EXOPLANET IDENTIFICATION: SIGNIFICANCE OF THE EXPRES SPECTROMETER

Gemma Wilson, ggw6@pitt.edu, Mena, 10:00AM

Abstract—Spectrometers, within the context of space telescopes, are instruments that analyze the wavelength of starlight (light spectrums) to deduce features of that planetary system. Some features may include, but are not limited to, the mass, composition, and placement of planets. However due to low resolution in the equipment and the great distances involved, is not uncommon to completely miss a planet of an earth-like mass. To overcome the shortcomings of current efforts in detecting exoplanets, planets outside our star system, the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) joint-commissioned the creation of the high-resolution Extreme Precision Spectrograph (EXPRES). This device, designed to augment the current capabilities of telescopes, acts as a supplement to calibrating the starlight that the telescope receives.

As of December 9, 2017, the EXPRES was relocated to the Lowell Observatory in Arizona. There, the EXPRES has become permanently mounted to the 4.3-m Lowell Observatory Discovery Channel Telescope (DCT) and is already fully operational.

Under the direction of Dr. Fischer and Dr. Jurgenson, this spectrometer was the third produced by the Yale Exoplanet Laboratory for the 100 Earths Project. This program’s main objective is to search nearby star systems in hope of finding 100 habitable worlds. Should this project prove successful, these planets—identified for being of the right mass, composition, and distance from their star—will be intensely studied to determine if life exists outside our solar system.

Learning about other habitable planets will aid us in the search to understand our own universe as well as provide the thrilling possibility of discovering other lifeforms. Furthermore, identifying the location and available resources of these exoplanets can be perceived as an infinitesimal step closer to living and traveling to these life-supporting planets. After all, it is often impossible to conceive how drastically the future will change by our current pursuits of scientific research.

Key Words— Exoplanet, EXPRES, Keplerian Doppler Shifts, NASA, Spectrometer, Sustainability, 100 Earths

HISTORICAL SIGNIFICANCE OF SPECTROMETRY

Spectrometry is the analysis of electromagnetic radiation as a means to uncover the chemical makeup of the test subject. Coupled with this field is a variety of spectrometers that are designed to read the emitted or absorbed wavelengths along the electromagnetic spectrum. The most recent feat in the field is the Extreme Precision Spectrograph (EXPRES). However, it wasn’t until the 1950s that the world began to see the first glimpses at a future of astronomic spectrometry.

Beginning with unmanned probes like the Aerobee rocket, spectrometers quickly established themselves as an invaluable pioneer in our aim to collect spectroscopic observations of stars [1]. Since then, spectrometers have been deeply integrated in space exploration and our efforts to advance the field. Finding themselves in missions like the last three Apollo flights, spectrometers have played vital roles in detecting atmospheric presence and composition [2]. The next advancement, similar to the case of the EXPRES, was designing spectrometers to attach to telescope instrument configurations (very much like a USB connecting to a computer but permanently joined). This connection between the equipment allows the collection of the same types of electromagnetic data but for a significantly greater distance.

What makes these spectrometers invaluable is their ability to collect both quantitative and qualitative data. When applied to the field of exoplanet detection, this technique detects planets’ atmospheric composition thereby determining suitability for human life. After humanity decides to initiate the colonization of nearby planets, this method will be heavily relied on when selecting planets that are eligible for colonization. In addition to atmospheric classification, a secondary benefit of spectrometers is their ability to identify available resources. Some examples include water and minerals; items that directly contribute to a hospitable environment and the progression of human civilization.

ROLE OF SPECTROMETRY IN EXOPLANET DETECTION

University of Pittsburgh, Swanson School of Engineering 1
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Exoplanets, classified by their position outside our solar system, are an important subfield of study within astronomy. Despite demonstrating an impressive rate of discovery, in order to reach new parameters of space the field will have to continue making sequential improvements to the current resolution and detection technologies [3]. In support of these efforts, prominent organizations including NASA and the National Science Foundation (NSF) have joined programs such as the 100 Earths Project to fund immense amounts of research into exoplanet detection. What makes the strenuous search for exoplanetary systems so rewarding is the considerable contribution of these discoveries to the understanding of our own solar system and the promise they hold for interstellar travel.

