ALIEN EARTHS

Recent Publications

An Integrative Analysis of the Rich Planetary System of the Nearby Star e Eridani: Ideal Targets for Exoplanet Imaging and Biosignature Searches

RV-detected planets around M dwarfs: Challenges for core accretion models

Searching for technosignatures in exoplanetary systems with current and future missions

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Of Algorithms and Hidden Planets

Earths in Other Solar Systems and **Alien Earths** are part of NASA's Nexus for Exoplanetary System Science program, which carries out coordinated research toward the goal of searching for and determining the frequency of habitable extrasolar planets with atmospheric biosignatures in the Solar neighborhood.

Our interdisciplinary teams includes astrophysicists, planetary scientists, cosmochemists, material scientists, chemists, biologists, and physicists.

The Principal Investigator of Project EOS and Alien Earths is Daniel Apai (University of Arizona). The projects' lead institutions are The University of Arizona's Steward Observatory and Lunar and Planetary Laboratory.

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Origins Seminar

The **Origins Seminar** series brings together ISM, star and planet formation people, exoplanets experts, planetary scientists and astrobiologists. Topics range from molecular clouds through star and planet formation to exoplanets detection and characterization and astrobiology.

The seminar series is organized by Serena Kim (SO), Sebastiaan Haffert (SO), and Chenliang Huang (LPL) from Steward Observatory/Dept. of Astronomy and Dept. of Planetary Sciences (LPL) at the University of Arizona. The Origins Seminar series is partly supported by the Earths in Other Solar Systems NExSS team.

Talks take place **12:00 – 1:00pm (MST) on Mondays**. To receive weekly updates and advertisements for talks, please subscribe to the **mailing list**. If you are interested in presenting your work during one of the open slots, feel free to contact **the organizers**.

During the Fall semester 2021 and Spring 2022, the Origins seminar will meet via Zoom or in Hybrid (in-person + zoom) due to the Covid-19 Pandemic. The Zoom information is sent via email, and the Origins seminar talks are recorded. The talk videos can be viewed from the Origins youtube channel.

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An Integrative Analysis of the Rich Planetary System of the Nearby Star e Eridani: Ideal Targets for Exoplanet Imaging and Biosignature Searches

Ritvik Basant, Jeremy Dietrich, Daniel Apai

➔ The Astronomical Journal, Volume 164, Issue 1

e Eridani, the fifth-closest Sun-like star, hosts at least three planets and could possibly harbor more. However, the veracity of the planet candidates in the system and its full planetary architecture remain unknown. Here we analyze the planetary architecture of e Eridani via DYNAMITE, a method providing an integrative assessment of the system architecture (and possibly yet-undetected planets) by combining statistical, exoplanet-population-level knowledge with incomplete but specific information available on the system. DYNAMITE predicts the most likely location of an additional planet in the system based on the Kepler population demographic information from more than 2000 planets. Additionally, we analyze the dynamical stability of e Eridani system via N-body simulations. Our DYNAMITE and dynamical stability analyses provide support for planet candidates g, c, and f, and also predict one additional planet candidate with an orbital period between 549-733 days, in the habitable zone of the system. We find that planet candidate f, if it exists, would also lie in the habitable zone. Our dynamical stability analysis also shows that the e Eridani planetary eccentricities, as reported, do not allow for a stable system, suggesting that they are lower. We introduce a new statistical approach for estimating the equilibrium and surface temperatures of exoplanets, based on a prior from the planetary albedo distribution. e Eridani is a rich planetary system with a possibility of containing two potentially habitable planets, and its vicinity to our solar system makes it an important target for future imaging studies and biosignature searches.

