

***Herschel* Offers a Front-Row Seat to the Merging of Galaxies in the Cold and Dusty Universe**

In showcasing the universe over the full terahertz range of frequencies for the first time, the *Herschel Space Observatory* is affording researchers an unprecedented spectroscopic view of the processes of planet and galaxy formation. *Herschel*, which hosts the largest single-mirror telescope in space and is in orbit about a point in space a million miles more distant from the Sun than Earth, is a European Space Agency-led effort with significant participation by NASA. Naval Research Laboratory scientists from the Remote Sensing Division contributed to the success of *Herschel* by measuring and modeling aspects of the telescope performance prior to launch, thereby allowing optimal use during the mission's predicted 3.8 year lifetime. NRL scientists and collaborators have used *Herschel* to make spectacular discoveries about how gas-rich spiral galaxies collide, merge, and evolve to form a single, elliptically shaped, gas-poor galaxy. They have witnessed previously unseen massive amounts of high velocity molecular gas outflowing from the central regions of the galaxy merger, that appear to be in the process of clearing away the star-forming fuel in the transformed galaxy. Early analysis suggests that the powerful outflows may be driven by activity generated by central supermassive black holes.

Terahertz Astrophysics with the Herschel Space Observatory*

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Naval Research Laboratory scientists are part of a multinational team that designed and built the European Space Agency's *Herschel Space Observatory*, home to the largest single-mirror telescope launched to space and the first observatory to cover the wide terahertz frequency range from 0.5 to 6 THz. Herschel, with its powerful suite of terahertz instrumentation, opens a new window on the cold and dusty universe. Now that Herschel is in operation, NRL scientists and their collaborators are using terahertz spectroscopy to study the distribution of water vapor and other molecules in planet-forming disks around young stars in our galaxy, and to investigate the transformation of merging gas-rich disk galaxies into single gas-poor elliptically shaped galaxies. In this article, we highlight early Herschel results on the most spectacular class of galaxy mergers, the ultraluminous infrared galaxies. Herschel terahertz spectroscopy of these merging galaxies reveals a rich absorption spectrum due to molecules and molecular ions, providing a wealth of information on the cool molecular environment and chemistry in the central regions of the mergers. Perhaps the most spectacular discovery is the existence of massive outflows of molecular gas from the merger centers, in some cases at velocities exceeding 1000 kilometers per second, or 2.2 million miles per hour. The results indicate that the galaxies with the strongest signatures of accreting black hole activity have the highest outflow rates and that the mass of gas expelled from the galaxy is higher than the mass of gas consumed in forming stars. These outflows appear capable of exhausting the galactic reservoirs of star-forming gas, as is necessary if they are to evolve into gas-poor elliptical galaxies.

TERAHERTZ RADIATION — AN UNDEREXPLORED SPECTRAL DOMAIN

The terahertz domain nominally subsumes the far-infrared and submillimeter spectral regions, extending from about $\nu \sim 0.3$ THz ($\lambda = 1$ mm) to 10 THz ($\lambda = 30$ μm). Sandwiched between two spectral bands with relatively high atmospheric transmission, the long-wave infrared (LWIR) and microwaves at centimeter wavelengths, the terahertz spectral domain is at a disadvantage for use on the Earth's surface due to its relatively poor transmission through the atmosphere. Moreover, terahertz detectors achieve their best sensitivities only when operated cryogenically at temperatures near zero degrees Kelvin using superfluid helium. These and other challenges have hampered terahertz technology advances as well as its application to biology, security and defense, and astrophysics. Large two-dimensional arrays of detectors needed for efficient terahertz astrophysical observations have only recently been developed and are still not comparable in size to those available for optical and near-infrared astronomy. Moreover, the approximately 1000-fold increase in wavelength of terahertz waves compared with optical light means that for the same diameter tele-

scope, the spatial resolution of terahertz observations is worse by the same factor! On the other hand, advantages for short-range terrestrial applications include transmission through optically opaque materials and unique spectroscopic features of various chemical and biological materials. Military and security applications of interest include spectroscopic detection and identification of chemical, biological, and nuclear weapons as well as security screening and identification of materials such as explosives, pharmaceuticals, and concealed weapons. In astrophysics, the terahertz range is key for understanding the physics of the medium between the stars — the (usually) cool interstellar medium (ISM).

