ATMOSPHERIC TECHNOSIGNATURES: SEARCHING FOR INTELLIGENT LIFE IN ALIEN SKIES

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Introduction

In 1950, the famed physicist Enrico Fermi was out to lunch with colleagues when he asked, "Do you ever wonder where everybody is?" The Fermi Paradox has come to describe the disparity between the abundance of star systems, with a multitude of planets that might harbor life, and the lack of detectable alien civilizations.[1] This question, rooted in a deeper existential curiosity about our place in the cosmos, has fueled researchers to search for signs of alien intelligence. So far, none have been detected.

Since 1992, over 4000 planets have been found orbiting stars outside of the solar system. Some of these planets, known as exoplanets, are similar to Earth in terms of their composition and the amount of radiation they receive from their host star.[2] The search for extraterrestrial intelligence has largely revolved around the search for alien radio transmissions, but there is a growing contingent of scientists who argue that we should be searching for other indicators of alien civilizations. Some of the most promising of these indicators, better known as technosignatures, can be found in the skies and orbits of exoplanets.

Technosignatures

Technosignature is a broad term that can be applied to anything that indicates the presence of a technologically developed civilization. Its list of engendering technologies runs the gamut from ones that are well within the grasp of human technological reality to ones that stretch the limits of imagination; both the burning of chemical fuels and Dyson Spheres, massive arrays of solar collectors that enclose an entire star to capture as much of its energy as possible, are fair game for technosignatures.[3] Although this technological speculation can be helpful in refining and inspiring our search for extraterrestrial intelligence, this paper neglects hypothetical technological sources and focuses instead on ones that are bounded by human experience and confined to exoplanet atmospheres.

Keeping the search for technosignatures grounded in human understanding is important because it limits the possibility of detecting false positives from natural sources. Famously, the first detections of pulsars were labeled as LGMs, little green men, because astronomers doubted that the precise intervals between the pulses they emitted could come from a natural source.[4] Similar cases have been made for the presence of Dyson Spheres, which should block out a significant portion of a star's light at irregular intervals, but prevailing evidence also supports natural causes: in this case, massive clouds of orbiting debris from asteroids or broken-up

[1] Paul Patton, "Beyond 'Fermi's Paradox' I: A Lunchtime Conversation- Enrico Fermi and Extraterrestrial Intelligence," Universe Today, December 6, 2020.
[2] National Aeronautics and Space Administration, "Exoplanet Exploration: Planets Beyond Our Solar System," NASA (NASA, December 17, 2015).
[3] Karl Tate, "Dyson Spheres: How Advanced Alien Civilizations Would Conquer the Galaxy (Infographic)," Space.com (Space, January 14, 2014).
[4] S. Jocelyen Bell Burnell, "Cosmic Search Vol. 1, No. 1," Cosmic Search Vol. 1, No. 1 - Little Green Men, White Dwarfs or Pulsars?, 2004.

planets.[5] Narrowing the search for physical technosignatures to technologies that are well understood by humanity overcomes many, but not all, false positive issues.

This paper explores three potential technological processes on exoplanets that can be detected using methods and sensors that are available today. The three areas of focus are industrial pollution, orbital debris, and nuclear warfare. By searching for signs of these activities in the atmospheres and high orbits of exoplanets, researchers may be able to develop a mosaic of signatures that eventually prove the existence, or previous existence, of an extraterrestrial civilization. The self-destructive nature of these technosignatures is due to the fact that they produce an outsized, and therefore detectable, impact on their planetary environment. It is ironic that the technologies and unsustainable practices that pose some of the greatest dangers to humanity might be the most promising indicators of alien intelligence.

Industrial Pollution

Industrialization has given Earth's atmosphere distinctive characteristics that can be analyzed from other star systems. The most obvious of these characteristics are greenhouse gases like methane and nitrous oxide. Although methane and nitrous oxide provide an indicator of industrialization, they do not rule out possible natural causes.[6] Saturn's moon Titan has vast, naturally produced quantities of both greenhouse gases.[7] Choloroflourocarbons (CFCs) on the other hand, have no significant natural sources, and are detectable in the atmospheres of exoplanets.[8] Much has been done over the past 30 years to limit the human release of CFCs due to their deleterious effects on the ozone layer, but many longer lived CFCs remain in Earth's atmosphere.[9] Before international regulations, CFCs were released in a variety of industrial processes and included in a wide range of consumer products, notably hairspray.[10] If extraterrestrial industrialization and the alien affinity for hair styling products follows the same trajectory as our own, then the presence of CFCs in exoplanet atmospheres is a promising, relatively long-lived technosignature to search for.