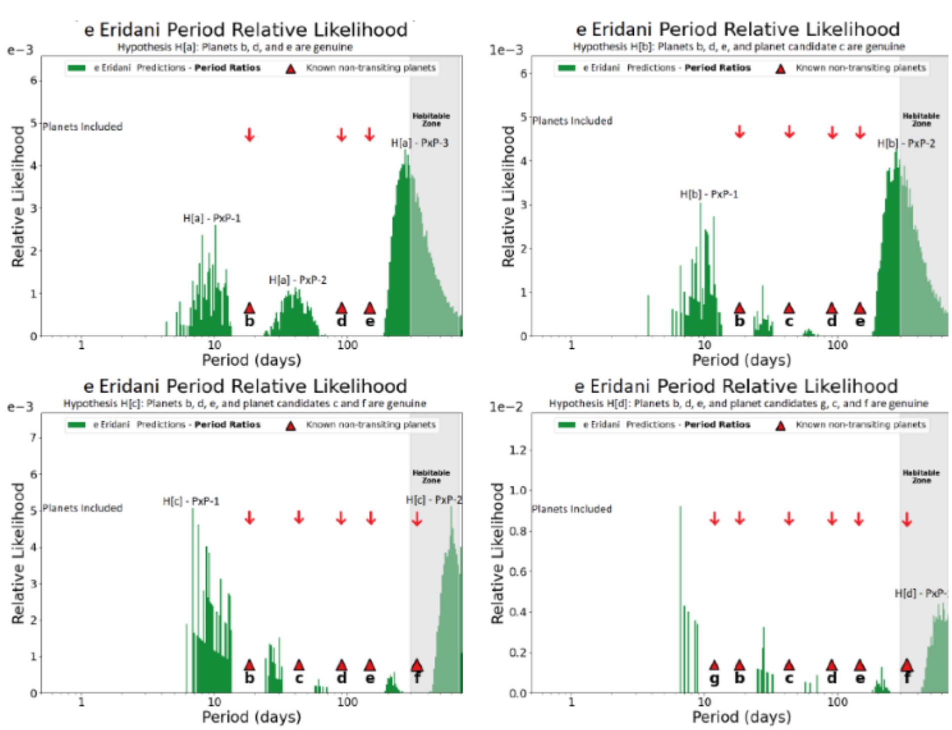


Figure 2. The upper left plot shows the DYNAMITE analysis without planet candidates g, c, and f. The upper right plot shows DYNAMITE analysis without planet candidates g and f. The lower left plot shows DYNAMITE analysis without planet candidate g while the lower right plot shows the DYNAMITE analysis with all the planets and planet candidates.

RV-detected planets around M dwarfs: Challenges for core accretion models

Martin Schlecker, Remo Burn, Silvia Sabotta, Antonia Seifert, Thomas Henning, Alexandre Emsenhuber, Christoph Mordasini, Sabine Reffert, Yutong Shan, Hubert Klahr

arXiv, May 2022

Planet formation is sensitive to the conditions in protoplanetary disks, for which scaling laws as a function of stellar mass are known. We aim to test whether the observed population of planets around low-mass stars can be explained by these trends, or if separate formation channels are needed. We address this question by confronting a state-of-the-art planet population synthesis model with a sample of planets around M dwarfs observed by the HARPS and CARMENES radial velocity (RV) surveys. To account for detection biases, we performed injection and retrieval experiments on the actual RV data to produce synthetic observations of planets that we simulated following the core accretion paradigm. These simulations robustly yield the previously reported high occurrence of rocky planets around M dwarfs and generally agree with their planetary mass function. In contrast, our simulations cannot reproduce a population of giant planets around stars less massive than 0.5 solar masses. This potentially indicates an alternative formation channel for giant planets around the least massive stars that cannot be explained with current core accretion theories. We further find a stellar mass dependency in the detection rate of short-period planets. A lack of close-in planets around the earlier-type stars ($M_* \gtrsim 0.4\ M_\odot$) in our sample remains unexplained by our model and indicates dissimilar planet migration barriers in disks of different spectral subtypes. Both discrepancies can be attributed to gaps in our understanding of planet migration in nascent M dwarf systems. They underline the different conditions around young stars of different spectral subtypes, and the importance of taking these differences into account when studying planet formation.