TERAHERTZ ASTROPHYSICS IS COOL

Terahertz photons dominate the emitting radiation distribution from cold material in the ISM. They can penetrate further through dusty regions that obscure the optical and ultraviolet radiation. The ISM in our own Milky Way galaxy, as well as in distant galaxies, consists of clouds of gas and dust particles that often surround and obscure forming stars and the super-massive black holes in galaxy centers. The gas and dust particles in these clouds are typically colder than

* Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

temperatures here on Earth, where matter is typically at “room temperature” (~300 degrees Kelvin). The small dust particles in interstellar space, estimated to be fractionally about 1/100 of the mass in gas, usually attain their local equilibrium temperatures of 10 to 100 K as a result of ultraviolet heating by stars balanced by radiative cooling. Dust particles at these temperatures produce spectral energy distributions that peak in the far-infrared half of the terahertz spectral range. Interstellar gases in these regions are typically in atomic or molecular form and are excited to similarly low kinetic temperatures, with spectral lines that fall within the terahertz range. Dust temperatures can be determined based on observations of their broadband continuum spectral energy emission, while gas excitation is estimated via spectroscopic observations of multiple spectral lines of an abundant gas constituent. The terahertz range includes many important cooling lines of abundant molecules in the ISM, including lines of water, CO, OH, and ammonia. These lines can be used as powerful diagnostics of the excitation, chemistry, and kinematics of the ISM and can be used to help unravel the intrinsic spectral energy distribution and thus the nature of energy sources that are obscured at shorter wavelengths by dust in the ISM. Even “cooler,” because the universe is expanding, the far-infrared radiation from the ISM in distant galaxies that is just now reaching us from earlier epochs of peak star-formation and black hole accretion is Doppler shifted to the “redder” submillimeter part of the terahertz range.

HERSCHEL — A TERAHERTZ OBSERVATORY AT THE EARTH-SUN SECOND LAGRANGE POINT

In order to study dust-embedded star and planet formation in our galaxy and in the distant universe, the Herschel Space Observatory¹ was launched to space by the European Space Agency (ESA) in May 2009 (see Fig. 1). Hosting a 3.5 m diameter telescope, Herschel is the largest single-mirror telescope ever launched to space and the first observatory to cover the full far-infrared to submillimeter spectral range (55 to 670 μm in wavelength / 0.5 to 6 THz in frequency). Herschel was launched to an orbit around the Earth-Sun second Lagrange point, known as L2, a point along the Sun–Earth axis, one million miles more distant from the Sun than the Earth (see Fig. 2). Because an object orbiting L2 always maintains the same approximate relative orientation with respect to the Sun and Earth, which both “shine” at terahertz wavelengths, thermal shielding is simplified. The observatory houses a suite of instruments built by a multinational team that includes partners from Europe, the United States (NASA), and Canada. It is named after Sir Frederick William Herschel, who discovered at the beginning of the 19th



FIGURE 1
Herschel was launched aboard an Ariane 5 rocket together with Planck, a mission to map the cosmic microwave background. (Figure courtesy of European Space Agency.)

century that there is electromagnetic radiation at wavelengths longer than those visible to the human eye.

