*Gemini*Focus

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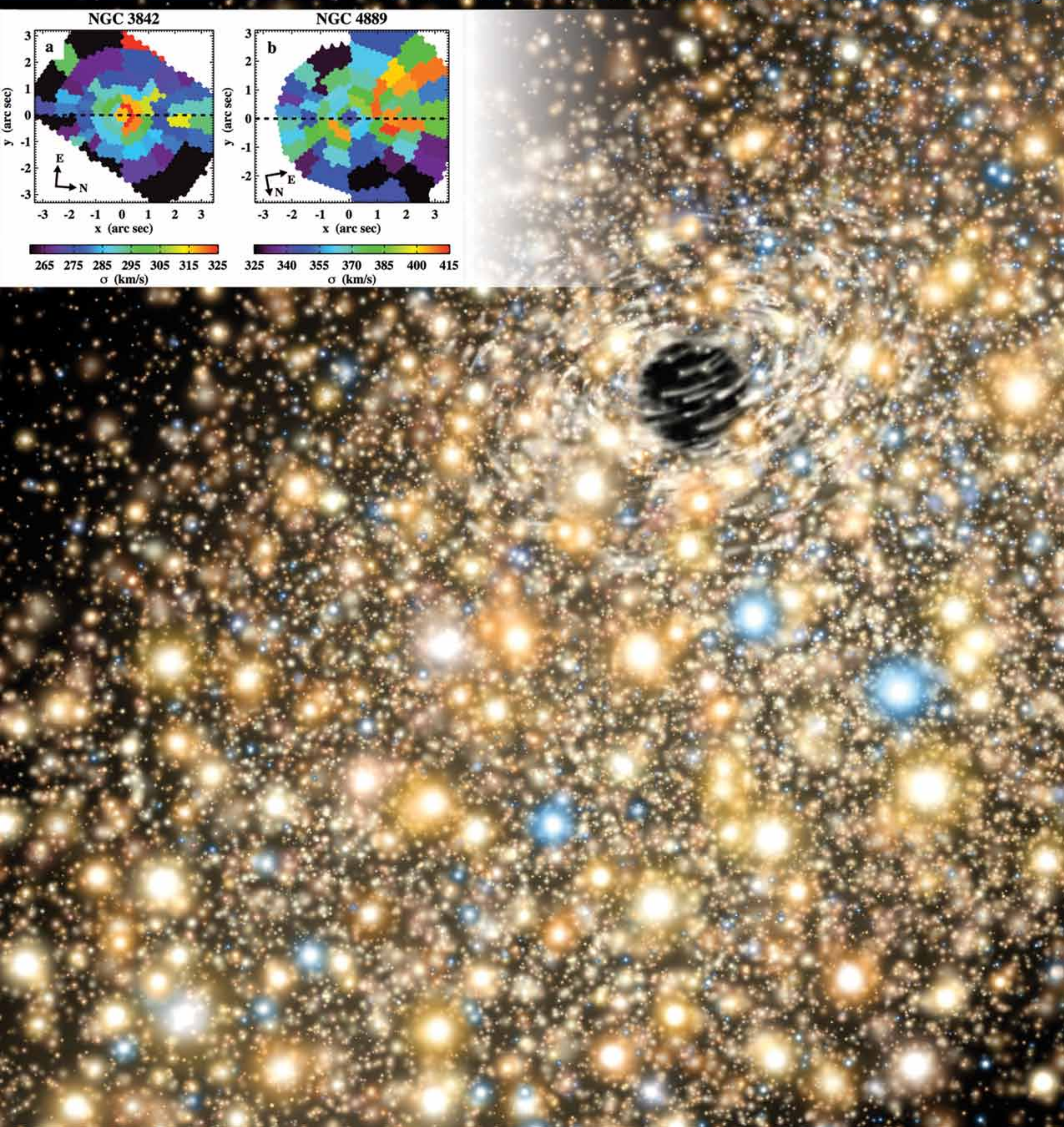