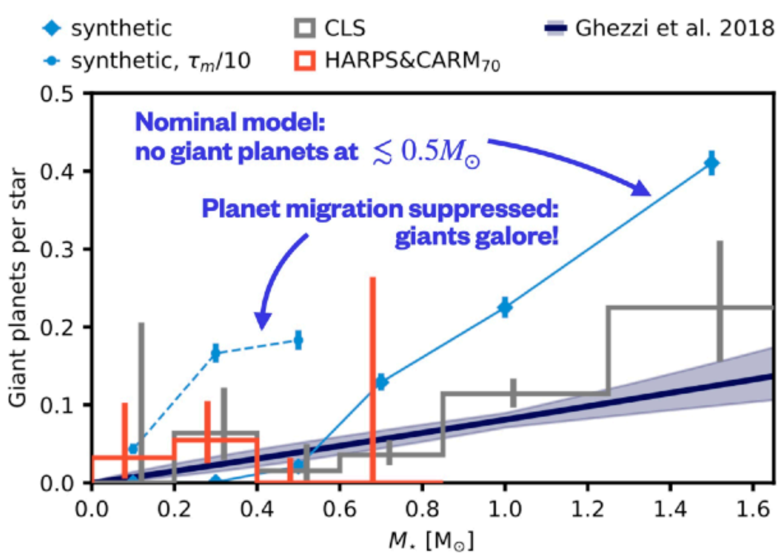


Figure. 8. *Giant planet detections as a function of stellar mass. From the HARPS and CARMENES planets presented here (red), the California Legacy Survey (Rosenthal et al. 2021, gray), and our synthetic NGM planets (blue), we include detections with RV semi-amplitude $K > 10$ m s^{-1}, $M \sin(i) > 100\ M_\oplus$, and $P < 1000$ d. We removed planets around close spectroscopic binaries ($P < 20$ yr) reported in Rosenthal et al. (2021). In addition, we show the fit of Ghezzi et al. (2018) for metallicities consistent with the assumptions made to draw the synthetic planets. Shaded areas and vertical lines denote 68% confidence intervals, respectively.*

Searching for technosignatures in exoplanetary systems with current and future missions

Jacob Haqq-Misra, Edward W. Schwieterman, Hector Socas-Navarro, Ravi Kopparapu, Daniel Angerhausen, Thomas G. Beatty, Svetlana Berdyugina, Ryan Felton, Siddhant Sharma, Gabriel G. De la Torre, Dániel Apai, the TechnoClimes 2020 workshop participants

arXiv, May 2022

Technosignatures refer to observational manifestations of technology that could be detected through astronomical means. Most previous searches for technosignatures have focused on searches for radio signals, but many current and future observing facilities could also constrain the prevalence of some non-radio technosignatures. This search could thus benefit from broader participation by the astronomical community, as contributions to technosignature science can also take the form of negative results that provide statistically meaningful quantitative upper limits on the presence of a signal. This paper provides a synthesis of the recommendations of the 2020 TechnoClimes workshop, which was an online event intended to develop a research agenda to prioritize and guide future theoretical and observational studies technosignatures. The paper provides a high-level overview of the use of current and future missions to detect exoplanetary technosignatures at ultraviolet, optical, or infrared wavelengths, which specifically focuses on the detectability of atmospheric technosignatures, artificial surface modifications, optical beacons, space engineering and megastructures, and interstellar flight. This overview does not derive any new quantitative detection limits but is intended to provide additional science justification for the use of current and planned observing facilities as well as to inspire astronomers conducting such observations to consider the relevance of their ongoing observations to technosignature science. This synthesis also identifies possible technology gaps with the ability of current and planned missions to search for technosignatures, which suggests the need to consider technosignature science cases in the design of future mission concepts.

