ASTRONOMY BEAT

Glasses for Mr. Magoo's Spectrograph

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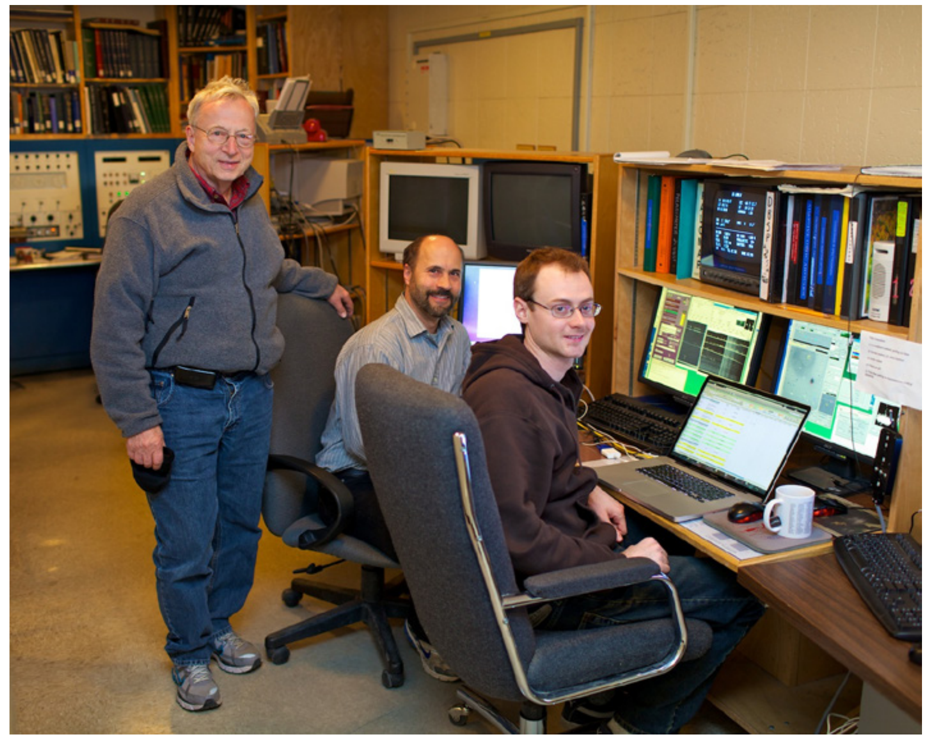
Trains, Stars, and Doppler Shifts

You have heard the Doppler effect, but perhaps not realized it. Anytime a train, ambulance, or fire truck goes by you with its horn blaring, you might have noticed the pitch lowering as the horn passes you and travels away. *Yeeeeuuuurrrmmmn!* That is because the sound waves get stretched out as the horn recedes from you, and when these stretched waves reach your ears, the crests and troughs are a bit delayed and thus appear to vibrate at a lower frequency than if the horn were stationary.

The Doppler effect also applies to light waves. When a light source moves toward you, the wavelengths are compressed and shorten (called "blueshifted"). When a light source moves away from you, the wavelengths are stretched and lengthen (called "redshifted"). Analyzing the Doppler shifts of starlight was the primary method used by astronomers looking for exoplanets in the 1990s — and it was a huge technological challenge.