Although it may seem like a distant dream, we have been making strides of unprecedented scope. One of the most memorable events took place “in March 2017, [when] SpaceX achieved the world’s first reflight of an orbital class rocket” [4]. This is a remarkable development for the sustainability of space travel as completely reusable rockets had yet to be accomplished. Before now, vehicles such as the Space Shuttle had been reusable to an extent, but maximum efficiency was lost due to flaws such as fuel tanks that burned up upon atmosphere reentry or were unrecoverable and now lie at the bottom of the ocean [5]. According to Elon Musk, founder and CEO of the SpaceX Program, “If one can figure out how to effectively reuse rockets just like airplanes, the cost of access to space will be reduced as much as a factor of a hundred” [4]. A complementary goal to Mr. Musk’s achievements is his desire to make us a “multi-planetary civilization.” Coupled with this is the significance of the EXPRES Spectrometer and the generations of spectrometers that follow; they are the key to identifying exoplanets’ available resources and whether or not they lie in the habitable zone.

**Habitable Planets and Where to Find Them**

A major incentive in the search for exoplanets is the promise of locating other habitable planets. For programs like the 100 Earths Project, the hope is to uncover exoplanets that demonstrate conditions necessary to sustain human life, planets otherwise referred to as “Exo-Earths” [3]. However this is no small task. In order to be considered “habitable” the exoplanets identified must comply with characteristics that make our own planet habitable. Of the many things that define life-supporting, there are a few specific characteristics astronomers look for, the most important of which includes the balance of gases in an atmosphere, a mass and composition similar to earth, and a position of orbit within the habitable zone. Fortunately, spectrometers are capable of identifying all of these features through advanced analysis of the electromagnetic spectrum. As mentioned before, spectrometers gather both quantitative and qualitative values of mass and composition. This data is acquired by measuring the positions of the absorption/emission lines on the electromagnetic spectrum. As demonstrated in Figure 1, there are two main methods for determining which elements are present within a celestial body. The first method, labelled as “hot gas,” is mostly used with stars and nebulae and requires the source to be emitting light itself. However, the second method which deals with absorption is much more common when working with planets. This is because their parent-star, the star which they orbit, can be utilized as the illuminating light source.

![FIGURE 1](image)

**FIGURE 1 [6]**
While the “Continuum Spectrum” demonstrates the unchanged light spectrum, below are data samples for the two methods of spectral detection; emission and absorption

Each element absorbs and emits a unique variety of wavelengths that can be consistently measured on the electromagnetic spectrum. By finding and measuring the displacements of the indicated lines and spaces, spectrometers can identify which elements are present within a planet [7]. From this comes the idea of “Keplerian Doppler Shifts” which, while keeping the line spacing the same, shift the entire pattern either towards lower or higher frequencies [3]. Looking at the absorption lines in Figure 2, the line spacing is unchanged—only slid towards the red or blue end of the spectrum. Based on these shifts, spectrometers predict which the direction the celestial body is moving in relation to the earth; red-shifted (lower frequency) is away while blue-shifted (higher frequency) is towards.

![FIGURE 2](image)

**FIGURE 2 [7]**
Unshifted absorption graph compared to a red and blue shifted data series
**Indirect Detection of Exoplanets**