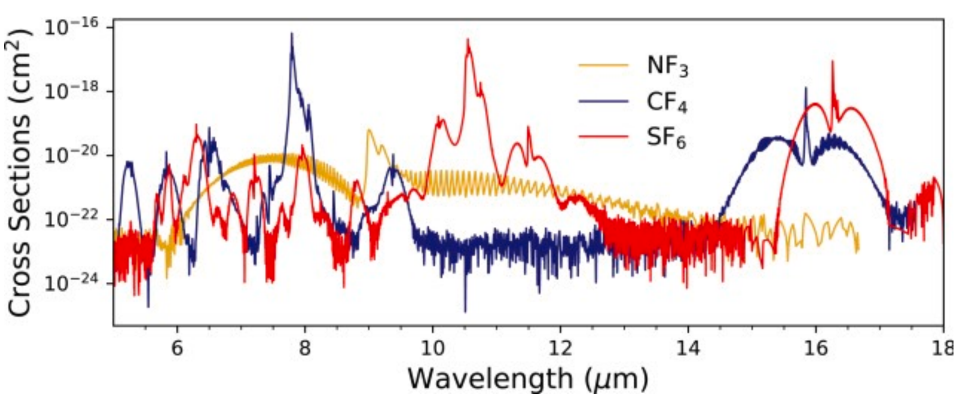


Figure 3: *Cross-sections for a subset of potential atmospheric technosignature molecules including NF3, CF4, and SF6. These long-lived artificial fluorine-containing gases have very limited abiotic sources and may serve as indicators of deliberate climate modification on inhabited terrestrial planets. These molecules could be detected in infrared emission or transmission spectral observations. Cross-section data were sourced from Sharpe et al. via Kochanov et al.*

Pterodactyls: A Tool to Uniformly Search and Vet for Young Transiting Planets In TESS Primary Mission Photometry

Rachel B. Fernandes, Gijs D. Mulders, Ilaria Pascucci, Galen J. Bergsten, Tommi T. Koskinen, Kevin K. Hardegree-Ullman, Kyle A. Pearson, Steven Giacalone, Jon Zink, David R. Ciardi, Patrick O'Brien

arXiv, June 2022

Kepler's short-period exoplanet population has revealed evolutionary features such as the Radius Valley and the Hot Neptune desert that are likely sculpted by atmospheric loss over time. These findings suggest that the primordial planet population is different from the Gyr-old Kepler population, and motivates exoplanet searches around young stars. Here, we present pterodactyls , a data reduction pipeline specifically built to address the challenges in discovering exoplanets around young stars and to work with TESS Primary Mission 30-min cadence photometry, since most young stars were not pre-selected TESS 2-min cadence targets. pterodactyls builds on publicly available and tested tools in order to extract, detrend, search, and vet transiting young planet candidates. We search five clusters with known transiting planets: Tucana-Horologium Association, IC 2602, Upper Centaurus Lupus, Ursa Major and Pisces Eridani. We show that pterodactyls recovers seven out of the eight confirmed planets and one out of the two planet candidates, most of which were initially detected in 2-min cadence data. For these clusters, we conduct injection-recovery tests to characterize our detection efficiency, and compute an intrinsic planet occurrence rate of 49+-20% for sub-Neptunes and Neptunes (1.8-6 Re) within 12.5 days, which is higher than Kepler's Gyr-old occurrence rates of 6.8+-0.3%. This potentially implies that these planets have shrunk with time due to atmospheric mass loss. However, a proper assessment of the occurrence of transiting young planets will require a larger sample unbiased to planets already detected. As such, pterodactyls will be used in future work to search and vet for planet candidates in nearby clusters and moving groups.

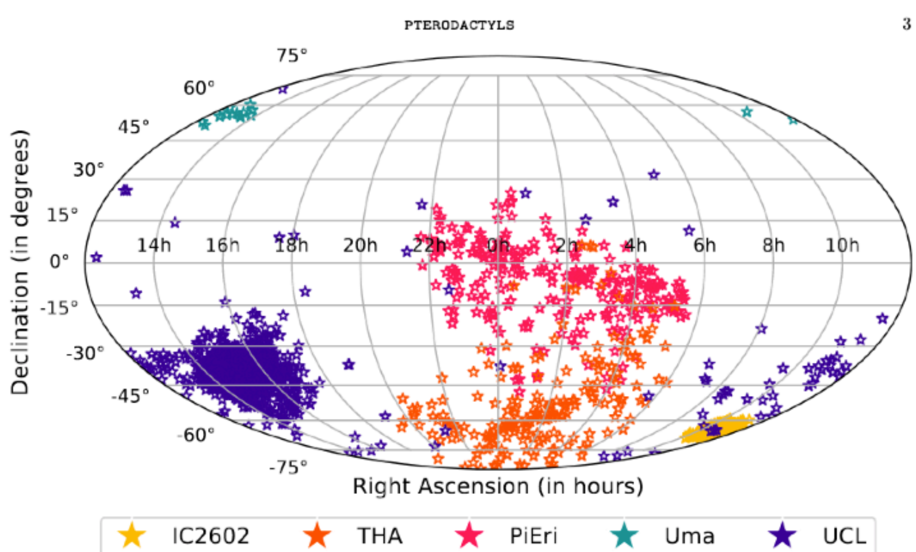


Figure 1. Equatorial locations of stars in selected clusters used in this study.