As one part of our contribution to the Herschel optical system, Naval Research Laboratory scientists in the Remote Sensing Division and our international collaborators carried out prelaunch laboratory measurements and modeling efforts to predict how the telescope would be expected to perform in space. Because cryogenics needed to cool the detectors limit the observatory to a relatively short lifetime of ~3.8 years, these predictions were vital for maximizing the scientific return of the mission. With sound predictions for the performance of the instrument package, astronomers worldwide were able to design and propose observational programs prior to launch that were well tuned to the sensitivity of the observatory and could make efficient use of the observing time. Because of Herschel’s large primary mirror size, it is passively, radiatively cooled, rather than cryogenically cooled. At its operating temperature of 80 to 90 K, the mirror’s own thermal radiation is the background photon noise determin-

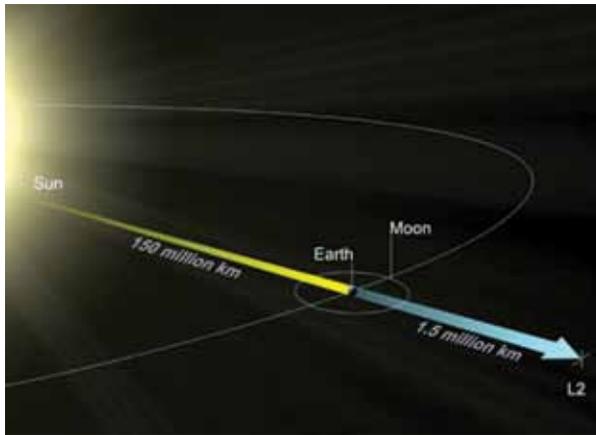


FIGURE 2
Herschel orbits around the second Lagrange point, L2. In this relatively constant environment, it can be well shielded from emission from the Earth and Sun and can hover without using too much fuel.

ing the sensitivity of astronomical observations. A set of NRL-led laboratory measurements of the terahertz emissivity of the aluminum-coated silicon carbide telescope mirror samples, with and without a precisely deposited thin layer of dust to simulate the actual condition of the mirrors after launch,² enabled prediction of the telescope background and thus the ultimate sensitivity of two of the three Herschel instruments. In another NRL-led study, a combination of theoretical and numerical analysis enabled accurate simulation of the interference effects of unwanted back reflection of instrument feedhorn noise from the central scatter cone of the Cassegrain telescope's secondary mirror surface,³ which was specifically designed to achieve a flat baseline for the third Herschel instrument.

GALAXY TRANSFORMATIONS — HERSCHEL DISCOVERIES

NRL studies with Herschel have centered on a class of galaxies known as ultraluminous infrared galaxies (ULIRGs), galaxies with infrared–submillimeter luminosities greater than that of a trillion Suns. In comparison, our relatively normal Milky Way galaxy has a *total* luminosity of just 25 billion times that of the Sun. The high luminosities of ULIRGs are more similar in magnitude to the optical luminosities of quasars, which are compact objects powered by accreting supermassive black holes. Studies of these galaxies have shown that they trace a spectacular stage in galaxy evolution: the morphological transformation of merging gas-rich galaxies into gas-poor elliptical galaxies. The Herschel studies of ULIRGs are being carried out in collaboration with an international team of astronomers and are aimed at determining the processes involved in this transformation.

Pre-Herschel spectroscopy of nearby ULIRGs showed that their far-infrared spectra are dramatically different from the spectra of other infrared-bright galaxies.⁴ Figure 3 (left) shows the spectra of the 10 brightest far-infrared galaxies. The only ULIRG in this sample, Arp 220, is plotted at the top of the figure. The far-infrared spectra of the other, lower luminosity galaxies typically consist of continua produced by radiation of warm dust particles and emission lines of neutral and ionized gaseous carbon, oxygen, and nitrogen. In these galaxies, the dust heating and gas excitation are predominantly due to irradiation by the ultraviolet radiation of bright young stars. In contrast, the infrared emission in ULIRGs is thought to be powered by a combination of UV heating due to young stars and accretion onto central supermassive black holes. As in lower luminosity galaxies, the far-infrared spectra of Arp 220 and other ULIRGs are characterized by warm dust continuum emission, but the gas spectra are dominated by absorption lines of water, OH, and other molecules. These stark differences are due to two different effects of dust absorption of radiation. Because of the strong UV radiation field at the centers of these galaxies, the ratio of ionized to atomic gas increases. The lower density of neutral gas means that there are fewer neutral atoms available to absorb the ultraviolet photons. The lower gas opacity, compared with the dust opacity, results in a smaller fraction of gas ionizations compared with the dust continuum emission.⁵ A second effect occurs because, due to infall of gas and dust into the galaxy centers during the early stages of the merger, the dust opacities are so high that even the far-infrared emission lines are absorbed.⁶