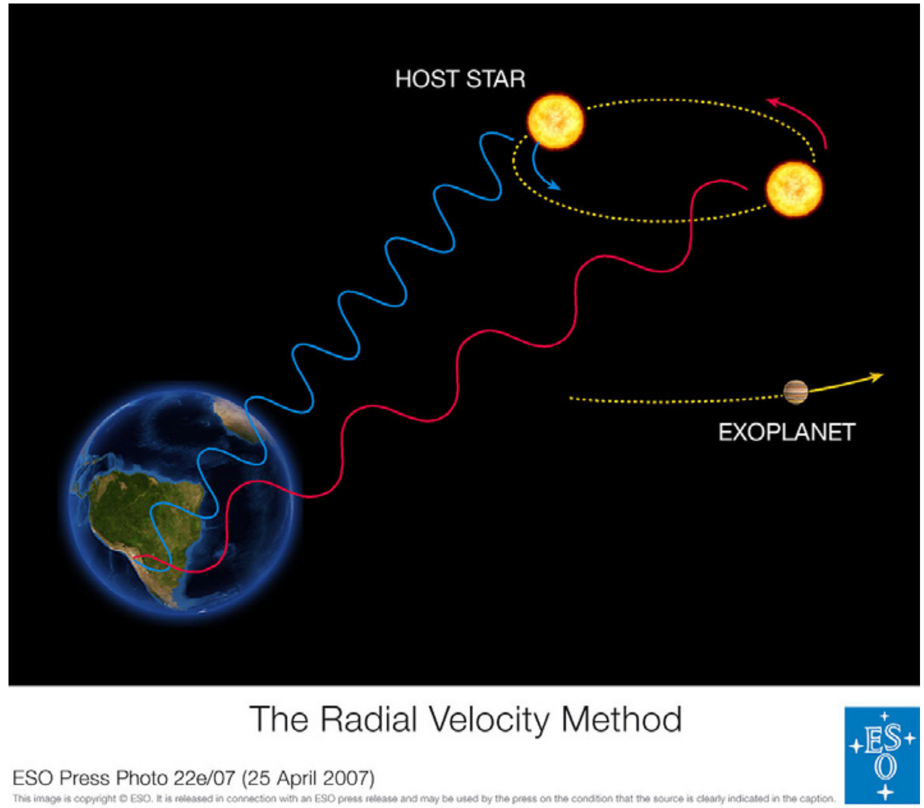
A star will be gravitationally tugged back and forth by an orbiting exoplanet. This wobble is particularly noticeable when the exoplanet is large — think Jupiter size and bigger. The star and its planet will orbit around their mutual center of mass. Because the exoplanet's mass is so much smaller relative to the huge stellar mass, this wobble is very small. By measuring the Doppler redshifts and blueshifts of the star's light, stellar wobbles were measured at



David Erskine (center) shows the control room at Hale Telescope of Mt. Palomar Observatory to his father John Erskine (left) while Cornell graduate student Phil Muirhead (right) takes Doppler velocimetry data using the EDI instrument for his Ph.D. thesis. *[Tim Erskine]* about 50 meters per second (about 110 miles per hour) for some of the first exoplanets discovered.

Measuring the Doppler shifts of these stars was a tremendous challenge, requiring exceedingly sensitive instruments. The Doppler change is given by the ratio of the star's velocity to the speed of light (300 million meter per second). Since the speed of light is such a large number, the Doppler ratio is extremely small, being 50/300 million or just one part per six million. This is a much smaller ratio than the acoustic Doppler pitch changes we hear from a train. For the sake of comparison, say we take the speed of a train (60 mph) and divide that by the speed of sound (770 mph). That would make the shift in wavelength an 8% effect — roughly the difference in pitch between middle C to the very next lower key B on a piano.

When astronomers use the optical Doppler effect to measure the wobble of a star due to the presence of an orbiting planet, they actually need to detect shifts 10 times smaller than one part in six million to keep their measurement errors under a 10% threshold. This requires astronomers to make Doppler shift measurements with an accuracy of five meters per second, which is only one part in 60 million.



The gravitational tugging of an orbiting exoplanet causes the host star to move in a tiny ellipse, which causes the apparent wavelength of the star's light to vary slightly over the period of the orbit. This Doppler wavelength shift can be measured to identify the presence an exoplanet. *[ESO]*