Mass Loss by Atmospheric Escape from Extremely Close-in Planets

Tommi Koskinen, Panayotis Lavvas, Chenliang Huang, Galen Bergsten, Rachel Fernandes, Mitchell Young

The Astrophysical Journal, Volume 929, Issue 1

We explore atmospheric escape from close-in exoplanets with the highest mass-loss rates. First, we locate the transition from stellar X-ray and UV-driven escape to rapid Roche lobe overflow, which occurs once the 10-100 nbar pressure level in the atmosphere reaches the Roche lobe. Planets enter this regime when the ratio of the substellar radius to the polar radius along the visible surface pressure level, which aligns with a surface of constant Roche potential, is $X/Z \gtrsim 1.2$ for Jovian planets ($M_p \gtrsim 100\ M_\oplus$) and $X/Z \gtrsim 1.02$ for sub-Jovian planets ($M_p \asymp 10\text{-}100\ M_\oplus$). Around a Sun-like star, this regime applies to orbital periods of less than two days for planets with radii of about 3-14$R_\oplus$. Our results agree with the properties of known transiting planets and can explain parts of the sub-Jovian desert in the population of known exoplanets. Second, we present detailed numerical simulations of atmospheric escape from a planet like Uranus or Neptune orbiting close to a Sun-like star that support the results above and point to interesting qualitative differences between hot Jupiters and sub-Jovian planets. We find that hot Neptunes with solar-metallicity hydrogen and helium envelopes have relatively more extended upper atmospheres than typical hot Jupiters, with a lower ionization fraction and higher abundances of escaping molecules. This is consistent with existing ultraviolet transit observations of warm Neptunes, and it might provide a way to use future observations and models to distinguish solar-metallicity atmospheres from higher-metallicity atmospheres.

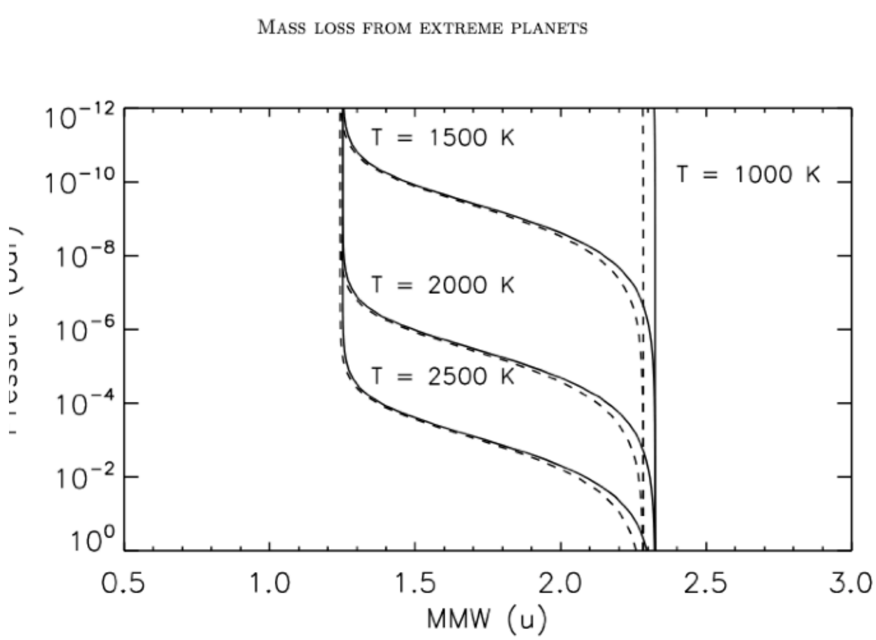


Figure 1. Mean molecular weight based on the CEA chemical equilibrium model (solid lines, Gordon & McBride 1994) compared with the mean molecular weight based on the simple equations (11)–(13) (dashed lines) for effective temperatures of 1000–2500 K.