Trying to find CFCs in alien atmospheres is a complicated process that revolves around a technique called transit spectroscopy. Transit spectroscopy is the analysis of an exoplanet's atmosphere using the background light of the planet's host star for illumination. When an exoplanet passes in front of its host star, a telescope receives the light that radiates through the planet's sky and analyzes the spectral data to determine the component chemicals of the atmosphere.[11] CFC's produce a distinctive spectral pattern that can be separated from

[5] Karl Tate, "Dyson Spheres: How Advanced Alien Civilizations Would Conquer the Galaxy (Infographic)," Space.com (Space, January 14, 2014).
[6] Blue Marble Space Institute of Science, "The Astrobiology of the Anthropocene," *The Astronomical Journal*.
[7] Space.com Staff, "Haze on Saturn's Moon Titan Is Similar to Earth's Pollution," Space.com (Space, June 7, 2013).
[8] Henry W. Lin, Gonzalo Gonzalez Abad, and Abraham Loeb, "Detecting Industrial Pollution In The Atmospheres Of Earth-Like Exoplanets," *The Astrophysical Journal* 792, no. 1 (2014).
[9] Ibid.
[10] Adam Stevens, Duncan Forgan, and Jack O'malley James, "Observational Signatures of Self-Destructive Civilizations," *International Journal of Astrobiology* 15, no. 4 (2015).
[11] Nikolai Piskunov, "Exoplanet Atmospheres," Department of Physics and Astronomy (Uppsala Universitet, 2018).

background light via the transit method.[12] It is a powerful capability that has yielded a majority of recent exoplanet findings and is currently our best tool in the hunt for atmospheric technosigntures.

Two specific types of CFC's are the most auspicious candidates for observation. Carbon tetraflouride (CFC-14) and trichlorofluoromethane (CFC-11) are the two most detectable types of CFCs for a telescope using transit spectroscopy.[13] A near future space based telescope like the James Webb Space Telescope, which will be described later, can be optimized to search for the spectral patterns of CFC-14 and CFC-11 in exoplanet atmospheres. Furthermore, CFC-11 is a longer lived CFC that only completely decays from an atmosphere in roughly 100,000 years.[14] Not only does it provide the best bet for detection because it is present in the atmosphere for the longest amount of time relative to other CFCs, it potentially yields information about the civilization that produced it. Finding evidence of long-lived CFC-11 in the absence of other forms might indicate a civilization that has gone extinct or a civilization that has strictly limited the emission of CFCs altogether, much like our own.[15]

Combining the positive detection of CFCs in the atmosphere of an exoplanet with the detection of greenhouse gases like methane and nitrous oxide might prove to be significant evidence for the presence of industrialization. However, some natural sources may interfere with the conclusion that the exoplanet is home to an intelligent civilization. Volcanoes are a natural source of CFCs, and roughly 16% of all CFCs in Earth's atmosphere are attributed to volcanism.[16] It will be difficult to determine whether a bulk of CFCs were produced via natural sources or industrialization in exoplanet atmospheres, but if these challenges can be overcome, it may soon be a reality to be able to detect alien civilizations by searching for evidence of an industrial chemical that is familiar on Earth.

Orbital Debris

There are nearly 3,000 satellites in orbit today, and this number is set to grow exponentially in the near future.[17] With companies like SpaceX decreasing launch costs by orders of magnitude compared to just a decade ago, human expansion into Earth orbit and beyond will likely explode over the second half of the 21st century.[18] Unfathomably large fleets of satellites that provide navigation, communication, and remote sensing capabilities and large commercial

[12] Henry W. Lin, Gonzalo Gonzalez Abad, and Abraham Loeb, "Detecting Industrial Pollution In The Atmospheres Of Earth-Like Exoplanets," *The Astrophysical Journal* 792, no. 1 (2014), https://doi.org/10.1088/2041-8205/792/1/l7.
[13] Ibid.
[14] Ibid.
[15] Adam Stevens, Duncan Forgan, and Jack O'malley James, "Observational Signatures of Self-Destructive Civilizations," *International Journal of Astrobiology* 15, no. 4 (2015).
[16] Leah Burrows , "How Future Volcanic Eruptions Will Impact Earth's Ozone Layer," How future volcanic eruptions will impact Earth's ozone layer | Harvard John A. Paulson School of Engineering and Applied Sciences, August 16, 2017, https://www.seas.harvard.edu/news/2017/08/how-future-volcanic-eruptions-will-impact-earths-ozone-layer.
[17] Loren Grush, "SpaceX Just Launched Two of Its Space Internet Satellites - the First of Nearly 12,000," The Verge (The Verge, February 15, 2018).
[18] Ibid.