New Herschel observations of Arp 220 provide dramatic insight into the chemistry of the “molecular atmosphere” surrounding the nucleus of this galaxy merger. The far-infrared spectrum of Arp 220 observed with the Herschel Photodetector Array Camera and Spectrometer (PACS)⁷ is shown in Fig. 4. It reveals a rich molecular chemistry, traced by absorption lines of H₂O, OH, H₂¹⁸O, ¹⁸OH, HCN, NH, CH, HF, NH₂, NH₃, H₂O⁺, H₃O⁺, and OH⁺.⁸ These lines arise from low energy levels, ranging from the ground state to greater than 600 K, that are populated via far-infrared pumping due to the high far-infrared photon densities in the nuclear regions of Arp 220. The high abundances of water- and nitrogen-bearing molecules are indicative of the evaporation of molecules from the mantles of dust grains, while the high abundances of OH are suggestive of the effects of X-rays or cosmic rays from a dust-obscured super-starburst or accreting supermassive black hole.⁸

An equally spectacular result is the discovery of massive amounts of molecular gas flowing outward from the central regions of some ULIRGs,^{9,10} with outflow velocities on the order of 1000 km s⁻¹, or 2.2 mil-

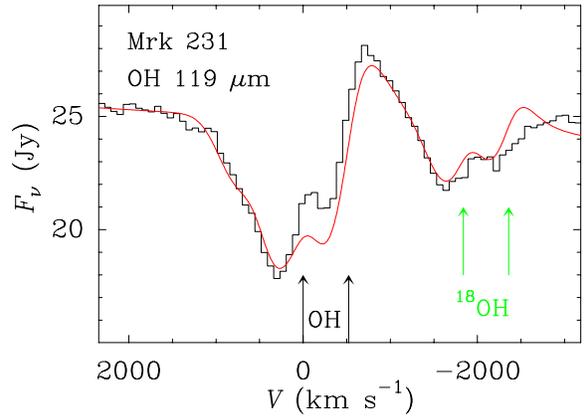
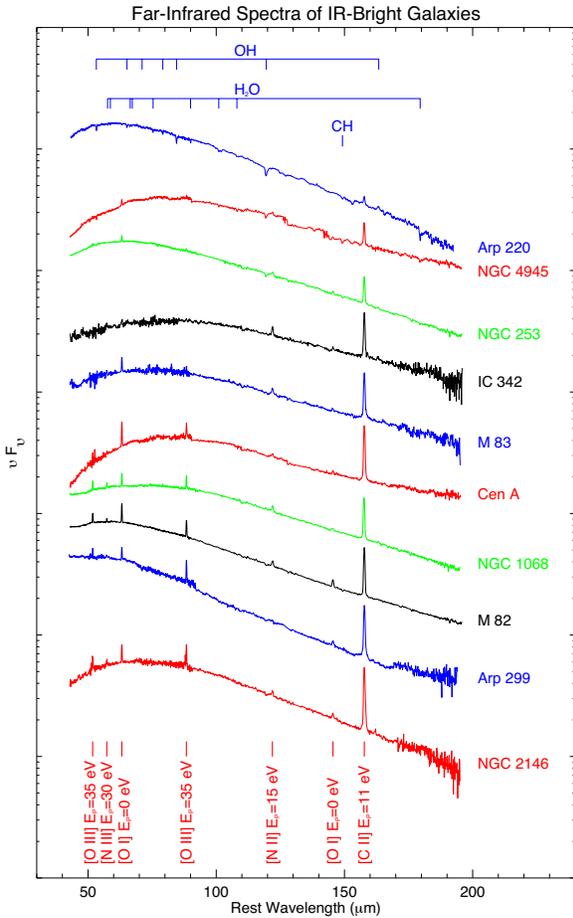