Exoplanet detection is unique in the fact that most of its subjects are studied indirectly, or rather by their effects on more visible objects [8]. As seen in Figure 3 it is the radial velocity of the parent star that is taken rather than that of the exoplanet. The radial velocity of an exoplanet is measured through the red and blue shifts detected as it moves towards or away from the earth. These spectrum shifts rotate at regular intervals from which data such as the period, frequency, velocity can be derived [3]. This technique has played a fundamental role in the first discoveries of exoplanets and will remain a powerful tool in our search for exoplanetary systems [3]. What makes it so valuable is that while these exoplanets remain unseen, what can be seen are gravitational repercussions on the star they orbit. These gravitational pulls are the reason that a majority of planetary systems do not simply “spin” around a parent star fixed in space. Rather, when spectra are in orbit, the bodies involved will revolve around the system’s common center of mass [7]. Since we cannot see the exoplanets, we instead look to reveal the wobble-like motion in the velocity of the parent star. As both objects are pulled towards each other by the other’s gravitational force, they must share the same period and momentum to remain stable. Knowing the momentum, the values of mass and velocity can be calculated for the star and then be equated to find the corresponding mass of the unseen planet. For this reason, the ease at which wobbles can be detected is impacted by a combination of the planets’ masses and proximity to the star.

![FIGURE 3](image)

**FIGURE 3 [9]**
The star’s radial velocities shift blue while moving towards earth then shift red while moving away

Typically, spectrometers rely on a situation with a high-mass exoplanet which can be of a significant distance from its star, or a smaller planet yet within close enough proximity to create gravitational disturbances in a host star. From there, the spectrometer measures the gravitational impact on that star to pinpoint the location of the hidden planets and to determine whether they lie in the habitable zone.

The habitable zone of a system, highlighted in Figure 4, is defined by the distance from the host star where the temperature allows for liquid water and therefore a possibility of life [10]. Of the five stars pictured, the yellow-dwarf in the middle most closely resembles the size and luminosity of our sun. Customarily, the energy given off by the host star is determined by the wavelengths of light that are emitted the strongest. This total amount of the energy emitted by a star per unit of time is then defined by the term “Luminosity” [11].

![FIGURE 4](image)

**GCSE Astronomy Diagram of the habitable zone in relation to the mass of the star**

The observable pattern from Figure 4 is that although the zone itself does not vary much in its width, its displacement from the parent star is directly correlated to the mass of the star. In addition to an increase of mass along the y-axis, Figure 4 makes a visual attempt to show an increase in “brightness.” This is no coincidence since the more massive the star, the hotter and more luminous it. Since we know these two constants are interdependent, the placement the habitable zone and the mass of the parent star can be determined by finding the luminosity [11]. For that reason, it should come as no surprise that luminosity can be calculated by using the relation between the stellar radius, surface temperature (of the star), and the Stefan-Boltzmann constant ($\sigma$) [11].

$$L = 4\pi R^2 \sigma T^4$$  \hspace{1cm} (Eq 1)

Where:
- $L$ = luminosity in watts
- $R$ = stellar radius in meters
- $T$ = surface temperature in Kelvin
- $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

In reference to Figure 5, in order to backcalculate for the stellar radius required in Equation 1, we must first find the measure of the parallax given by the variable $\theta_p$. Since the calculations are referenced by our position in space, the parallax is the half the angle given by the diameter of the earth’s orbit (see Equation 2). Knowing that, the law of right
triangles shows that the displacement between the earth’s center of orbit and the star can be represented by the trigonometric function given in Equation 3, assuming we hold Equation 2 to be true [13].

\[
\theta_p = \frac{\theta}{2} 
\]

\[
\tan\left(\frac{\theta}{2}\right) = \frac{B}{D} \tag{Eq 3}
\]

Where:
- B = radius of Earth’s orbit
- D = displacement from the center of the Earth’s orbit to the star

\[\text{FIGURE 5 [13]}\]
\text{The angle } \theta/2 \text{ is the parallax, a variable used in the backcalculation for luminosity}

The last value necessary for the luminosity calculation is the star’s surface temperature which can be found by Equation 4 [11]:

\[
T = 4600K\left(\frac{1}{0.92(B_0 - V) + 1.7} + \frac{1}{0.92(B_0 - V) + 0.62}\right) \tag{Eq 4}
\]

Where:
- \(B_0\) = magnitude of starlight through a blue filter
- \(V\) = magnitude of starlight through a visual filter