Two Doppler Techniques: Dispersive vs. Interferometry

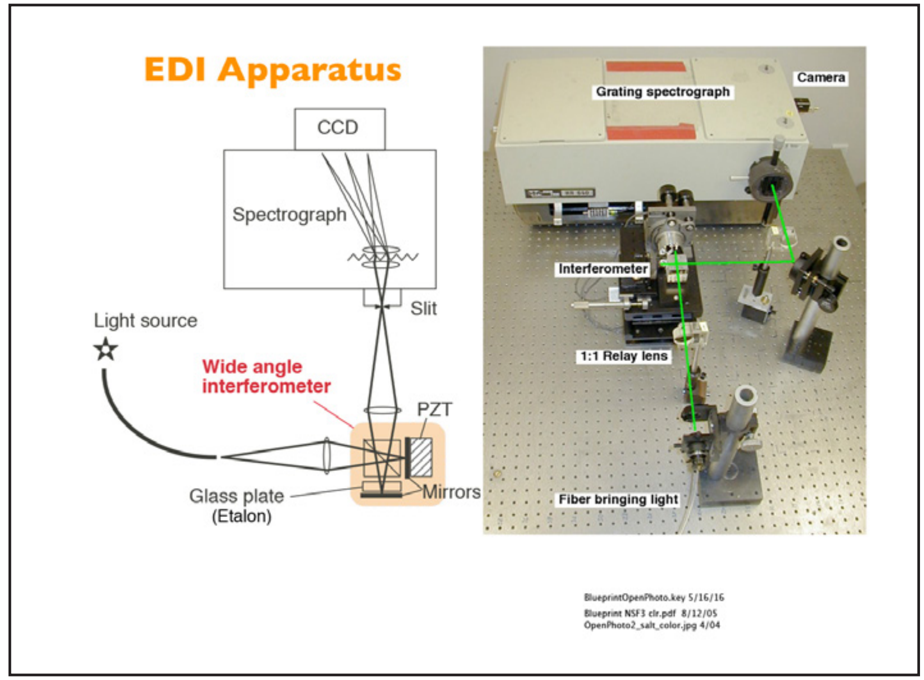
In 1997, optical scientists had developed at least two ways of measuring such small wavelength changes in light. The more widely adopted by astronomers is called dispersive spectroscopy, where light is passed through a prism or diffraction grating and spread out into a spectrum. This spectrum falls on a pixelated detector, similar to that inside your digital camera. The Doppler effect shifts this spectrum on the detector. However, it is an extremely small shift, typically just 1/100th of a pixel for 50 m/s, making it extremely difficult to discern against a host of unwanted effects such as thermal expansion of the detector and random mechanical vibrations.

Another of the challenges of dispersive spectrographs is that to spread the spectrum out across enough pixels, the spectrograph must be large in size, sometimes several meters in length or the size of a kitchen. The mirrors and lenses in such a large instrument must be held rigid to a thousandth of a millimeter, which requires heavy metal beams. The cost of building a spectrograph capable of exoplanet Doppler measurements was often in the few million-dollar range. This made it out of reach of small observatories lacking a large budget.

The other method of measuring wavelength shift is called interferometry, a technique where bright light sources emitting a single wavelength (also called monochromatic light) are analyzed. Interferometry is not typically used in astronomy because starlight is weak and composed of many wavelengths at once. Interferometry is a technique that counts wavelengths. It does this by comparing, or interfering, two beams of light, to form sinusoidal fringes. Imagine that you analyze a beam of light and you count one million wavelengths passing by you. Then you count the wavelengths from the second beam and come up with 1,000,001 wavelengths. The difference is 1 wavelength out of 1,000,000 wavelengths. That is essentially interferometry, and it can be extremely precise if the wavelengths are pure (monochromatic) so that the interfered waves or fringes are of high contrast and thus easy to count.

The other advantage of interferometry is that interferometers can often be made more compact and inexpensive than a comparable dispersive spectrograph, and they often do not require as many detector pixels to record the fringes. These interferometers are more affordable by a small observatory budget.