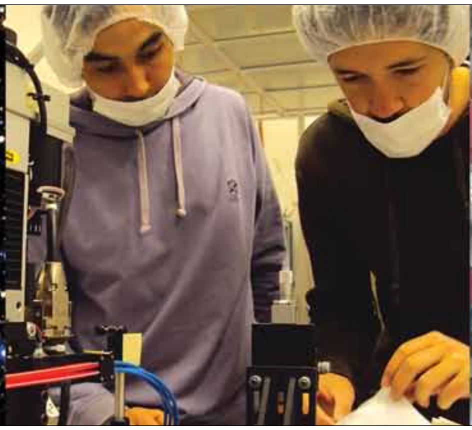

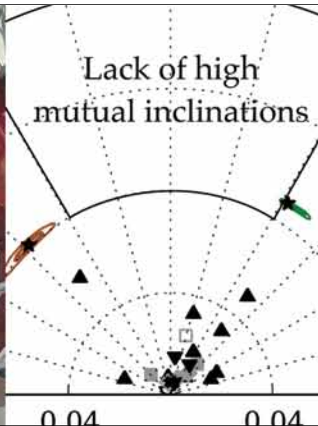

*Gemini*Focus

by Tom Geballe

Infrared Diffuse Interstellar Bands in the Galactic Center

Infrared spectroscopy at Gemini North of hot and luminous stars in the Galactic Center has unexpectedly revealed an emission line leaking through the dusty cocoon around one of the mysterious "Quintuplet" stars. Additional observations of these stars have resulted in the surprising discovery of 13 new "diffuse interstellar bands," which could someday help solve the 90-year-old mystery as to the source of these bands.

Astronomical observations occasionally result in unexpected discoveries made while pursuing completely unrelated scientific goals. In addition to resulting in exciting new science, such occurrences can provide opportunities to enlarge our knowledge. Best of all, they are just plain fun. Together with colleagues, Paco Najarro of the Center of Astrobiology in Spain, his student Diego de la Fuente, Don Figer of the Center for Detectors at the Rochester Institute of Technology, and former Gemini Science Intern Barret Schlegelmilch, I have recently been fortunate enough to stumble upon two such discoveries. Both of them were made while pursuing one of our major research themes: infrared spectroscopic studies of stars and gas in the center of our Galaxy.

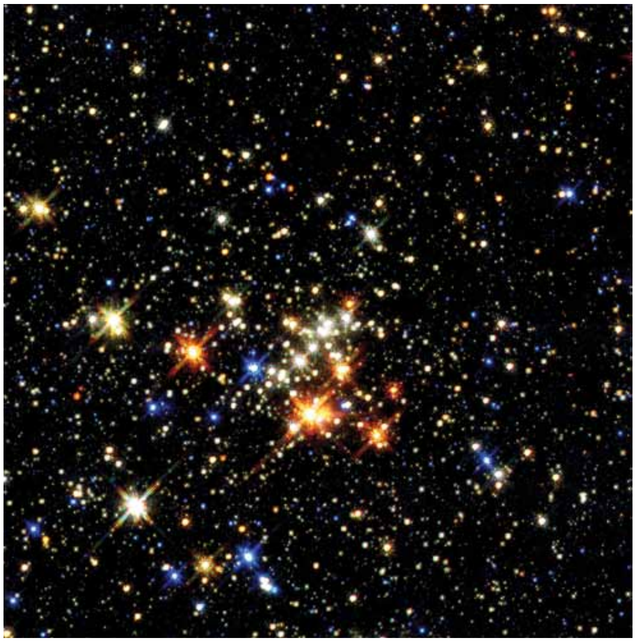

Figure 1.

Infrared multi-wavelength false-color image of the Quintuplet Cluster obtained by the NASA Hubble Space Telescope. The five brightest red stars near the center of the image are the infrared "Quintuplet" for which the cluster is named. Most of the white objects are hot stars in the cluster that, unlike the Quintuplet stars, are not encased in their own dusty cocoons. The blue objects are foreground stars.

The Galactic Center (GC) is a fascinating environment, containing a multitude of extraordinary phenomena and objects, including a four million solar mass black hole right at the center, three dense clusters of young hot stars within 30 parsecs (pc, one parsec is approximately 3.26 light-years) of the black hole, and a vast amount of gas existing in a wide range of physical conditions within 200 pc of the center. All of these are some 8 kiloparsecs from the Sun. Some of our recent research has crystallized around studying the young hot stars in one of those clusters, known as the Quintuplet Cluster (Figure 1). One of the most massive resolved young clusters in the Local Group, the Quintuplet lies only 30 pc distant (in projection) from the black hole.

The name "Quintuplet" comes from five bright infrared stars located near the cluster's center; the discovery of them 20 years ago led to the discovery of the cluster itself. The natures of these five stars have long been a mystery. Stars in the GC are obscured from view by approximately 30 visual magnitudes of extinction due to dust particles situated between the Sun and the GC. That means we can observe those stars only at infrared wavelengths.