space stations, are years away from being a technological reality.[19] However, as Earth's orbital highways become increasingly congested, the opportunity for collisions between objects in orbit increases geometrically. There is a chance that in a dense orbital environment, an increasingly devastating cascade of orbital collisions could render certain orbits uninhabitable for satellites and space stations.[20] If extraterrestrial civilizations, only slightly more advanced than our own, with millions of satellites in orbit fall victim to this phenomena, called Kessler Syndrome, the resulting debris cloud could serve as a promising technosignature.[21] Although orbital debris clouds are not technically an a*tmospheric* technosignature, they are found in much the same way that atmospheric signatures are, and it is important to recognize that the defining line between a planet's atmosphere and orbital regions is literally hazy.[22]

To find these debris clouds, the focus will be placed on the higher geosynchronous orbits of an exoplanet. Geosynchronous orbits are much longer lived than lower orbits due to their distance from the surface of an exoplanet; on Earth, geosynchronous orbit is around 35,000 km above the surface.[23] Satellites that orbit closer to their planet decay back into the atmosphere on much shorter timescales than geosynchronous satellites, which are hypothesized to stay in orbit for up to 100,000 years.[24] If the geosynchronous orbital plane of an exoplanet is saturated with satellites and undergoes a Kessler catastrophe, the density of satellite shrapnel and debris would be high enough to noticeably block the light from the host star that shines around the exoplanet.[25] This geosynchronous band of debris is known as a Clarke Exobelt after the science fiction author Arthur C. Clarke who first advocated for the use of geostationary satellites for communiction in 1945.[26]

Using a similar process to transit spectroscopy called transit *photometry,* a technosignature hunting telescope would be able to search for irregularities in the brightness of a star's light as it filters through the geosynchronous orbit of an exoplanet.[27] Transit *photometry* differs from transit *spectroscopy* in that it does not search for the spectra of star light that passes through an exoplanet atmosphere to determine its chemical composition. Rather, transit photometry simply detects differing levels of brightness around an exoplanet.[28] If the brightness of a star's light significantly decreases in the geosynchronous regions of an exoplanet's orbit, it might indicate the presence of a large orbital debris cloud left behind by an intelligent civilization.

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[19] Ibid.
[20] Adam Stevens, Duncan Forgan, and Jack O'malley James, "Observational Signatures of Self-Destructive Civilizations," *International Journal of Astrobiology* 15, no. 4 (2015): pp. 333-344.
[21] Ibid.
[22] Hector Socas-Navarro, "Possible Photometric Signatures of Moderately Advanced Civilizations: The Clarke Exobelt," *The Astrophysical Journal* 855, no. 2 (2018).
[23] Ibid.
[24] Ibid.
[25] Ibid.
[26] Ibid.
[27] Ibid.
[28] Ross McCluney, "Photometry," Photometry - an overview | ScienceDirect Topics, 2003.

Although the Clarke Exobelt is a promising technosignature due to its long 100,000 year time horizon and relatively simple detection method compared to spectral atmospheric analysis, there are a few challenges with the idea. First, computer models of geosynchronous orbits around exoplanets indicate that they are significantly more susceptible to orbital decay, than previously thought. This is especially true if the exoplanet is in orbit around smaller M-type stars like red dwarfs, which are the most common star in the observable universe.[29] Second, there is a chance that some earth-like planets may have natural ring systems or debris clouds that would produce false positives for a Clarke Exobelt hunting effort.[30] That being said, evidence of an orbital debris cloud in geosynchronous orbit in conjunction with other atmospheric technosignatures could produce a compelling indication of an alien civilization.

Nuclear Warfare

The threat of nuclear war has loomed over humanity since the rapid global armament of the 1950s and 60s. If alien civilizations deploy nuclear weapons, the effects on exoplanet atmospheres would be detectable, albeit for an extremely brief time, here on Earth. For the purposes of this analysis, an all-out planetary level nuclear war between an alien civilization will be considered because it would have the most noticeable impact on an exoplanet's atmosphere.