But the challenge in applying traditional interferometry to measuring starlight is that this light is not monochromatic, but composed of a jumble of wavelengths ranging between 400 nm and 700 nm — a 300 nm range of wavelengths which is large compared to the average wavelength of starlight, or 550 nm. This means you will only be able to count about two wavelengths (or fringes) before the interference pattern weakens to nothing and stops your counting. So that inspired the idea, *what if we could make the starlight monochromatic? Then maybe we could use interferometry to hunt for planets!*



Schematic and photo of an early externally dispersed interferometer (EDI) used in proof of principle experiments of sunlight, to measure fringe shifts that revealed the rotation of the Earth relative to the Sun. An iodine vapor cell inserted into the beam was also used but is not present here. *[David Erskine]*

The Origins of Externally Dispersed Interferometry

That is exactly what I thought in 1997. For many years (since 1987) at Lawrence Livermore National Laboratory I had used interferometry to measure Doppler shifts of targets that were accelerated by explosives or impacts of projectiles. We illuminated the back of the target by a monochromatic laser beam. When the target moved, the light bouncing off the back was Doppler shifted. This light was sent through an interferometer where it was split into two beams. One of these beams had a longer path length than the other (we call the difference a "delay"). Then the two beams were brought back together and thus interfered. When the wavelength changed, such as due to the Doppler effect, the interfered light cycled through constructive interference (where crest aligns with crest), and destructive interference (where crest aligns with trough). The intensity of the interferometer output thus rose and fell each time the wavelength differed by one wavelength over the length of the delay. This rise and fall we call a "fringe." Typically our delays were 50 mm long and contained 100,000 waves. So when we measured a fringe's shift of one cycle, it was a Doppler shift of 1 part in 100,000. This was due to a target motion of the speed of light divided by 100,000, which is 3,000 meters per second (actually half that, because of the round-trip path bouncing off the target).

David Erskine (in hat) assisted by Michael Feuerstein, mounts an EDI built on a 1 x 1 foot board in front of the slit of the Hamilton spectrograph at Lick Observatory in 2002. The EDI doubled the resolution of the Hamilton while maintaining the original bandwidth. *[Tim Erskine]*

Then in 1995 I discovered a technique for using broadband white light instead of monochromatic and coherent laser illumination in the interferometer. This was surprising, since everyone (including myself) believed that monochromatic illumination was required to produce interference and thus fringes. Amazingly, I was able to use light from a standard light bulb to measure Doppler fringe shifted speeds of a few meters per second (the blade of a small fan), not using any lasers or any high-tech components that were not available 100 years earlier. This taught me that not everything in optics had already been invented — a fear I had earlier. This buoyed my spirits and gave me confidence in proposing more things that were "outside the box."

When I learned of how astronomers were measuring Doppler shifts of a few meters/second with (white) starlight, I naturally thought that using an interferometer would be a great way to increase the precision. I knew I had to make the light monochromatic somehow to produce highly visible fringes. So it seemed that I should essentially put a dispersive spectrograph in front of an interferometer. The grating would split the white starlight into many monochromatic channels, organized spatially. Then the interferometer would make fringes out of them. This should work. Except for practical reasons it is easier to put the interferometer in front of the spectrograph, since then one can work with a spatially compact beam. So that became the externally dispersed interferometry (EDI) idea I proposed to my physics department in 1997. They agreed to fund me for two years to conduct proof of principle experiments, and I set up a new lab for the project, and hired a post doc, Jian Ge, who was trained in astronomy as I had no astronomy experience.

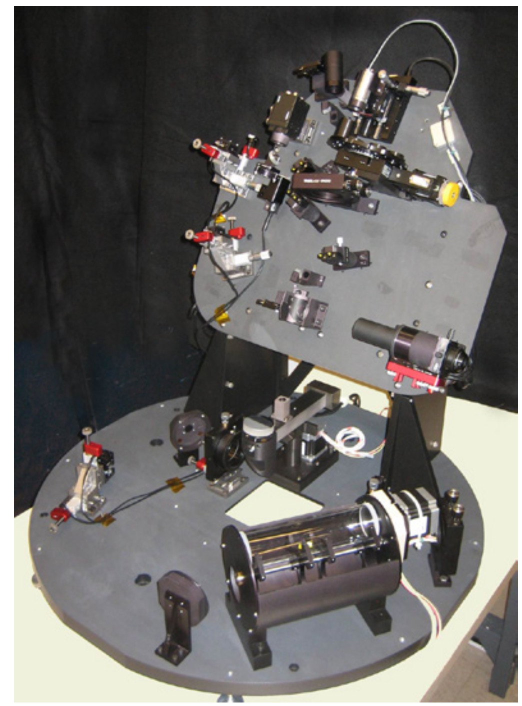


Photo of the EDI assembly (called "TEDI") designed to fit inside the Cassegrain output hole of the 200-inch Hale Telescope mirror at Mt. Palomar Observatory, to measure fringes of cool M-dwarf stars. *[Jerry Edelstein]*