The five bright infrared stars not only suffer that interstellar extinction, but also are obscured by dust surrounding each one of them. It is these warm dusty "cocoons," each heated by the star inside it, that makes them so bright at infrared wavelengths compared to other stars. However, the cocoons make the surfaces of those stars impossible to observe, even at infrared wavelengths, or so everyone thought until recently.

An Unexpected Discovery

Because of its smooth dust-continuum spectrum, astronomers often use the brightest of the Quintuplet stars, known as GCS3-2, to calibrate measurements of fainter stars in the GC that have more interesting infrared spectra. In 2009, while using a low-resolution spectrum of GCS3-2, obtained with Gemini's Near-infrared Imager and Spectrometer (NIRI) as a calibrator, I made the first unexpected discovery: a weak and broad emission line in its spectrum near 1.70 microns (μm). This emission, due to excited helium in very hot gas, apparently leaks through GCS3-2's dust cocoon. It provides strong evidence that the embedded star is hot and massive, and in many respects similar to the other cocoonless hot stars in the Quintuplet Cluster. It also hinted that the four other members of the Quintuplet are probably similar objects. The idea that the cocoon of each Quintuplet object contained a hot star had been put forth previously, but virtually no direct evidence existed to support it.

To test that idea, we applied for, and received, Gemini North time in Semester 2010B to obtain medium-resolution H-band (1.5 - 1.8 μm) spectra of each of the Quintuplet sources, as well as spectra of them at even shorter infrared wavelengths. Although the effects of foreground extinction are more severe at shorter wavelengths, making objects in the GC appear much dimmer there, we reasoned that the contamination by the continuum radiation from the dust cocoons would be much less. If so, then key diagnostic short-infrared wavelength emission lines from the central stars, although heavily attenuated along with the continua, would be more prominent above those continua.

No one had previously obtained such short wavelength infrared spectra of GC objects, but estimates of the performances of both the Gemini Near-Infrared Spectrometer (GNIRS) and the Near-infrared Integral-Field Spectrograph (NIFS) on Gemini showed that good quality spectra of the Quintuplet objects should be obtainable. We also obtained additional observing time in 2010B and again in 2011A to obtain more detailed spectra of many of the "naked" hot stars in the Quintuplet Cluster and nearby, including pushing measurements of them down to shorter infrared wavelengths.

Another Surprise

The first set of these spectra, obtained in 2010B with NIFS, was reduced by Gemini science intern Barret Schlegelmilch, at that time an undergraduate student at the University of California, Los Angeles. The spectra that we have obtained since 2010B use GNIRS and are being reduced by Diego and myself. To date we have found that the short wavelength infrared spectra of some of the Quintuplet's other four members indeed contain emission lines of hydrogen and helium, showing that our technique works and that the embedded stars are hot and massive like GCS3-2. The spectra of the cocoonless hot stars reveal that they cover a wide range of spectral types and evolutionary stages. Detailed analysis of them by Paco, Diego, and Don is under way. We expect to use them to derive abundances of other elements such as carbon, oxygen, and nitrogen, in order to test theories of the cluster's initial mass function and evolution.

But buried in the 1.5 - 1.8 µm spectra of each of these stars was the second unexpected discovery: a number of narrow absorption lines, which we had never seen before. Several of these are shown in Figure 2. Initially we assumed that these lines were intrinsic to the stars themselves, even though we could not identify them as we could every other spectral feature. However, we soon realized that they were invariant in wavelength and almost invariant in strength from star to star. This indicated that they were of interstellar origin, but what kind of interstellar material produced them? Nobody had previously reported these spectral features in any interstellar environment and their wavelengths did not match the absorption bands of any simple molecules.