An Evolution in the Search for Earth-like Worlds

All the processes and data observations outlined in the previous paragraphs would be near impossible without the aid of high caliber spectrometers, yet for the study of exoplanets to continue making such leaps and bounds it must continue to advance its technology. Spectrometers are a particular interest to researchers for as their resolution increases, so does the distance we can analyze. Recognizing the value of these instruments, NASA and the NSF invested in the work of the Exoplanet Lab at Yale University by commissioning the creation of the EXtreme PREcision Spectrograph (EXPRES), capable of “a radial velocity (RV) measurement precision of 10cm/s” [14]. This is significant because “a small planet like Earth only induces a 10cm/s reflex velocity in its host star” [15] making the target velocity the minimum resolution necessary for finding Earth analogs. Additionally, the EXPRES has been estimated to “induce mean radial velocity (RV) estimation errors of order 1cm s\(^{-1}\)” [16]. In contrast to previous spectrometers Yale’s Exoplanet Lab constructed, the EXPRES has a resolution of R=150,000, a figure 2.5 times stronger than the others’ spectral resolution of R=60,000. What is important to understand is that ground-based equipment must accommodate for not only the immense distance between earth and the object of interest, the equipment must also factor in the earth’s own dense atmosphere and outside interferences like stellar jitter. To get a grasp on how impressive this feat is, consider Alpha Centauri. Alpha Centauri is our nearest star system and resides 1.3 parsecs away, an approximated 4.3 light-years [17]. The resolution of the EXPRES is so strong, it will allow the observation of distances that span more than 20 parsecs (65 light years) [18], a figure that should not be belittled.

**EXPRES OPTIC DESIGN AND CONSTRUCTION**

The EXPRES was designed as an experiment to reinvigorate the field of exoplanet detection by spear-heading a new generation of spectrometers. What makes the EXPRES unique, other than its extraordinary resolution, is the boost in the wavelength calibration due to the implementation of a laser frequency comb with the built-in precision of 1 cm/s [15]. While designing this, Fischer and her team took lessons from other spectrometers such as the CHIRON spectrometer that demonstrated “wavelength calibration is not always an easy retrofit; it is something that needs to be designed into the instruments form the start” [3]. Taking this to heart, the EXPRES was designed to be the best it can possibly be—without relying on the idea of future upgrading.

The EXtreme PREcision Spectrograph is a “white pupil design spectrometer” [3] commissioned for the 4.3m Discovery Channel Telescope (DCT) located at the Lowell Observatory in Arizona. Although completed during the summer of 2017, it wasn’t until December of 2017 that the EXPRES’s telescope interface was permanently mounted to one of the DCT’s five cube ports [15].

**Major and Minor Components**

The EXPRES is composed of two major subsystems; a Front-End Module (FEM) and a Back-End Module (BEM) [15]. The major difference is that while the FEM is secured to the DCT cube port, the BEM is located in an environmentally controlled room that is “fed via fibers from the telescope interface” [14].

Visible in the right half of Figure 6 is the EXPRES’s Front-End Module whose function is to “direct starlight from the telescope into a fiber that feeds the spectrograph” [15]. Additionally, it is responsible for: atmospheric compensation, correction for “tip-tilt image motion,” centering the light from
the telescope into the fiber and inserting calibration light to aid data calibration [14].

Visible on the left half of Figure 6 is the Back-End Module and its “three major assemblies; the vacuum enclosed spectrograph, the double scrambler/pupil slicer, and the calibration unit” [15]. This is the section responsible for the interpretation and calibration of the light received from the DCT. However, since this involves a very sensitive process from delicate technology, these major components have been situated within an isolated, environmentally-controlled room.

**FIGURE 6 [14]**

Layout of both subsystems and how their major components are interconnected

**Necessary Compensations for Precise Results**

Pictured in Figure 6, directly attached to the spectrograph is the charged coupled device (CCD) detector which is responsible for capturing of light and converting it into digital data [8]. Since the light has been converted into digital data, measured in pixels, shifts of stellar lines are also measured within units of pixels. However, within the case of the EXPRES, “a doppler precision of 1 ms⁻¹ corresponds to shifts of stellar lines across 1/10000th of a CCD pixel” [8]. This simply means the EXPRES’s resolution is extraordinarily better than single pixel measurements.