Methanol at the Edge of the Galaxy: New Observations to Constrain the Galactic Habitable Zone

J. J. Bernal, C. D. Sephus, L. M. Ziurys

The Astrophysical Journal, Volume 922, Issue 2

The Galactic Habitable Zone (GHZ) is a region believed hospitable for life. To further constrain the GHZ, observations have been conducted of the J = 2 → 1 transitions of methanol (CH_3OH) at 97 GHz, toward 20 molecular clouds located in the outer Galaxy (R_{GC} = 12.9-23.5 kpc), using the 12 m telescope of the Arizona Radio Observatory. Methanol was detected in 19 out of 20 observed clouds, including sources as far as R_{GC} = 23.5 kpc. Identification was secured by the measurement of multiple asymmetry and torsional components in the J = 2 → 1 transition, which were resolved in the narrow line profiles observed ($\Delta V_{1/2}$ ~ 1-3 km s^{-1}). From a radiative transfer analysis, column densities for these clouds of N tot = 0.1-1.5 × 10^{13} cm^{-2} were derived, corresponding to fractional abundances, relative to H2, of f (CH_3OH) ~ 0.2-4.9 × 10^{-9}. The analysis also indicates that these clouds are cold (T_K ~ 10-25 K) and dense ($n(H_2)$ ~ 10^6 cm^{-3}), as found from previous H_2CO observations. The methanol abundances in the outer Galaxy are comparable to those observed in colder molecular clouds in the solar neighborhood. The abundance of CH_3OH therefore does not appear to decrease significantly with distances from the Galactic Center, even at R_{GC} ~ 20-23 kpc. Furthermore, the production of methanol is apparently not affected by the decline in metallicity with galactocentric distance. These observations suggest that organic chemistry is prevalent in the outer Galaxy, and methanol and other organic molecules may serve to assess the GHZ.