FIGURE 3

(Left) The Infrared Space Observatory (ISO) Long Wavelength Spectrometer far-infrared spectra of 10 infrared-bright galaxies, including the bright ULIRG Arp 220 (top), whose spectrum is dominated by molecular absorption of OH and water. The vertical axis, νF_{ν} , is the power measured at Earth per unit area at a given frequency, ν . The spectra are shifted in order of the relative strength of the [O III] 88 μm line. The excitation potential, the energy required to create the species, is given in electron volts for each species. The Roman numeral next to the atomic species identifier refers to the ionization state, with the convention that [O I] is a forbidden line of neutral oxygen and [O III] is a forbidden line of twice ionized oxygen. (Right) P-Cygni absorption/emission profiles (black histograms) around the OH 119 μm and ^{18}OH 120 μm partially resolved doublets in the ULIRG Mrk 231 are compared with our modeled profiles (red curve).⁹ F_{ν} is the power measured at Earth per unit frequency per unit area. The velocity scale is with respect to the rest-frame of the leftmost OH doublet component. Outflowing gas in front of the continuum dust emission appears in absorption and is blueshifted because it is moving toward the observer, while gas moving laterally and away from the observer appears in emission.

lion miles per hour. Figure 3 (right) shows the Herschel PACS velocity-resolved line profiles of the OH and ^{18}OH doublets at 119 and 120 μm in Mrk 231, the most luminous of the local ULIRGs and host to an accreting supermassive black hole. The Doppler velocities are plotted with respect to the shorter wavelength transition of the OH doublet. The observed combination of absorption at negative velocities (Doppler shifted to the blue) and emission at positive velocities (redshifted) is known as a P-Cygni profile and is indicative of an outflow away from a central source, here traced by the OH and ^{18}OH gas. The absorbing gas is moving toward the observer and must be along the line of sight and in front of the nuclear continuum emission, while the

emitting gas is moving away from the observer and may be alongside or behind and laterally displaced from the nucleus. Figure 5 presents the PACS velocity profiles for Mrk 231 and four other ULIRGs that were observed early in the mission in the OH transition at 79 μm . The figure also shows the profile for the lower luminosity IR-bright galaxy NGC 253 (lower right panel), whose Infrared Space Observatory (ISO) spectrum was plotted in the far-infrared spectral sequence (Fig. 3, left). The rest frame wavelength of a nearby water line that appears to also trace the outflow is marked. Models for the outflowing gas based on multiple velocity components (black curves) were fit to the data and are plotted in Fig. 5. In all of these cases, P-Cygni profiles