Like other stabilized spectrographs, changes of temperature or pressure in the EXPRES’s BEM may lead to variations in the positioning on the CCD. So to preserve the internal workings, the BEM is “housed in a large vacuum chamber maintained at a pressure better than 10⁻⁵ Torr” [14], which is located in a room that is “thermally stabilized to +/- 0.5K and incorporates radiation shields and an insulating shell” [14]. Other forms of interference include vibrations from the building itself. For example, while the Discovery Channel Telescope is observing, “the dome will follow the telescope movement and shield the telescope from wind and stray light” [19]. Unfortunately, the Lowell Observatory will still experience vibrations from the wind buffeting against the side of the building as well as the actual movement of the dome rotating. To compensate for this interference, further modifications have been made to ensure the spectrometers environmental stability: To isolate the vacuum chamber from the vibrations it sits on spring isolators located on a concrete slab that remains detached from the enclosure’s foundation and therefore detached to the Observatory itself.

Within the FEM, the stable coupling of light is equally sensitive. This results in similar precautions required for the FEM. Of the FEM’s components, compensation starts where “atmospheric dispersion compensation and fast tip-tilt control ensure stable illumination of the science fiber” [14]. Furthermore, the EXPRES must include an exposure meter to account for the changes in radial velocity due to the Earth’s own rotation. However, out of concern of “Barycentric motion broadening the lines and degrading the RV precision” [14], the time for exposure has been limited to 20-30min intervals.

**Calibration Assembly**

Cited in one of the Yale Exoplanet reports, the “photolithographic CCD fabrication results in per-pixel positioning errors of around 1-3% of a pixel width” [16]. This is mainly due to the challenging requirement on “instrument stability, illumination, uniformity, sensitivity, wavelength calibration, and data analysis techniques” [14]. Directly linked to these high specs are the systems designed specially to filter and calibrate the starlight coming in; these four components are known under the sub-name “calibration assembly.”

Due to their sensitive nature, the equipment involved with the interpretation of the light data is located in the sheltered interior of the BEM’s spectrograph. The four technologies responsible for the calibration include a novel laser frequency comb, a Thorium Argon (ThAr) lamp, a flat-field source, and the light control that feeds into the three subdivided technologies.

After directed through the LED light control, the first subdivision is the option of the laser frequency comb (LFC). Of the various methods possible, the LFC was chosen to be the best fit after analysis of the previously mentioned CHIRON spectrometer. CHIRON, similar to the EXPRES, demonstrated possible advantages of a fiber-fed instrument with a high cadence Doppler observation. However, due to CHIRON’s shortcomings in early design, it lacked a vacuum enclosure and wasn’t stable enough to integrate laser frequency combs after its construction [3]. To avoid similar circumstances, the EXPRES was designed to be a vacuum-enclosed white pupil spectrometer with the necessary modifications to employ a broad wavelength range as well as a laser frequency comb [3]. As for the comb itself, it was selected for its ability to “produce a dense grid of stable, equally spaced, narrow lines of similar brightness” [14]. Each of the four sources of calibration has a purpose: the laser frequency comb to deal with broadband wavelength calibration, the ThAr lamp for secondary wavelength reference, and the flat-field source to “produce a flat white’ spectrum for flat field calibration” [14]. Through the placement of the calibration assembly, light from any of these sources is allowed to be redirected into the spectrograph or through the science fiber that feeds into the FEM.
Factors Limiting Data Collection

In addition to the specific needs of the instrumentation, another challenge presented to the collection of data is the existence of stellar photospheric noise given off by the host star. This can come in a variety of forms including but not limited to star spots, p-mode oscillations, and variable granulation [8]. Otherwise known as “stellar jitter,” these phosphoric velocities are classified by their ability to “produce line variations that skew the center of mass for a spectral line in a way that is (mis)interpreted by Doppler code as a velocity change in the star” [8]. To distinguish between the desired radial velocities and the phosphoric velocities, there are two properties of stellar jitter that can be utilized. Firstly, the conveyed velocity signals are inconsistent and vary on periods different from the center of mass radial velocities [14]. Therefore, the velocities wished for fall into a different, predictable sync these extra values can be ruled as reliable data. The second way that they can be identified is through the way they affect the spectrum; stellar jitters don’t follow simple wavelength shifts like Doppler shifts, instead they have an asymmetrical velocity component that results in a warped likeness.