The most obvious and definitive signature of extraterrestrial nuclear warfare is atmospheric ionization. After a global nuclear war, large amounts of radioactive particles produced by nuclear fission blasts would be scattered into the atmosphere. The beta radiation emitted from the particles would ionize atmospheric gases and produce a noticeable airglow effect.[31] This effect naturally occurs on Earth when electrons emitted by the Sun and other astronomical sources interact with the upper layers of the atmosphere to create the stunning "green oxygen line".[32] In the event of a global nuclear war, this airglow would increase by an order of magnitude. Using highly sensitive telescopes that utilize transit spectroscopy, the outsized airglow effect would be detectable for around five years before the beta emitting particles decayed to background levels.[33] That being said, detection would require a pristine understanding of the host star to filter out any natural effects that it might have on the exoplanet's upper atmosphere.[34]

Another atmospheric signature of nuclear war comes from its effect on the ozone layer. Oxides of nitrogen serve as catalysts for chemical processes that break down ozone in the upper atmosphere, and massive amounts of nitrogen oxides created in the nuclear fireballs of a global war would noticeably deplete the ozone layer of an exoplanet. Telescopes would be able to

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[29] Shauna Sallmen, Eric J. Korpela, and Kaisa Crawford-Taylor, "Improved Analysis of Clarke Exobelt Detectability," *The Astronomical Journal* 158, no. 6 (2019).
[30] Charles Q. Choi, "Ringed, Rocky Alien Planets May Hide in Plain Sight," Space.com (Space, May 21, 2018).
[31] Adam Stevens, Duncan Forgan, and Jack O'malley James, "Observational Signatures of Self-Destructive Civilizations," *International Journal of Astrobiology* 15, no. 4 (2015).
[32] *Credit: NASA*, 2020, *Iaa.csic.es*, 2020.
[33] Adam Stevens, Duncan Forgan, and Jack O'malley James, "Observational Signatures of Self-Destructive Civilizations," *International Journal of Astrobiology* 15, no. 4 (2015).
[34] Ibid.

detect the diminished ozone layer by analyzing transit spectra in the ultraviolet range.[35] Although there are two traceable effects of nuclear war on an exoplanet, airglow and ozone depletion analysis, there are significant challenges involved with the detection of each.

The most serious of these challenges comes from the fact that both of these signatures are based on differential data that require observation before and after a nuclear event. In order to find evidence that the level of airglow or amount of ozone in the atmosphere of an exoplanet has changed, an analysis team needs two points of data to compare.[36] It is overwhelmingly unlikely, given that SETI has not found any evidence for extraterrestrial intelligence, much less civilizations, that a technosignature detection platform will catch these changes in the half decade time horizon required. Five years might seem like a long time for humans, but on astronomical timescales, it is an infinitesimally small drop in the bucket. Detecting evidence of extraterrestrial nuclear technology will likely only be meaningful in conjunction with other forms of evidence like the detection of orbital debris rings or industrially derived chemicals.

Detection Platforms and Analysis

The search for atmospheric technosignatures will rely on a suite of detection platforms. Transit spectroscopy and photometry are currently the only known ways of analyzing exoplanet atmospheres and orbital environments, and two space based telescopes in particular will be crucial in the use of transit astronomy for the search for atmospheric technosignatures.

The Transiting Exoplanet Survey Satellite (TESS) was launched in 2018 into a highly elliptical orbit around the Earth to survey broad swathes of sky for signs of exoplanets.[37] It uses transit spectroscopy and photometry to detect exoplanets and analyze their atmospheres. As of May 2020, NASA announced that the telescope had identified nearly 2000 exoplanet candidates.[38] TESS is currently our most powerful tool in the search for atmospheric technosigntures, but this is set to change soon.

The James Webb Space Telescope (JWST) is the successor to NASA's historic Hubble Space Telescope. Originally planned to launch in 2016, the $10 billion JWST is now set to liftoff in late 2021.[39] Unlike TESS, which searches for exoplanets in the visible spectrum, JWST is an infrared telescope.[40] It is by far the most capable space based detection platform ever built. Using the same transit spectroscopy and photometry employed by TESS, it will be able to analyze exoplanet atmospheres and orbital planes at unparalleled levels of detail.

