A SEARCH FOR FISSILE WASTE IN STELLAR SPECTRA AS A POTENTIAL TECHNOSIGNATURE

Introduction

Broadly speaking, the signatures of life elsewhere in the universe can be categorized as either *biosignatures*, the natural consequences of biological processes like photosynthesis or metabolism, or *technosignatures*, evidence of a technologically advanced civilization intentionally manipulating its environment. While the search for biosignatures often dominates conversations about detecting extraterrestrial life, technosignature searches (also called SETI, or Searches for Extra-Terrestrial Intelligence) should not be overlooked [1]. While technological civilizations will necessarily be rarer than any lifeform capable of producing conventional biosignatures, technosignatures are a) more profound, in that they reveal the presence not just of life, but intelligence and technology, b) more feasible to detect with existing technology, and c) potentially less ambiguous and subject to false positive scenarios.

We propose to search for evidence of extraterrestrial civilizations by identifying radioactive elements in the spectra of stars. SETI researchers have speculated that an advanced civilization might deliberately pollute its host star with radioactive elements, either as an eco-friendly way to dispose of waste from nuclear energy production [2], or to signal its presence to nearby civilizations [3]. Radioactive elements like plutonium and einsteinium have half-lives of days to years—orders of magnitude shorter than typical stellar lifetimes—so if these elements are found in stars, they must have formed, *or been deposited*, recently. The presence of short-lived radioactive elements in the atmospheres of stars (far from the nuclear furnace in the core) is very difficult (though perhaps not impossible [4]) to explain with natural processes, making it a promising avenue for a technosignature search.

This scenario may seem far-fetched, but **astronomers have already identified one star with short-lived radioactive elements in its atmosphere**. In 1961, Polish astronomer Antoni Przybylski discovered that the star HD 101065 (now known as Przybylski's Star) has an extremely unusual elemental composition [5]. Modern analyses have identified the presence of short-lived radioactive elements like promethium (half-life of 17.6 years), neptunium, plutonium, americium, curium, berkelium, californium, and einsteinium [6]. Not only are these short-lived elements present, they are abundant; the atmosphere of Przybylski's Star's contains, for example, 10,000 times more cesium than the Sun [7].

While the strange abundances in Przybylski's Star are hard to explain, more work is needed to determine whether it, or any other stars with similar elemental makeup, are indeed promising SETI targets. Przybylski's Star is classified as an "roAp" star [8], which are themselves known to have atypical elemental abundances. Are the unusual abundances in Przybylski's Star just an extreme example of the phenomenon that causes the chemical peculiarity of roAp stars? **A systematic search for similar stars is badly needed to determine just how uncommon the abundances in Przybylski's Star are**, and to determine if other stars show similar abundance patterns, whether their other physical parameters are similar (implying a natural explanation).

Work Plan

We will search for spectroscopic cousins of Przybylski's Star to determine how common—or rare—such stars may be. In 1961, when the unusual composition of Przybylski's star was first discovered, only thousands of stars had spectroscopic observations with the sensitivity to identify unusual elemental compositions. Since then, astronomy has entered the big-data era, and the number of stars with measured, and *publicly accessible*, spectra is in the tens of millions. These archives provide a treasure trove to search for absorption features from exotic atomic species. Particularly valuable collections of data include the LAMOST [9], SDSS [10], GALAH [11], APOGEE [12], and Gaia-ESO [13] surveys.

Efficiently searching for radioactive species among these archives requires an automated algorithm to process and analyze thousands of spectra from disparate sources. We will develop a automatic data analysis pipeline that: 1) parses various archives to extract appropriate targets—main-sequence stars with sufficiently high signal-to-noise, resolution, and wavelength coverage—2) identifies and excludes stellar binaries and other complicating features, and 3) searches for absorption features at the wavelengths of radioactive species (such as those suggested by [2] and observed for Przybylski's Star) and measures their line strengths. Our approach will take advantage of both cutting-edge machine learning methods for anomaly detection [14] and fundamental atomic astrophysics to identify the spectroscopic signatures of radioactive elements.

We expect this algorithm will produce a list of candidate stars with radioactive element enrichment, which we will manually vet to exclude false positives and further characterize true candidates. We will publish our full catalog of final candidate stars, and pursue followup observations as detailed below.

Expected Results and Future Avenues for Exploration

Whether or not unusual abundances in Przybylski's Star can be interpreted as technosignatures, our study will place the first firm statistical constraints on the fraction of stars with detectable amounts of heavy, radioactive species in their atmospheres. This result will have important implications for understanding the physical processes responsible for heavy-element enrichment [15] in stellar atmospheres, and understanding whether Przybylski's Star represents an extreme outcome of those processes.

If our search reveals new candidates for stars enriched in radioactive material, we expect to pursue followup observations to further inform the possibility that such enrichment is a technosignature. Avenues for further exploration include:

- Follow-up spectroscopy would elucidate several key properties of a candidate star. First, we can confirm the presence of radioactive elements with higher-quality spectra than the initial survey observations. Moreover, measurements of the star's radial velocity may reveal its planetary system via the Doppler method [16]. Additionally, searching for temporal variability in the depth of the radioactive species' absorption lines could indicate whether a civilization is periodically dumping new material onto the star, or whether elements with radioactive elements are decaying on human timescales.
- Monitoring for coherent radiation: If the radioactive enhancement is a technosignature, the system may exhibit other technosignatures. Monitoring a candidate star for coherent radio (communication) and/or laser (communication or propulsion of photon sails [17]) emission could betray the activity of a technological civilization.

Team Qualifications and Responsibilities

Andrew Vanderburg is an expert in developing novel data analysis techniques for exoplanet detection. Recently, he has been exploring the use of machine learning with deep neural networks for exoplanet detection [18, 19, 20, 21]. He will lead the development of the software pipeline for identifying stars with unusual elemental abundance patterns.

Paul Robertson is an expert in stellar spectroscopy, stellar astrophysics, and exoplanet detection. He is a Project Scientist for two new spectrometers designed to detect Earthlike exoplanets orbiting nearby stars: the Habitable-zone Planet Finder [22] and NEID [23, 24]. He will lead the detailed vetting of stars identified as candidates for radioactive-element enrichment. This vetting will include ruling out false positives related to instrumental systematics, as well as determining detailed stellar properties of genuine candidates.

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