EARTHS IN OTHER SOLAR SYSTEMS

Recent Publications

From Pebbles and Planetesimals to Planets and Dust: the Protoplanetary Disk--Debris Disk Connection

Why do M dwarfs have more transiting planets?

New evidence for wet accretion of inner solar system planetesimals from meteorites Chelyabinsk and Benenitra

An Integrative Analysis of the HD 219134 Planetary System and the Inner Solar System: Extending DYNAMITE with Enhanced Orbital Dynamical Stability Criteria

The Scorpion Planet Survey: Wide-Orbit Giant Planets Around Young A-type Stars

Hidden Water in Magma Ocean Exoplanets

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

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.

For a complete list of publications, please visit the **EOS Library** and **AE Library** on the SAO/NASA Astrophysics Data System.

ALIEN EARTHS | EARTHS IN OTHER SOLAR SYSTEMS

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.

Origins Seminars YouTube Channel

From Pebbles and Planetesimals to Planets and Dust: the Protoplanetary Disk--Debris Disk Connection

Joan R. Najita, Scott J. Kenyon, Benjamin C. Bromley

➔ [arXiv, November 2021]

The similar orbital distances and detection rates of debris disks and the prominent rings observed in protoplanetary disks suggest a potential connection between these structures. We explore this connection with new calculations that follow the evolution of rings of pebbles and planetesimals as they grow into planets and generate dusty debris. Depending on the initial solid mass and planetesimal formation efficiency, the calculations predict diverse outcomes for the resulting planet masses and accompanying debris signature. When compared with debris disk incidence rates as a function of luminosity and time, the model results indicate that the known population of bright cold debris disks can be explained by rings of solids with the (high) initial masses inferred for protoplanetary disk rings and modest planetesimal formation efficiencies that are consistent with current theories of planetesimal formation. These results support the possibility that large protoplanetary disk rings evolve into the known cold debris disks. The inferred strong evolutionary connection between protoplanetary disks with large rings and mature stars with cold debris disks implies that the remaining majority population of low-mass stars with compact protoplanetary disks leave behind only modest masses of residual solids at large radii and evolve primarily into mature stars without detectable debris beyond 30 au. The approach outlined here illustrates how combining observations with detailed evolutionary models of solids strongly constrains the global evolution of disk solids and underlying physical parameters such as the efficiency of planetesimal formation and the possible existence of invisible reservoirs of solids in protoplanetary disks.