Other factors limiting the processes of data collection come from the shortcomings of spectrometers in general. Of the processes involved in exoplanet detection, two of the common methods include the transit and the Doppler techniques which are optimal in situations where the planet is larger in mass or within tight orbit. Unfortunately, not all planets fall under these two categories. Of the many complementary methods that compensate for the blind spots, some examples consist of microlensing, astrometry, and direct imaging [8]. All of these additional methods are more sensitive to planets in wider orbits and therefore cover different parameters (of space) than the Doppler and transit techniques. By rotating these complimentary methods, they compensate for the others’ blind spots and allow for larger areas of space to be documented. For those exact reasons, the techniques are generally not applied to the same sample of stars [8], however this also means that common weaknesses result in gaps of what can be studied. In this way, the analysis of space is actually “a patchwork quilt that still has several missing squares” [8], pieces that will hopefully be collected after our technology has improved enough to expand our reach.

BENEFITS OF THE EXPRES AND ITS PREDICTED IMPACT TO EXOPLANET DETECTION

Built off decades of innovation, the EXPRES is destined to inspire a new generation of spectrometers which will revolutionize the methods of exoplanet detection. Supported by enthusiastic space programs and the public’s curiosity, this field has and will continue to thrive. In line with the mission of the 100 Earths Project, the EXPRES’s goal is to find and document candidates that could potentially be classified as “habitable.” Already we’ve made light years of progress from the resolution specs of the 1950s and it can be predicted to improve future high-resolution spectrometers and their search for other habitable earths. One major outcome from the EXPRES’s high resolution is the guarantee of more space being charted and therefore expansion of the parameters we’ve so far compiled.

Sometime in the far future, humanity may find themselves needing this data as it is our first guide to the galaxy, especially once humanity decides to leave earth and travel to new, preferably habitable, worlds. Possible scenarios that could initiate the migration of humankind could be anything from a nuclear war, global warming, overpopulation, human fascination, or perhaps due to the SpaceX program’s groundbreaking technology. Even after such the successful launch and recovery of the first reusable rocket, SpaceX has begun designs for its newest model “BFR.” If everything goes well with the BFR’s development, Elon Musk, founder of SpaceX, estimates that “the first crewed flights to Mars could lift off in the 2020s” [20]. Less appealing reasons for leaving earth include the popular fear regarding the upcoming death of our sun. Although it isn’t estimated to undergo any serious changes until another five billion years, when it inflates into a red giant, it has been estimated that it will transform the earth’s surface into an uninhabitable wasteland.

A secondary application of space-applied spectrometers is as an early-warning detection system for impact with celestial bodies that were too dim to appear under normal circumstances. And in situations such as Bernard’s Star, a star racing towards us with impressive velocity, being able to interpret the radial velocity can determine whether it carries a payload (possibly large rocks or entire planets) capable of dislodging and damaging the earth as it races by. For whatever reasons that motivate us, the research done now will prove to be an invaluable first step to ensure our place in the stars.

As defined by the UN Brundtland Commission in 1987, sustainable development is “meeting the needs of the present without compromising the ability of future generations to meet their own needs” [21]. These first decades of space travel must be built on the foundation of sustainable practices to ensure a promising future for the next generations. This is both applicable to the sustainably of our rockets but also the planets we choose to inhabit. Planetary selection is especially crucial in order to equip future generations with the resources necessary to be self-sufficient. In that way, spectrometers like the EXPRES will prove essential to the relocation and sustainability of the human race.

SOURCES

Gemma Wilson


ADDITIONAL SOURCES


Gemma Wilson


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