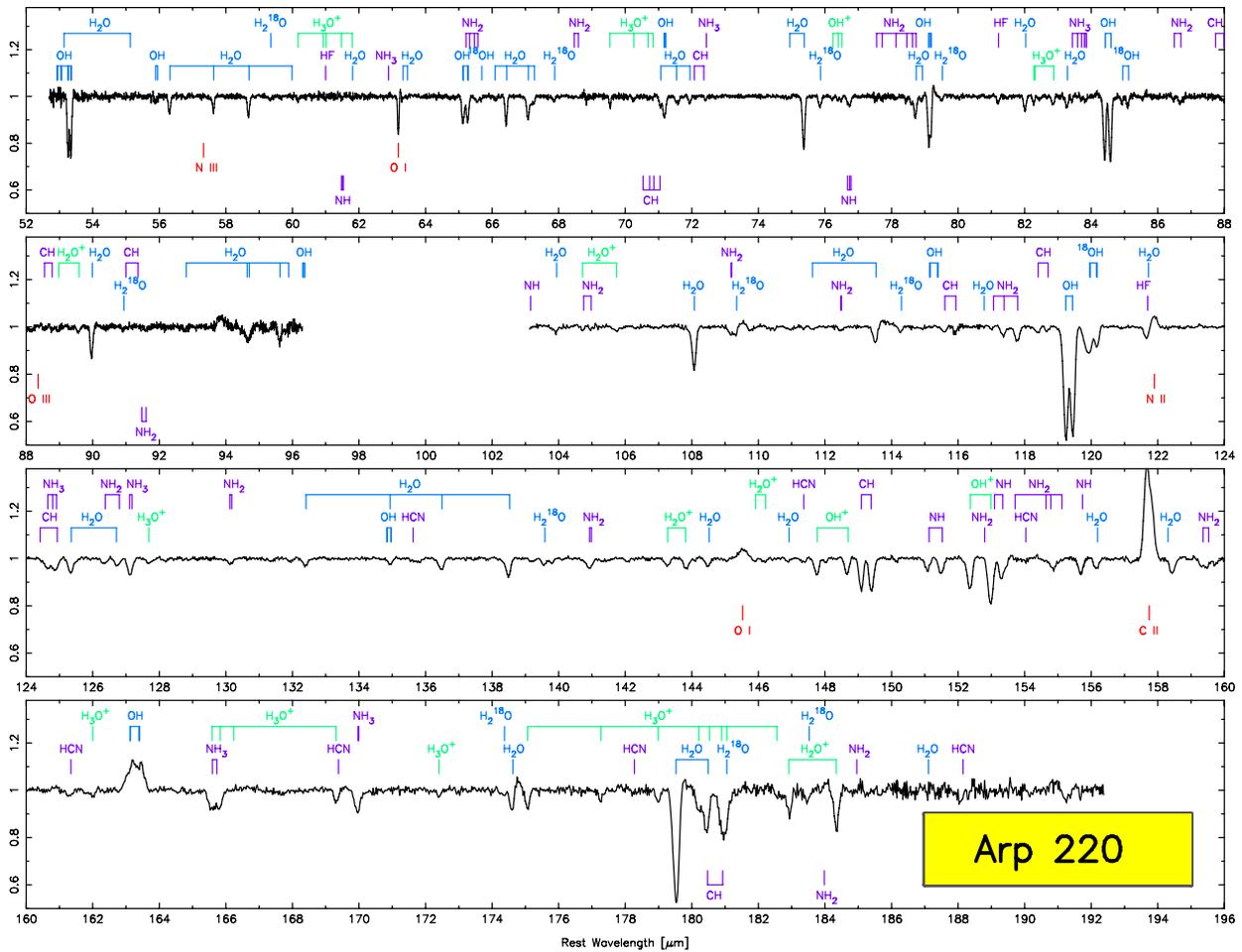


FIGURE 4

Far-infrared spectrum of the nearest ULIRG, Arp 220, taken with the PACS spectrometer on Herschel, normalized to a fit to the continuum. Molecular lines from species detected in Arp 220 are marked. The positions of lines of atomic and ionized gas that are usually detected in emission in infrared-bright galaxies are marked in red.

indicative of outflows are observed, with blue-shifted velocities greater than 1000 km s^{-1} in some ULIRGs.

Massive outflows of gas from galactic centers are telltale signs that powerful processes affecting the global galactic balance of mass and energy are under way. They may be triggered by stellar winds or supernova explosions associated with galaxy-wide star formation. They can also be triggered close to the central black hole, where radiation pressure from the accretion disc drives the surrounding gas away. When powerful enough, outflows can sweep away the galaxy's entire reservoir of gas, depleting it of the raw material from which stars are formed and that feeds the central black hole. Thus, galactic outflows cause negative feedback, eventually halting the mechanisms that produce them.

Powerful outflows are key features in models of galactic formation and evolution, but while there have been other detections of galactic outflows, almost all previous observations dealt only with neutral and ion-

ized gas. The Herschel discovery is unique in that, for the first time, the outflows were detected in the cool molecular gas from which stars are born, allowing their direct impact on star formation to be studied.