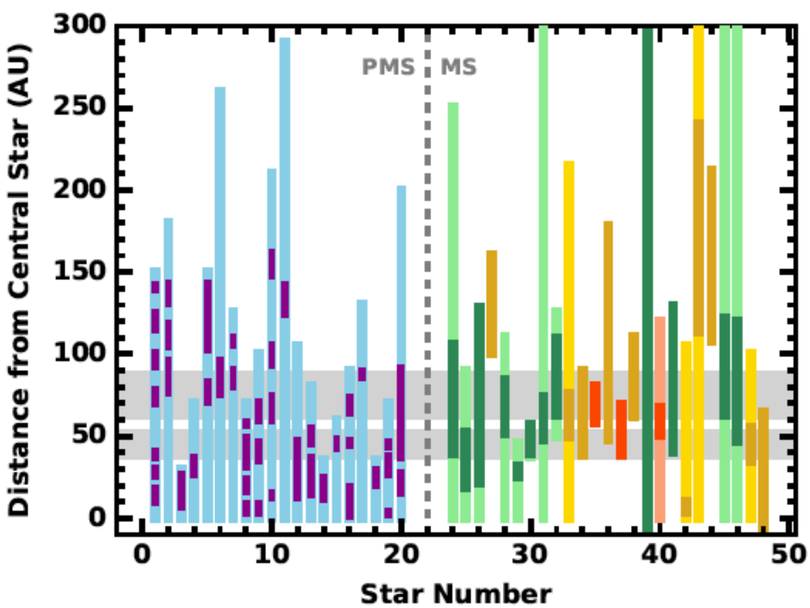

Figure 1. Comparison of the observed positions of bright rings in the continuum emission from protoplanetary disks around T Tauri stars (left side; Huang et al. 2018) to bright rings within extended dusty debris disks surrounding FGK main sequence stars (right side; Hughes et al. 2018). For each vertical bar, light (dark) regions indicate the extent of the disk (rings). Disks around main sequence stars are ordered by age, from 12 Myr for star 24 (HD 146897) to 8.2 Gyr for star 48 (τ Cet). Colors denote the spectral type|F (green), G (gold), or K (orange)|of the central star. The vertical grey dashed line separates premain-sequence (PMS) from main sequence (MS) stars. The horizontal grey bands represent the two grids used in the numerical calculations described in section 3.

Why do M dwarfs have more transiting planets?

Gijs D. Mulders, Joanna Drążkowska, Nienke van der Marel, Fred J. Ciesla, Ilaria Pascucci

➔ The Astrophysical Journal Letters, Volume 920, Issue 1

We propose a planet formation scenario to explain the elevated occurrence rates of transiting planets around M dwarfs compared to sun-like stars discovered by Kepler. We use a pebble drift and accretion model to simulate the growth of planet cores inside and outside of the snow line. A smaller pebble size interior to the snow line delays the growth of super-Earths, allowing giant planet cores in the outer disk to form first. When those giant planets reach pebble isolation mass they cut off the flow of pebbles to the inner disk and prevent the formation of close-in super-Earths. We apply this model to stars with masses between 0.1 and 2 solar mass and for a range of initial disk masses. We find that the masses of hot super-Earths and of cold giant planets are anti-correlated. The fraction of our simulations that form hot super-Earths is higher around lower-mass stars and matches the exoplanet occurrence rates from Kepler. The fraction of simulations forming cold giant planets is consistent with the stellar mass dependence from radial velocity surveys. A key testable prediction of the pebble accretion hypothesis is that the occurrence rates of super-Earths should decrease again for M dwarfs near the sub-stellar boundary like Trappist-1.