Regardless of the technology employed, positive verification of an alien civilization will rely on multiple source detection. One detection of a plausible technosignature is not falsifiable enough to distinguish it from an unknown natural phenomena. Instead, multiple positive

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[35] Adam Stevens, Duncan Forgan, and Jack O'malley James, "Observational Signatures of Self-Destructive Civilizations," *International Journal of Astrobiology* 15, no. 4 (2015).
[36] Ibid.
[37] David Latham, "Transiting Exoplanet Survey Satellite," *Encyclopedia of Astrobiology*, 2015.
[38] Ibid.
[39] J. K. Barstow et al., "Transit Spectroscopy with James Webb Space Telescope: Systematics, Starspots and Stitching," *Monthly Notices of the Royal Astronomical Society* 448, no. 3 (April 2015)..
[40] Ibid.

technosignature detections will need to be linked together to build a body of evidence. Finding CFCs in an exoplanet atmosphere, a dense debris cloud in its geosynchronous orbits, and strangely high levels of atmospheric ionization would indicate the presence of an extraterrestrial civilization: odds are an extinct one at that.

Furthermore, it is likely that if what you are looking at is truly a technosignature, then other signatures will be found as well. If an alien equivalent of the JWST were to analyze Earth today, it would find both long-lived CFCs and high levels of methane and nitrous oxide in our atmosphere compared to other Earth-like planets. Although this would not be conclusive proof to extraterrestrial researchers that a species of intelligent, hairless bipeds lives on the third planet from an unnamed G-type star, it would at least be strong evidence that something very strange is going on that warrants intensive investigation.

Conclusion

With the help of new detection platforms like the James Webb Space Telescope, searching for atmospheric technosignatures may prove to be a successful facet of the search for extraterrestrial intelligence. More importantly however, these technosignatures, which embody humanity's most destructive and unsustainable technological practices, can teach us to reconsider our relationship with the dangerous capabilities we have only recently developed. Finding evidence of the hyper industrialized nuclear wastelands and orbital graveyards of an extinct alien species will give us pause and hopefully motivate us to pursue a more mature technological future.

Bibliography

Barstow, J. K., S. Aigrain, P. G. J. Irwin, S. Kendrew, and L. N. Fletcher. "Transit Spectroscopy with James Webb Space Telescope: Systematics, Starspots and Stitching." *Monthly Notices of the Royal Astronomical Society* 448, no. 3 (2015): 2546–61. https://doi.org/10.1093/mnras/stv186.

Bell Burnell, S. Jocelyen. "Cosmic Search Vol. 1, No. 1." Cosmic Search Vol. 1, No. 1 - Little Green Men, White Dwarfs or Pulsars?, 2004. http://www.bigear.org/vol1no1/burnell.htm.

Berdyugina, Svetlana V., Jeff R. Kuhn, Maud Langlois, Gil Moretto, Joshua Krissansen-Totton, John Lee Grenfell, David Catling, et al. "The Exo-Life Finder (ELF) Telescope: New Strategies for Direct Detection of Exoplanet Biosignatures and Technosignatures." *Ground-based and Airborne Telescopes VII*, 2018. https://doi.org/10.1117/12.2313781.

Blue Marble Space Institute of Science. "The Astrobiology of the Anthropocene." *The Astronomical Journal*, 2018. https://doi.org/arXiv:1801.00052 .

Breitman, Daniela. "Wow! Signal Explained after 40 Years?" EarthSky, 2017. https://earthsky.org/space/wow-signal-explained-comets-antonio-paris.

Burrows , Leah. "How Future Volcanic Eruptions Will Impact Earth's Ozone Layer." How future volcanic eruptions will impact Earth's ozone layer | Harvard John A. Paulson School of Engineering and Applied Sciences, August 16, 2017. https://www.seas.harvard.edu/news/2017/08/how-future-volcanic-eruptions-will-impact-earths-ozone-layer.

Choi, Charles Q. "Ringed, Rocky Alien Planets May Hide in Plain Sight." Space.com. Space, May 21, 2018. https://www.space.com/40650-astronomers-may-miss-rocky-planet-rings.html.

Dorminey, Bruce. "NASA's TESS Telescope May Spot Alien Geo-Satellites, Say Astronomers." Forbes. Forbes Magazine, February 25, 2018. https://www.forbes.com/sites/brucedorminey/2018/02/24/nasas-tess-telescope-could-detect-belt-of-alien-geo-satellites-says-new-paper/?sh=7e6452f84eb4.

Green Oxygen Line on Earth. 2020. *Iaa.csic.es*. https://www.iaa.csic.es/en/news/detection-green-line-oxygen-atmosphere-mars.