The first measurements made to test the EDI technique were made on sunlight in 1998 using a roof-mounted heliostat supplying sunlight into a fiber. It was the happiest day of my scientific life to see these fringes for the first time, because it was relatively simple to build the interferometer and place it in front of a borrowed spectrograph. However, writing the software to analyze the fringes to sufficient precision took months of thinking and writing. After the software started working in December 1998, we saw that we could measure the effect of the Earth's rotation relative to the Sun to a precision of about eight meters per second, which was very good. We then knew the idea would work!

David Erskine in December 1999 standing by Lick Observatory Nickel 1-meter telescope, used to send Arturus starlight down a fiber (blue cord) to an EDI apparatus at a nearby table, where fringes were recorded to measure stellar Doppler velocity. *[Jian Ge]*

However, that was with bright sunlight. It was much more challenging to adapt the instrument for use with the weaker light of stars, by using longer time exposures. This in turn required stabilizing the interferometer cavity against drifts caused by wind-induced air pressure changes. We took successful stellar data using the 1-meter Nickel telescope at Lick Observatory in 1999. The project funding ended before all of our data analysis was complete. I took a sabbatical in 2000–2001 at UC Berkeley to develop a theory for the instrument, and sought other funding, and Jian Ge left to start his own lab. Eventually a new exoplanet, HD102195b, was discovered using the EDI technique in 2005 by his team at University of Florida, using a 0.90-meter Kitt Peak telescope.

EDI Can Also Do Spectroscopy

Later I realized EDI was useful for something other than measuring Doppler shifts. It was also useful for measuring the shape of a spectrum to very high precision, a technique called high-resolution spectroscopy. Spectroscopy is important for detecting chemical elements in distant stars (and other celestial objects) and their temperature and abundance, as well as their Doppler velocity. Each element has its own characteristic set of wavelengths that it emits or absorbs, and these can be used like fingerprints to identify them. For example, if these wavelengths are broadened instead of being narrow, you can infer that the element is under high pressure.

