154** (September 2004).
13. W. Holmes et al., in *Millimeter and Submillimeter Detectors for Astronomy*, T. G. Phillips, ed., Proc. SPIE, vol. 4855, SPIE, Bellingham, WA (2003).
14. G. Chattopadhyay et al., *IEEE Trans. Microwave Theory Tech.* **51**, 2139 (2003).
15. M. Myers, et al., *J. Appl. Phys.* (in press).
16. C. D. Reintsema et al., *Rev. Sci. Instrum.* **74**, 4500 (2003).
17. T. Lanting et al., *IEEE Trans. Appl. Supercond.* **13**, 626 (2003). ■

A NEW GENERATION of BIPOLAR POWER

HIGH POWER BOP from KEPCO



1000 WATTS in a 400 WATT PACKAGE

The High Power BOP are true 4-quadrant programmable voltage and current supplies capable of full source and sink operation. To achieve low dissipation and high efficiency when sinking power from a load, the High Power BOP recovers the energy for reuse. The key to this is a bidirectional power factor correction (PFC) circuit, which allows transparent energy interchange without dissipative sinking. They meet the EN61000-3-2 harmonic limits. A built-in EN55022 Class B input EMI filter is provided.

For more information visit the Kepco website
www.kepcopower.com/kephb.htm



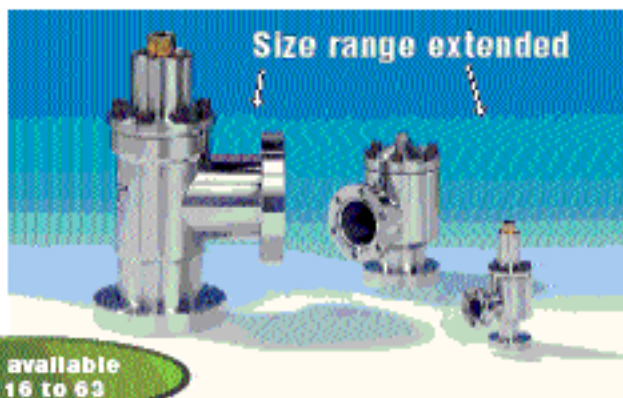
KEPCO, INC. • 131-38 Sanford Ave. • Flushing, NY 11352 USA • Tel: (718) 467-7000
Fax: (718) 767-1102 • Email: bj@kepcopower.com • www.kepcopower.com

www.pt.ims.ca/4625-21 or Circle #21



«Easy close» All-metal Angle Valves

Series 54 for UHV applications



Now available
DN 16 to 63

- High conductance
- No torque wrench needed
- Maintenance-free
- Low price

Swiss Headquarters
Tel ++41 81 771 61 61
reception@vat.ch

VAT Japan
Tel (045) 333 11 44
sales@vatask.co.jp

VAT Taiwan
Tel 08 516 90 88
taiwan@vatvalve.com

VAT France
Tel 01 69 20 60 11
france@vatvalve.com

VAT U.K.
Tel 01926 452 753
uk@vatvalve.com

VAT USA
Tel (781) 935 1446
usa@vatvalve.com

VAT Korea
Tel 031 704 68 57
korea@vatvalve.com

VAT Benelux
Tel ++31 (30) 6018251
benelux@vatvalve.com

VAT Germany
Tel (089) 46 50 15
deutschland@vatvalve.com

www.vatvalve.com