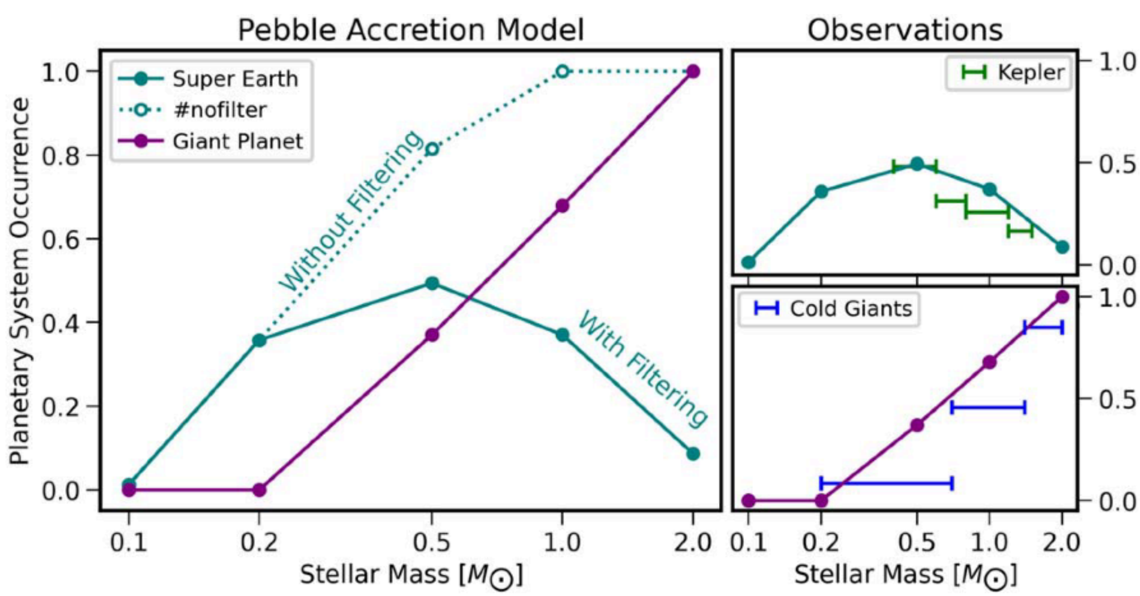

Figure 4. Fraction of models (from Figure 3) that form super-Earth cores (teal) or giant planet cores (purple). For reference the fraction of models that would form super-Earths in the absence of giant planet filtering is indicated with a dotted line. The right panels show the observed planetary system occurrence rates from Kepler (top) and radial velocity (bottom).

New evidence for wet accretion of inner solar system planetesimals from meteorites Chelyabinsk and Benenitra

Ziliang Jin, Maitrayee Bose, Tim Lichtenberg, Gijs Mulders

The Planetary Science Journal, Volume 2, Issue 6

We investigated the hydrogen isotopic compositions and water contents of pyroxenes in two recent ordinary chondrite falls, namely, Chelyabinsk (2013 fall) and Benenitra (2018 fall), and compared them to three ordinary chondrite Antarctic finds, namely Graves Nunataks GRA 06179, Larkman Nunatak LAR 12241, and Dominion Range DOM 10035. The pyroxene minerals in Benenitra and Chelyabinsk are hydrated (~0.018-0.087 wt.% H_2O) and show D-poor isotopic signatures (δDSMOW from -444‰ to -49‰). On the contrary, the ordinary chondrite finds exhibit evidence of terrestrial contamination with elevated water contents (~0.039-0.174 wt.%) and values (from -199‰ to -14‰). We evaluated several small parent body processes that are likely to alter the measured compositions in Benenitra and Chelyabinsk, and inferred that water-loss in S-type planetesimals is minimal during thermal metamorphism. Benenitra and Chelyabinsk hydrogen compositions reflect a mixed component of D-poor nebular hydrogen and water from the D-rich mesostases. 45-95% of water in the minerals characterized by low δDSMOW values was contributed by nebular hydrogen. S-type asteroids dominantly composed of nominally anhydrous minerals can hold 254-518 ppm of water. Addition of a nebular water component to nominally dry inner Solar System bodies during accretion suggests a reduced need of volatile delivery to the terrestrial planets during late accretion.