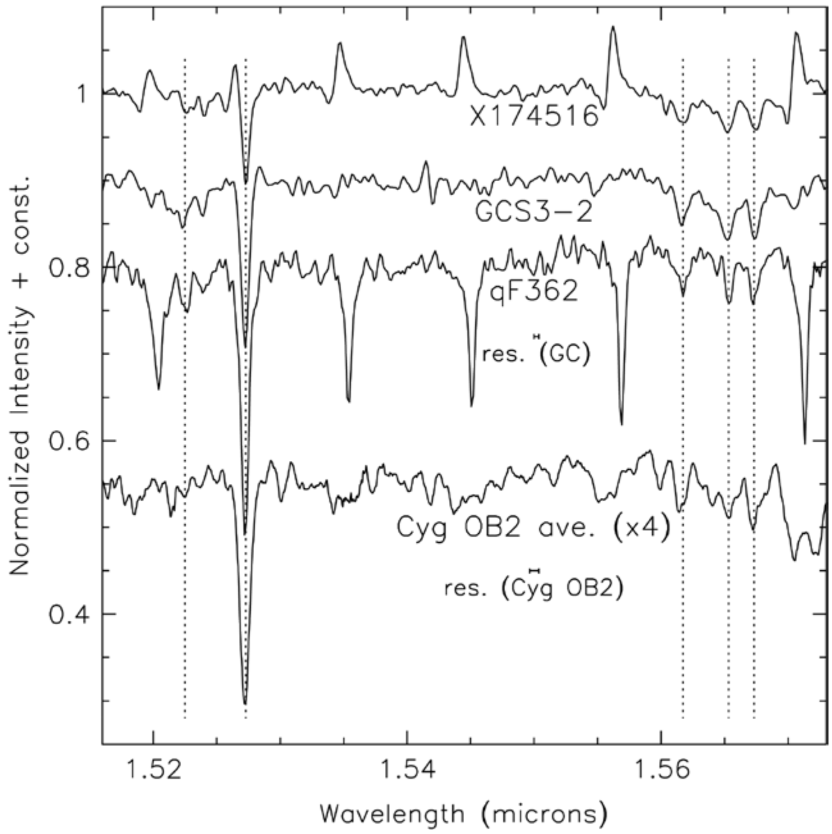

Figure 2.

Observed spectra of three hot stars in the GC, and an average spectrum (magnified by a factor of four) of seven stars in the Cygnus OB2 association. The wavelengths of five newly discovered diffuse interstellar bands (DIBs) are indicated by vertical dotted lines. The prominent emission lines in the spectrum of X174516, and absorption lines in the spectrum of qF362, are Brackett series transitions of atomic hydrogen, which are often present in hot, luminous stars. The strongest DIB, at 1.5273 µm, is blended with one of the Brackett lines in the spectra of X174516 and qF362, but is uncontaminated in the spectrum of GCS3-2.

Our initial and tentative conclusion, which was quickly supported by other evidence, was that they were new members of the family of "diffuse interstellar bands," or DIBs. Most astronomers are aware that the optical spectrum of any star viewed through a sufficient quantity of diffuse interstellar material (that is, interstellar gas that is less dense than the gas clouds out of which stars form) contains a large number of DIBs. The first DIBs were reported 90 years ago by Mary Lea Heger, while she was a graduate student at the Lick Observatory. At present well over 500 different ones are known (Figure 3).

Surprisingly, none of the DIBs have been convincingly identified with a specific element or molecule. Indeed, identifying them, individually and collectively, presents one of the greatest challenges in astronomical spectroscopy. Over the years, many scientists have proposed identifications for some of them, but none has held up under close scrutiny. The pioneering astro-chemist William Klemperer once remarked, "There is no better way to lose a scientific reputation than to speculate on the carrier for the diffuse bands." That point notwithstanding, recent studies have suggested that the DIB carriers are large carbon-containing molecules.

Almost all of the previously known DIBs occur at visible and very near-infrared wavelengths, with only two known at wavelengths beyond 1 µm (10,000 Å), The longer wavelength of those two J-band DIBs is at 1.318 µm. Thus, the new H-band DIBs, lying between 1.50 and 1.80 µm, are by far the longest wavelength DIBs detected to date. We found 13 H-band DIBs in total, with the four most prominent ones occurring between 1.52 and 1.57 µm, as shown in Figure 2.