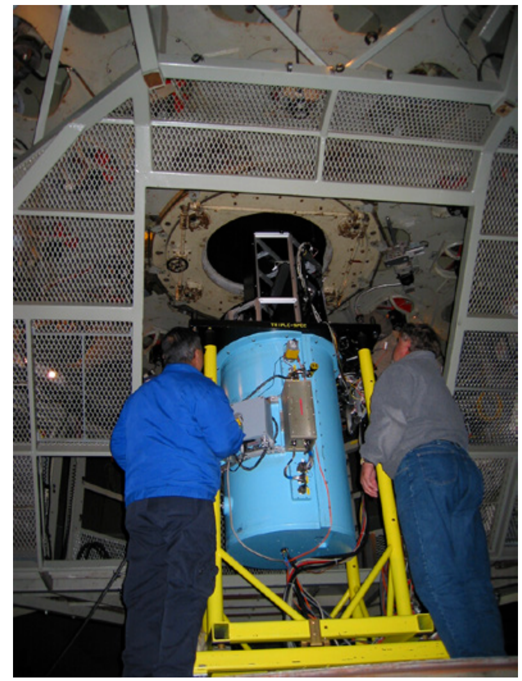
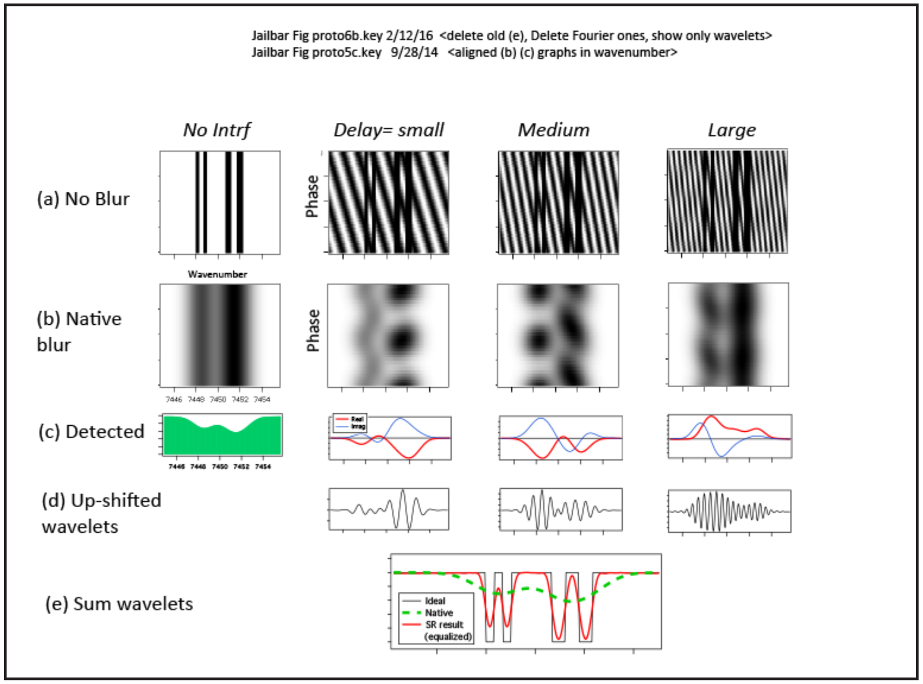
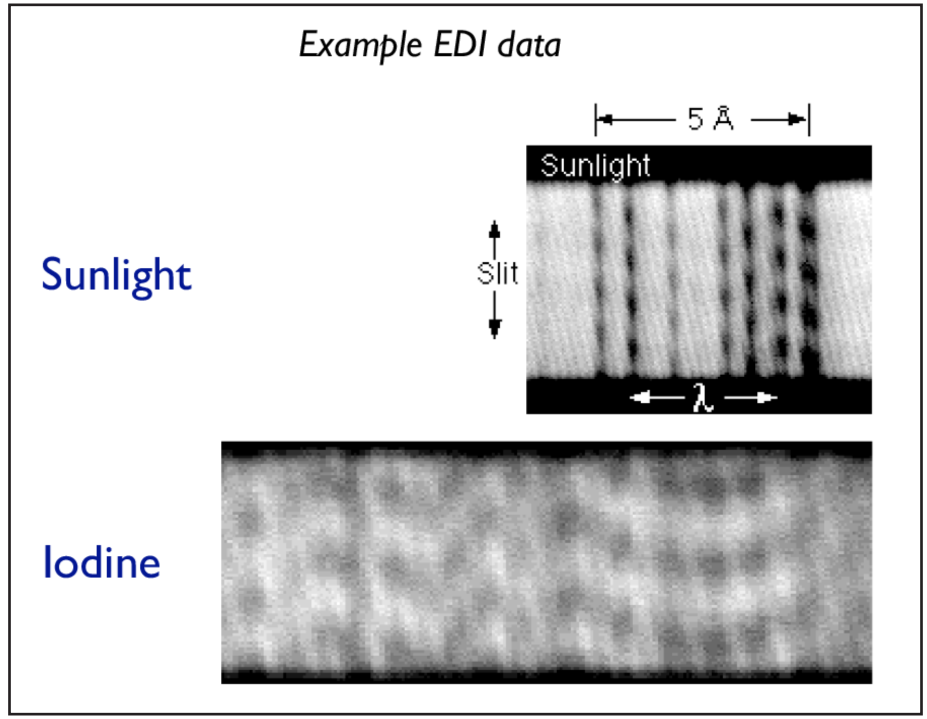