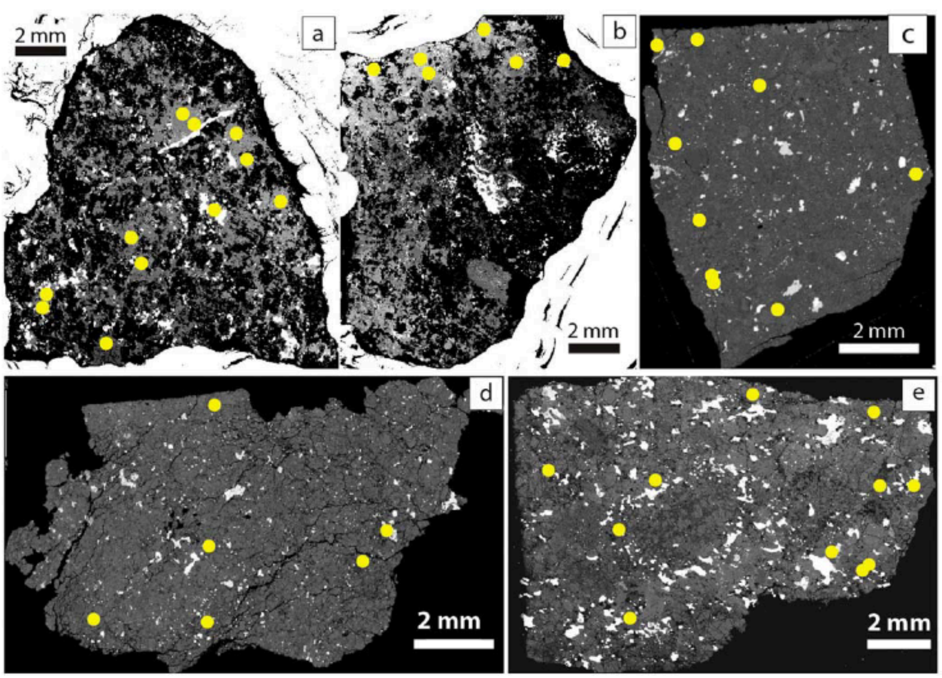

Figure 1. Backscattered electron images of OCs. The measured OCs are (a) Benenitra, (b) Chelyabinsk, (c) LL4 GRA 06179, (d) LL5 LAR 12241, and (e) L6 DOM 10035. The yellow circles show the analyzed spots with the SIMS instruments.

An Integrative Analysis of the HD 219134 Planetary System and the Inner Solar System: Extending DYNAMITE with Enhanced Orbital Dynamical Stability Criteria

Jeremy Dietrich, Dániel Apai, Renu Malhotra

→ arXiv, December 2021

Planetary architectures remain unexplored for the vast majority of exoplanetary systems, even among the closest ones, with potentially hundreds of planets still ``hidden" from our knowledge. DYNAMITE is a powerful software package that can predict the presence and properties of these yet undiscovered planets. We have significantly expanded the integrative capabilities of DYNAMITE, which now allows for (i) planets of unknown inclinations alongside planets of known inclinations, (ii) population statistics and model distributions for the eccentricity of planetary orbits, and (iii) three different dynamical stability criteria. We demonstrate the new capabilities with a study of the HD 219134 exoplanet system consisting of four confirmed planets and two likely candidates, where five of the likely planets are Neptune-size or below with orbital periods less than 100 days. By integrating the known data for the HD 219134 planetary system with contextual and statistical exoplanet population information, we tested different system architecture hypotheses to determine their likely dynamical stability. Our results provide support for the planet candidates, and we predict at least two additional planets in this system. We also deploy DYNAMITE on analogs of the inner Solar System by excluding Venus or Earth from the input parameters to test DYNAMITE's predictive power. Our analysis finds the system remains stable while also recovering the excluded planets, demonstrating the increasing capability of DYNAMITE to accurately and precisely model the parameters of additional planets in multi-planet systems.