For each of the 22 nearby ULIRGs in the Herschel sample, velocity profiles of three OH transitions were observed in order to constrain the masses and mass loss rates involved in the outflows. The analysis of five ULIRGs observed early in the mission suggests that accretion onto their central supermassive black holes may provide the driving force for the observed gas outflows.¹⁰ The early analysis indicates that outflow mass loss rates are up to 10 times greater than the star formation rate in ULIRGs with high accretion luminosities. On the other hand, ULIRGs with the highest star formation rates and low accretion luminosities have lower outflow velocities and mass loss rates. If continued at the current mass loss rate, the molecular outflows we observe will expel the cold gas reservoirs from their

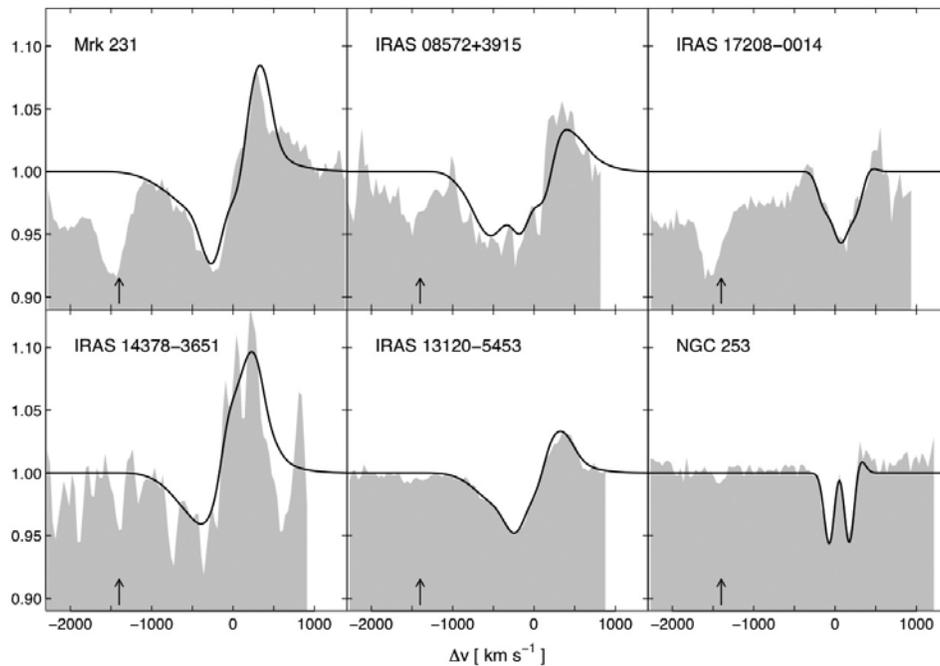


FIGURE 5

Observed PACS continuum-normalized spectra of the OH 79 μm doublet transitions (gray shaded) of five ULIRGs and of the infrared-bright lower luminosity galaxy NGC 253. The velocity scale is with respect to the rest-frame of the leftmost OH doublet component. Overplotted are the best fit model fits (solid curve).¹⁰ The arrows indicate the rest position of an H₂O line at 78 μm .

galactic centers within 10^6 to 10^8 years. The analysis of the full Herschel ULIRG dataset will enable study of the effects of dust obscuration and ionizing photon rate and will help shed further light on this important stage of morphological transformation in galaxy evolution.

TERAHERTZ ASTROPHYSICS POST-HERSCHEL

Even with the largest single-mirror primary in space, the diffraction-limited resolution of Herschel at far-infrared wavelengths is not sufficient to spatially resolve the newly discovered ULIRG molecular outflows. Spatial information is necessary to understand how the outflows are driven and to examine the possible role of dense focusing structures in directing the gas flows. To obtain the angular resolution required to characterize the spatial structure of these molecular outflows, interferometers are required. The newly operational Atacama Large Millimeter Array (ALMA) in Atacama, Chile, is an international astronomical spatial interferometer that operates at submillimeter wavelengths and will be able to observe molecules in ULIRGs and to study the coldest dust components. Ideally, observations should be carried out at far-infrared wavelengths where ULIRGs emit the bulk of their luminosity. Someday, astronomers will be able to spatially resolve nearby ULIRGs in the far-infrared by building an interferometric array of telescopes like Herschel and flying them in formation in space.