Photo of the EDI assembly mounted on top of the TripleSpec near-infrared spectrograph (in blue cryostat cylinder to keep it very cold at liquid nitrogen temperatures) while both are being raised to be bolted to the Cassegrain output hole of the 200-inch Hale Telescope mirror. *[David Erskine]*

Usually high resolution requires a large, "kitchen-size" instrument. However, EDI can springboard a small low-resolution spectrograph to effectively produce a much higher resolution, beyond the capability of the spectrograph used alone. By analyzing the shape of the fringes, the interferometer can provide the high-reso-



Simulation of moiré pattern spectra formed between a uniform grid, which is the spectrum of the EDI interferometer illuminated by featureless white light, and four absorption lines. Each atom in a star's atmosphere creates a set of similar lines, like a fingerprint. Note that blurring caused by a wide spectrograph slit does not prevent the moiré. Different grid spacings create different moiré patterns. *[David Erskine]*



Example EDI moiré patterns measured in 1998 for sunlight (upper) and iodine absorption cell (lower), for green light (540 nm). A Doppler velocity shift causes the moiré pattern to shift vertically, because of the slant in the interferometer grid. *[David Erskine]*

lution details too fine for a native spectrograph alone to resolve. It's like the coarse and fine adjustments to an instrument. The interferometer can split hairs and provide the fine-tuning information, but not the broader shape. The native spectrograph is the opposite, it cannot resolve fine details but it provides the broader shape.

Together as EDI, they can deduce a spectrum's shape to a much higher resolution than with native spectrograph alone, by a factor we call "boost." We demonstrated a 2x resolution boost at the Lick Observatory Hamilton Spectrograph in 2002, and then a 10x boost at the Mt. Palomar 5-meter Hale Telescope in measurements taken from 2008 to 2011. In that project we also showed we could measure Doppler velocities from cool M-dwarf stars that emit most of their light in the near infrared wavelengths, similar to the star discovered recently in the TRAPPIST project to harbor seven earth-like planets. Picture a sun that glows red like a barbecue coal. With EDI we were able to mount a small spectrograph to the Cassegrain output hole of the main mirror and measure precision Doppler velocities. Without the interferometer, we would not have been able to make such precise measurements, since the spectrograph's resolution was too low, and also because the direction of gravity changes through the night, which can distort a spectrograph by a fraction of a pixel, which normally would be prohibitive.

The EDI developed by Jian Ge's group is taking advantage of the low-resolution requirement of the native spectrograph by measuring Doppler velocities of many objects simultaneously, connected to the telescope by many fibers, each individual to each star. This can help with survey work. We recently have begun exploring the use of the EDI technique with the Gemini Planet Imager, to greatly increase its spectral resolution (which is currently very low) so that it can better identify signatures of life-related molecules such as water, oxygen, and methane on exoplanets.

About the Author

David J. Erskine (Ph.D. experimental physics, Cornell University 1984) has been exploring and innovating diagnostic techniques in a wide variety of fields (i.e., femtosecond lasers, semiconductor physics, superconductivity, diamond cell high pressure, shock physics, Doppler interferometry, and digital holography). A common thread is his love of optics. Since 1987 he has been at Lawrence Livermore National Laboratory. Since 1997 he has collaborated with astronomers to develop new interferometric techniques for Doppler velocimetry and high-resolution spectroscopy. In his spare time he loves to compose piano music and explore the outdoors.

Resources

- Spectrographs (Multi-Wavelength Astronomy): http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/08.html
- Interferometer Animation (UffcomINFN): https://www.youtube.com/watch?v=UA1qG7Fjc2A
- Five Ways To Find A Planet (NASA): https://exoplanets.nasa.gov/interactable/11/ ✦

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Astronomy Beat Update

We are pleased to announce the exciting update of the ASP members-only *Astronomy Beat*. Every other month, starting in April, members and eNewsletter subscribers will receive *AstroBeat — Inside the ASP* featuring the exciting work our members and donors support. The renamed members-only *AstroBeat* will now offer bi-monhtly columns on astronomy.