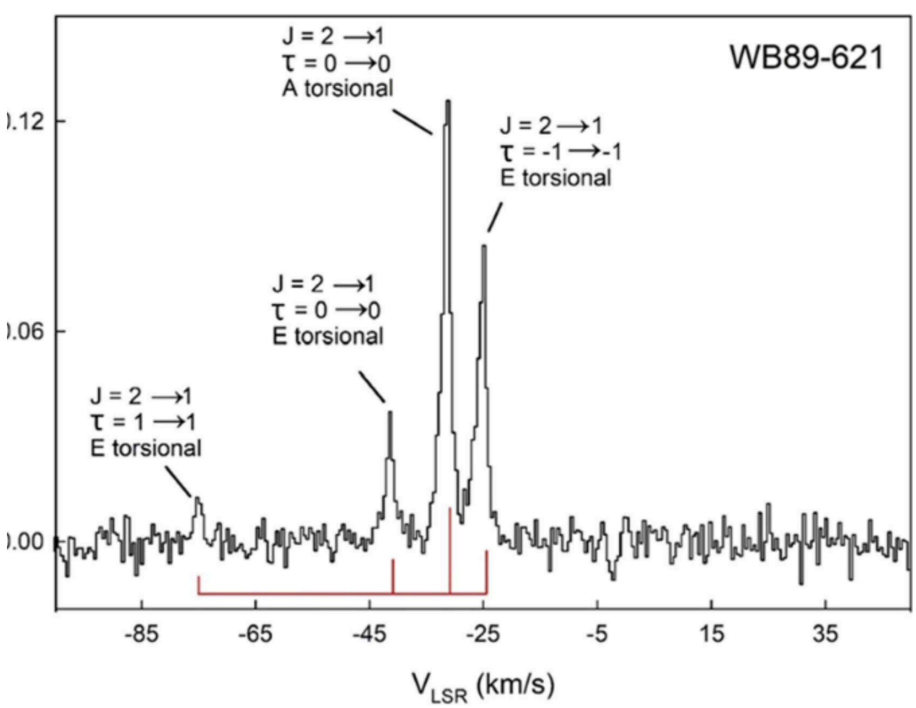


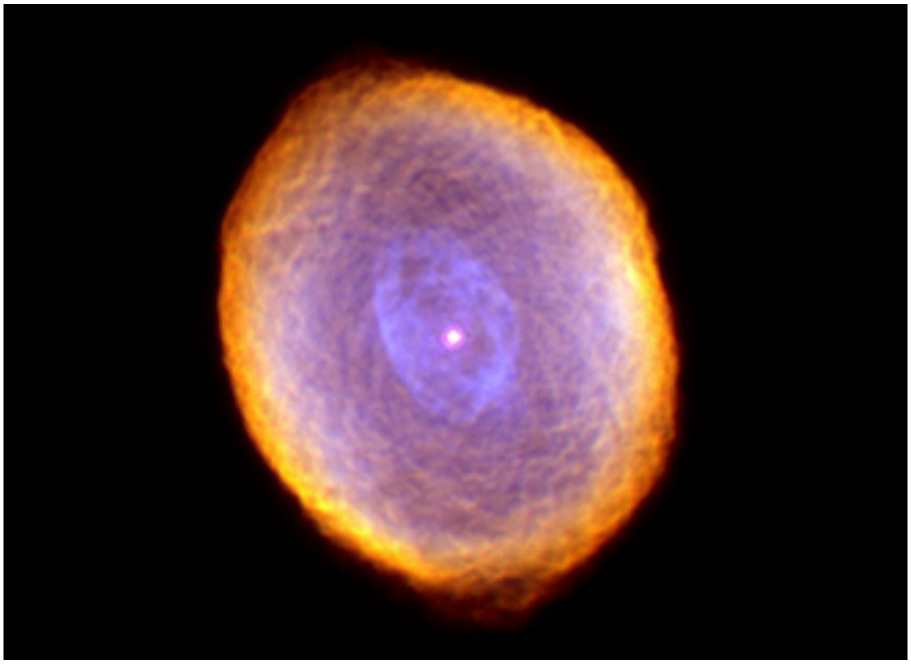
Figure 3. Spectrum of the J = 2 → 1 transition of methanol, observed at 96.7 GHz with the ARO 12 m telescope toward cloud WB89–621(RGC = 22.6 kpc). Here the three E and one A torsional components observed in this study are clearly visible. LTE relative intensities are shown under the spectrum. The intensity scale is TA(K). Spectral resolution is 156 kHz (0.48 km s^{-1})*

Dying stars could seed interstellar medium with carbon nanotubes

Daniel Stolte

University of Arizona News, June 16, 2022

In the mid-1980s, the discovery of complex carbon molecules drifting through the interstellar medium garnered significant attention, with possibly the most famous examples being Buckminsterfullerene, or "buckyballs" – spheres consisting of 60 or 70 carbon atoms. However, scientists have struggled to understand how these molecules can form in space. In a paper accepted for publication in the Journal of Physical Chemistry A, researchers from the University of Arizona suggest a surprisingly simple explanation. After exposing silicon carbide – a common ingredient of dust grains in planetary nebulae – to conditions similar to those found around dying stars, the researchers observed the spontaneous formation of carbon nanotubes, which are highly structured rod-like molecules consisting of multiple layers of carbon sheets. The findings were presented on June 16 at the 240th Meeting of the American Astronomical Society in Pasadena, California…According to study co-author Tom Zega, a professor in the UArizona Lunar and Planetary Lab, the challenge is finding nanotubes in these meteorites, because of the very small grain sizes and because the meteorites are a complex mix of organic and inorganic materials, some with sizes similar to those of nanotubes. "NASA's UArizona-led OSIRIS-REx mission scooped up a sample in October 2020. Scientists are eagerly awaiting the arrival of that sample, scheduled for 2023. "Asteroid Bennu could have preserved these materials, so it is possible we may find nanotubes in them," Zega said. "If they survived the journey to our local part of the galaxy where our solar system formed some 4.5 billion years ago, then they could be preserved inside of the material that was left over."