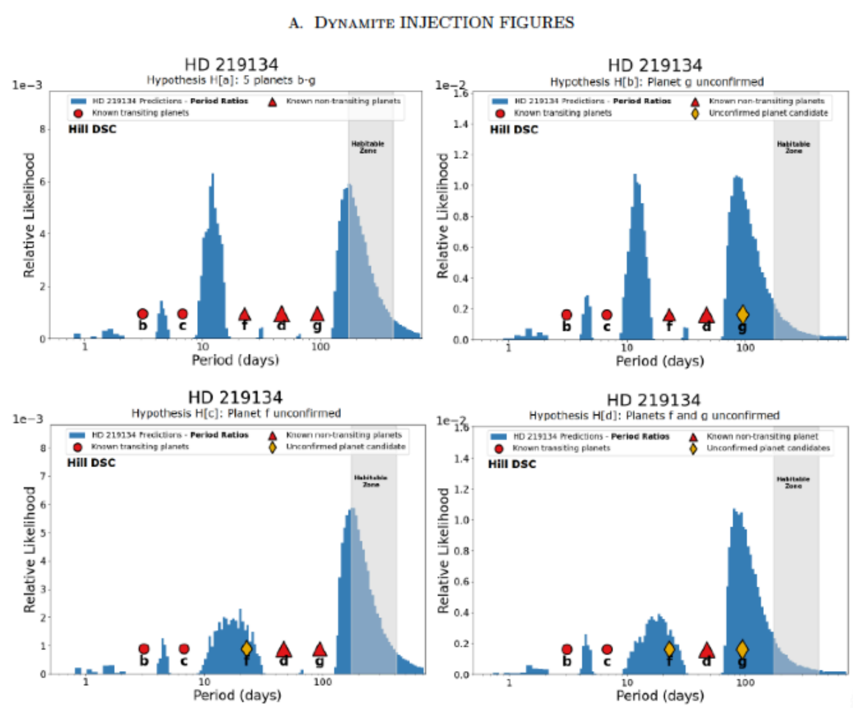

Figure 11. Dynamite analysis utilizing the simple dynamical stability criterion requiring neighboring planets' separation in semimajor axis to exceed 8 mutual Hill radii. Top left: Analysis assuming Hypothesis a, the full 5-planet system. Top right: Analysis assuming Hypothesis b, with no planet f (orbital period near stellar rotation period). Bottom left: Analysis assuming Hypothesis c, with no planet g (not found in all studies). Bottom right: Analysis assuming Hypothesis d, with no planet f nor planet g. Excluding planet f causes the predictions to spread out in period space, indicative of two planets possibly missing. Excluding planet g moves the exterior injection space to center almost directly on the period of planet g.

The Scorpion Planet Survey: Wide-Orbit Giant Planets Around Young A-type Stars

Kevin Wagner, Daniel Apai, Markus Kasper, Melissa McClure, Massimo Robberto

Accepted for pubication in The Astronomical Journal

The first directly imaged exoplanets indicated that wide-orbit giant planets could be more common around A-type stars. However, the relatively small number of nearby A-stars has limited the precision of exoplanet demographics studies to ≳10%. We aim to constrain the frequency of wide-orbit giant planets around A-stars using the VLT/SPHERE extreme adaptive optics system, which enables targeting ≳100 A-stars between 100−200 pc. We present the results of a survey of 84 A-stars within the nearby ~5−17 Myr-old Sco OB2 association. The survey detected three companions−one of which is a new discovery (HIP75056Ab), whereas the other two (HD 95086b and HIP65426b) are now-known planets that were included without a priori knowledge of their existence. We assessed the image sensitivity and observational biases with injection and recovery tests combined with Monte Carlo simulations to place constraints on the underlying demographics. We measure a decreasing frequency of giant planets with increasing separation, with measured values falling between 10−2% for separations of 30−100 au, and 95% confidence-level (CL) upper limits of ≲45−8% for planets on 30−100 au orbits, and ≲5% between 200−500 au. These values are in excellent agreement with recent surveys of A-stars in the solar neighborhood−supporting findings that giant planets at ≲100 au are more frequent around A-stars than around solar-type hosts. Finally, the relatively low occurrence rate of super-Jupiters on wide orbits, the positive correlation with stellar mass, and the inverse correlation with orbital separation are consistent with core accretion being their dominant formation mechanism.