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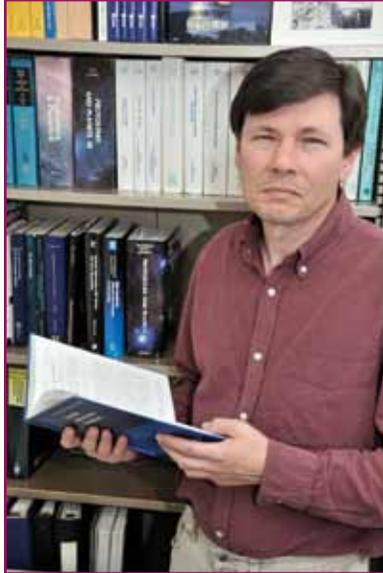


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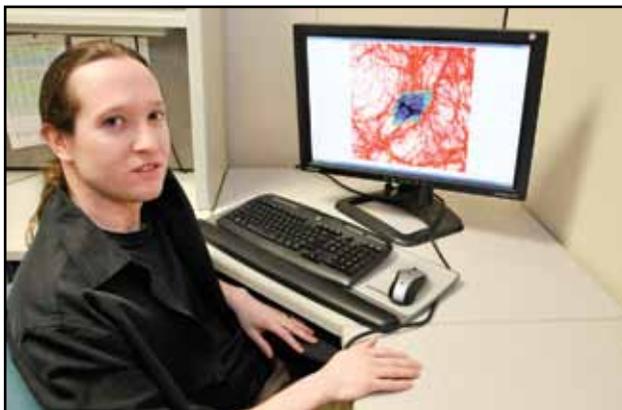
A model of Herschel is on display in the background.



JOHN S. CARR is an astrophysicist in the Radio/Infrared/Optical Sensors Branch of the Remote Sensing Division. He received a bachelor's degree in physics from Harvey Mudd College in 1980 and a Ph.D. in astronomy from the University of Texas at Austin in 1988. Following postdoctoral fellowships at the Institute for Astronomy, University of Hawaii, and at the Ohio State University, he joined NRL as a staff researcher in 1995. His research interests include the origins of planetary systems, star formation, molecular abundances in stars and the interstellar medium, and infrared instrumentation. In his work, he analyzes data collected from both space and ground-based telescope facilities using a variety of spectrographs, ranging from near-infrared to terahertz wavelengths.



ROBERT L. LUCKE received the Ph.D. degree in physics from the Johns Hopkins University in 1975 and came to the Optical Sciences Division of NRL in 1982, where he developed airborne optical systems and analyzed the data they returned. He has worked extensively in optical modeling, including the use of aberration theory and of Fourier optics, which he applied to analyzing the terahertz behavior of the Herschel telescope. He has been in the Remote Sensing Division since 1994, where he has worked in the areas of sparse-aperture and synthetic-aperture imaging, optical system design, and hyperspectral imaging from air- and spaceborne platforms. He was the systems engineer for the Hyperspectral Imager for the Coastal Ocean (HICO), which has been returning images from the International Space Station since October 2009.



EMIL J. POLISENSKY began his career at NRL under an internship in the summers of 2002 and 2003. Upon completing his M.S. degree in astronomy studying X-ray binaries at San Diego State University, he came to work full-time in the radio astronomy group of the Remote Sensing Division. He has been involved with the research and development of low-frequency antennas and interferometers, simulations of phased array design and imaging with sparse arrays, modeling the low frequency radio sky, and reducing spectrometer data from the Herschel Space Observatory. He is also pursuing a Ph.D. degree at the University of Maryland under the NRL Edison Graduate Training Program, conducting numerical research in cosmology.