That figure also contains a composite spectrum of several hot stars in the Cygnus OB2 star-forming region, which is located far from the GC, but which is also significantly obscured by dust in diffuse foreground gas. Paco had obtained full H-band spectra of those stars in 2002 at the Telescopio Nazionale Galileo on La Palma. Our discovery prompted him

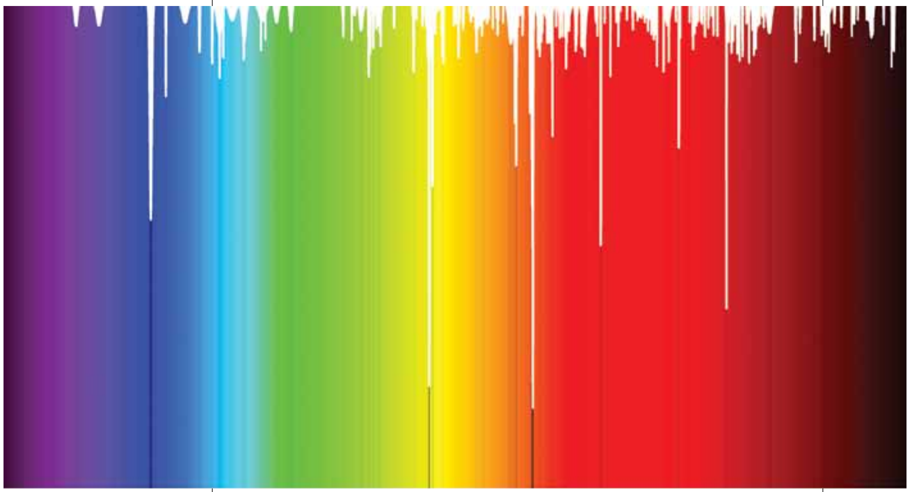

Figure 3. *Simulated 3500 - 9800Å (left to right) spectrum of diffuse interstellar bands discovered prior to 2005. Each white line segment corresponds to a DIB. Its length and the darkness of the line below it each correspond to the strength of the DIB. Figure is courtesy of B. J. McCall.*

to take a closer look at those spectra. Indeed the four strong absorption features mentioned above were present, at about one-quarter the strength of their counterparts toward the GC.

As the optical spectra of the Cygnus OB2 stars are already known to contain DIBs, the presence of the H-band absorptions in both sightlines is consistent with the identification of the absorptions as DIBs. Their relative weakness toward the Cygnus OB2 association also makes sense, as the quantity of diffuse cloud material in front of the GC is known to be about four times the amount in front of Cygnus OB2.

Where along the 8-kiloparsec-long sightline to the GC are the carriers of the H-band DIBs located? We have good reason to think that most of them are found close to the very center, in a ~400-pc-diameter region known as the Central Molecular Zone (CMZ). Infrared spectroscopy of the molecular ion H_3^+ toward GC sources, including GCS3-2, obtained at Gemini, Subaru, and UKIRT by another set of scientists including me, has shown that the CMZ contains a vast quantity of diffuse gas and that compared to it, relatively little such gas is present elsewhere along our sightline to the GC.

The diffuse interstellar medium in the GC is a considerably harsher environment than the diffuse clouds where DIBs have been observed previously. The gas temperatures in the center are 200 - 300 K, compared to 30 - 100 K in Galactic diffuse clouds and the cosmic ray ionization rate is an order of magnitude higher. Thus, our finding — that the strengths of the H-band DIBs in Cyg OB2 and the Galactic Center are in rough proportion to their diffuse cloud extinctions — suggests that the carriers of these bands survive equally well in both environments.

Future Research

The discovery of the H-band DIBs should widen the study and use of these enigmatic absorptions. The new bands, together with the two J-band DIBs, can serve as infrared probes of the diffuse interstellar medium in regions that heretofore have remained inaccessible due to high optical extinction, which prevents observations of shorter wavelength DIBs on those sightlines. For example, clusters of hot, massive stars in distant regions of the Galaxy could be the background stars for such studies, as they are bright and some stars in them have relatively featureless spectra.

Astronomers might also use the infrared DIBs to constrain the nature of gas in front of heavily obscured extragalactic nuclei, such as Seyfert II nuclei and both luminous and ultra-luminous infrared galaxies. Studies of the correlation of the strengths of the strong J-band and H-band DIBs may also prove valuable in understanding whether they arise from the same molecule or families of molecules. Finally, because this portion of the infrared spectrum is less congested than the visible spectrum, accurate knowledge of the wavelengths of the infrared DIBs should improve the chances for their identification, e.g. via laboratory spectroscopy.

My colleagues and I look forward to the promise of future research and perhaps more "unexpected" discoveries as we begin to investigate these new and longest wavelength examples of a long-standing interstellar mystery.

The discovery of the H-band DIBs has recently been published by Geballe, T. R., *et al.*, *Nature*, **479**: 200, 2011. Previous observations of the diffuse gas in the GC have been published by Oka, T., *et al., The Astrophysical Journal*, **632**: 882, 2005.

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