Grush, Loren. "SpaceX Just Launched Two of Its Space Internet Satellites - the First of Nearly 12,000." The Verge. The Verge, February 15, 2018. https://www.theverge.com/2018/2/15/17016208/spacex-falcon-9-launch-starlink-microsat-2a-2b-paz-watch-live.

Latham, David. “Transiting Exoplanet Survey Satellite.” *Encyclopedia of Astrobiology*, 2015. https://doi.org/10.1007/978-3-662-44185-5_101151.

Lin, Henry W., Gonzalo Gonzalez Abad, and Abraham Loeb. “Detecting Industrial Pollution In The Atmospheres Of Earth-Like Exoplanets.” *The Astrophysical Journal* 792, no. 1 (2014). https://doi.org/10.1088/2041-8205/792/1/l7.

Ma, Alexandra. “Jeff Bezos Wants Floating Colonies in Space with Weather like Maui All Year Long - Here's What He Thinks They'll Look Like.” Business Insider. Business Insider, May 10, 2019. https://www.businessinsider.com/jeff-bezos-proposes-floating-colonies-with-weather-as-good-as-maui-2019-5.

McCluney, Ross. “Photometry.” Photometry - an overview | ScienceDirect Topics, 2003. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/photometry.

National Aeronautics and Space Administration. “Exoplanet Exploration: Planets Beyond Our Solar System.” NASA. NASA, December 17, 2015. https://exoplanets.nasa.gov/.

National Aeronautics and Space Administration. “NASA and the Search for Technosignatures: A Report from the NASA Technosignatures Workshop.” *The Astronomical Journal*, 2018. https://doi.org/arXiv:1812.08681.

Patton, Paul. “Beyond ‘Fermi's Paradox’ I: A Lunchtime Conversation- Enrico Fermi and Extraterrestrial Intelligence.” Universe Today, December 6, 2020. https://www.universetoday.com/119727/beyond-fermis-paradox-i-a-lunchtime-conversation-enrico-fermi-and-extraterrestrial-intelligence/.

Piskunov, Nikolai. “Exoplanet Atmospheres.” Department of Physics and Astronomy. Uppsala Universitet, 2018. https://www.physics.uu.se/research/astronomy-and-space-physics/research/planets/exoplanet-atmospheres/.

Sagan, Carl. “The Abundance of Life-Bearing Planets.” hawaii.edu. The Bioastronomy News, 1995. http://www2.hawaii.edu/~pine/sagan.html.

Sallmen, Shauna, Eric J. Korpela, and Kaisa Crawford-Taylor. “Improved Analysis of Clarke Exobelt Detectability.” *The Astronomical Journal* 158, no. 6 (2019): 258. https://doi.org/10.3847/1538-3881/ab5300.

Socas-Navarro, Hector. “Possible Photometric Signatures of Moderately Advanced Civilizations: The Clarke Exobelt.” *The Astrophysical Journal* 855, no. 2 (2018): 110. https://doi.org/10.3847/1538-4357/aaae66.

Staff, Space.com. “Haze on Saturn's Moon Titan Is Similar to Earth's Pollution.” Space.com. Space, June 7, 2013. https://www.space.com/21470-saturn-moon-titan-haze-cassini.html.

Stevens, Adam, Duncan Forgan, and Jack O'malley James. “Observational Signatures of Self-Destructive Civilizations.” *International Journal of Astrobiology* 15, no. 4 (2015): 333–44. https://doi.org/10.1017/s1473550415000397.

Tate, Karl. “Dyson Spheres: How Advanced Alien Civilizations Would Conquer the Galaxy (Infographic).” Space.com. Space, January 14, 2014. https://www.space.com/24276-dyson-spheres-how-advanced-alien-civilizations-would-conquer-the-galaxy-infographic.html.

Turtledove, Harry. “The Road Not Taken.” eyeofmidas.com, 2005. https://eyeofmidas.com/scifi/Turtledove_RoadNotTaken.pdf.

Wehrmann, Heidi. “Natural Ozone Depletion Long before Industrialisation.” ESKP, 2017. https://www.eskp.de/en/pollutants/natural-ozone-depletion-long-before-industrialisation-935393/.

Zeigler, Jim. “When Did the Anthropocene Begin? A Mid-Twentieth Century Boundary Level Is Stratigraphically Optimal.” *The Anthropocene Biosphere*, 2016. https://doi.org/10.15763/dbs.anthbiosphere.011.