In this picture of the Spirograph Nebula, a dying star about 2,000 light-years from Earth, NASA's Hubble Space Telescope revealed some remarkable textures weaving through the star's envelope of dust and gas. UArizona researchers have now found evidence that complex carbon nanotubes could be forged in such environments. NASA and The Hubble Heritage Team (STScI/AURA)

Of Algorithms and Hidden Planets

Paul Gilster

Centauri Dreams, June 24, 2022

In a new paper in the *Astronomical Journal*, Ritvik Basant (University of Arizona) and colleagues go to work on the planetary architecture of 82 Eridani with a software package called DYNAMITE (developed by co-author Daniel Apai) that folds information specific to this system into a broader analysis incorporating what the authors call 'exoplanet demographics.' At stake here is this question: If an additional planet exists in a given system, what can we say about the probability distributions of its orbit, its eccentricity, its likely size? Let me quote from the paper: "To answer this question, DYNAMITE uses the robust trends identified in the Kepler exoplanet demographics data (orbital period distribution, planet-size distribution, etc., based on the ~2400 exoplanets that form the Kepler population) with specific data for a given single exoplanet system (detected planets and constraints on their orbits and sizes). Based on this information, DYNAMITE uses a Monte Carlo approach to map the likelihood of different planetary architectures, also considering the orbital dynamical stability and allowing for the freedom of statistical model choice."

Their work showed in multiple instances that an already discovered planet, if initially hidden from the software, would be retrieved by DYNAMITE, a test the software also passed when applied to the system at TOI-174, where more than one planet was removed and the probability of additional planets was noted in the software. It will be interesting indeed to see how accurately this assessment describes what we will one day find with improved observational techniques. Beginning with the assumption of a system consisting of only the three known planets, DYNAMITE provides further support for the earlier work that predicted three more potential worlds (no information from the 2017 study, mentioned above, was used as input for the software). The accomplishments of DYNAMITE can be further examined in the paper, but I'll mention its utility in the Tau Ceti system and its prediction of a habitable zone planet there, as well as interesting work on the K2-138 system, where it made what turns out to have been accurate predictions on two planets. So this seems to be a robust package, drawing heavily on existing data on planetary populations – it works best with the typical rather than the outlier, in other words, a fact to keep in mind before we extrapolate too freely.

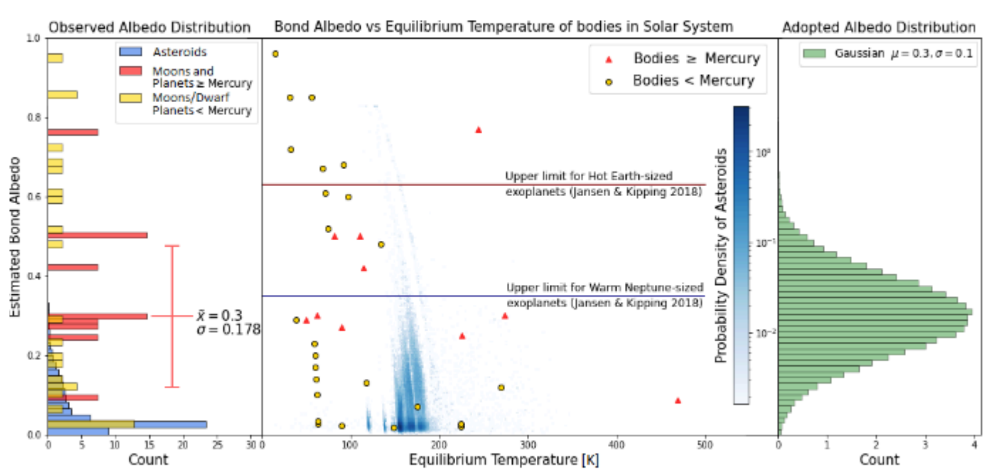


Figure 3. *Relationship between Bond albedos and calculated radiative equilibrium temperatures for planets, satellites, and asteroids in the Solar System. For the adopted Gaussian albedo prior (μ = 0.3, σ = 0.1), roughly 69% and 99.8% of the drawn albedo value fall below AB = 0.35 and AB = 0.63 respectively. Thus our adopted albedo prior is consistent with known Solar System and exoplanet constrains.*