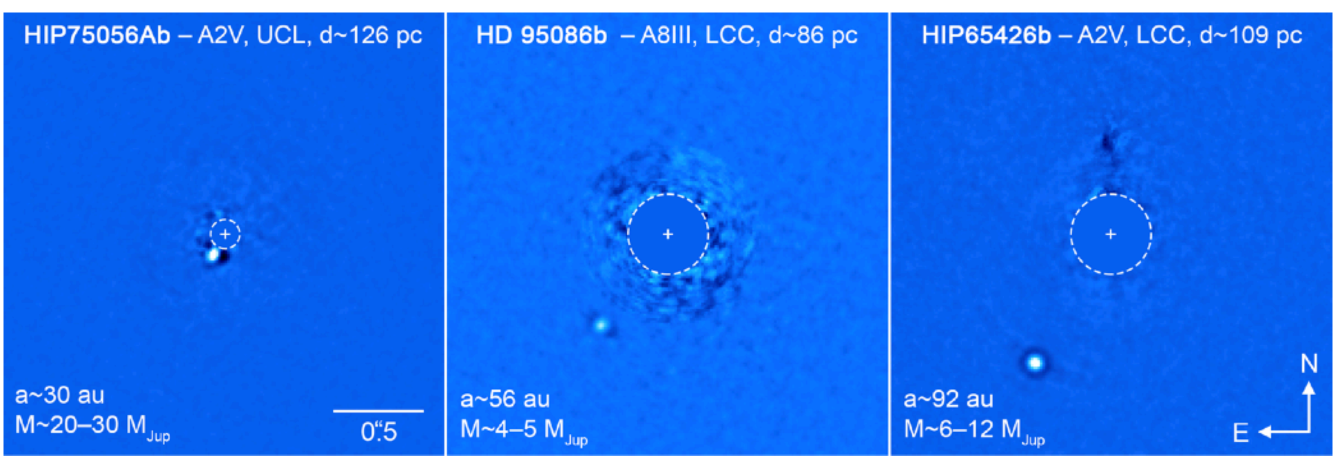

Fig. 1. Corirmed substellar companions among Sco-Cen A-type stars. These three objects span masses of ~4–30 M_{Jup} and separations of ~15–100 au. The discoveries and initial analyses of HIP75056Ab, HD 95086b, and HIP65426b can be found in Wagner et al. (2020), Rameau et al. (2013), and Chauvin et al. (2017), respectively.

Hidden Water in Magma Ocean Exoplanets

Caroline Dorn, Tim Lichtenberg

The Astrophysical Journal Letters, Volume 922, Issue 1

We demonstrate that the deep volatile storage capacity of magma oceans has significant implications for the bulk composition, interior, and climate state inferred from exoplanet mass and radius data. Experimental petrology provides the fundamental properties of the ability of water and melt to mix. So far, these data have been largely neglected for exoplanet mass-radius modeling. Here we present an advanced interior model for water-rich rocky exoplanets. The new model allows us to test the effects of rock melting and the redistribution of water between magma ocean and atmosphere on calculated planet radii. Models with and without rock melting and water partitioning lead to deviations in planet radius of up to 16% for a fixed bulk composition and planet mass. This is within the current accuracy limits for individual systems and statistically testable on a population level. Unrecognized mantle melting and volatile redistribution in retrievals may thus underestimate the inferred planetary bulk water content by up to 1 order of magnitude.

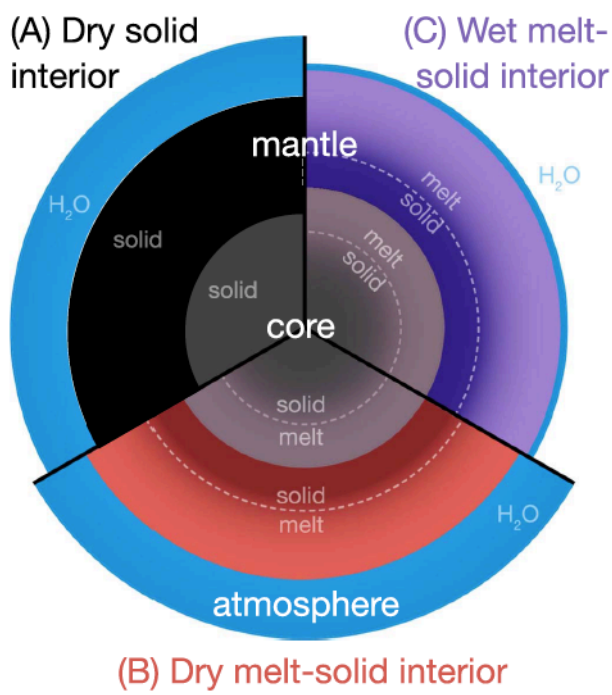

Figure 1. Three model scenarios employed in our study. Model A is very similar to models presented in Dorn et al. (2015, 2017b), and other commonly used exoplanet interior models follow model A, where liquid rock phases are neglected. Characteristically, the total radius is largest for model B, where solid and melt phases are present in the core and mantle. Generally, the radius is smallest for model C, where, additionally, the effect of water partitioning into the magma ocean is taken into account. Model C most accurately reflects our current knowledge of mineral physics and exoplanet interiors.

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 H_2, 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.

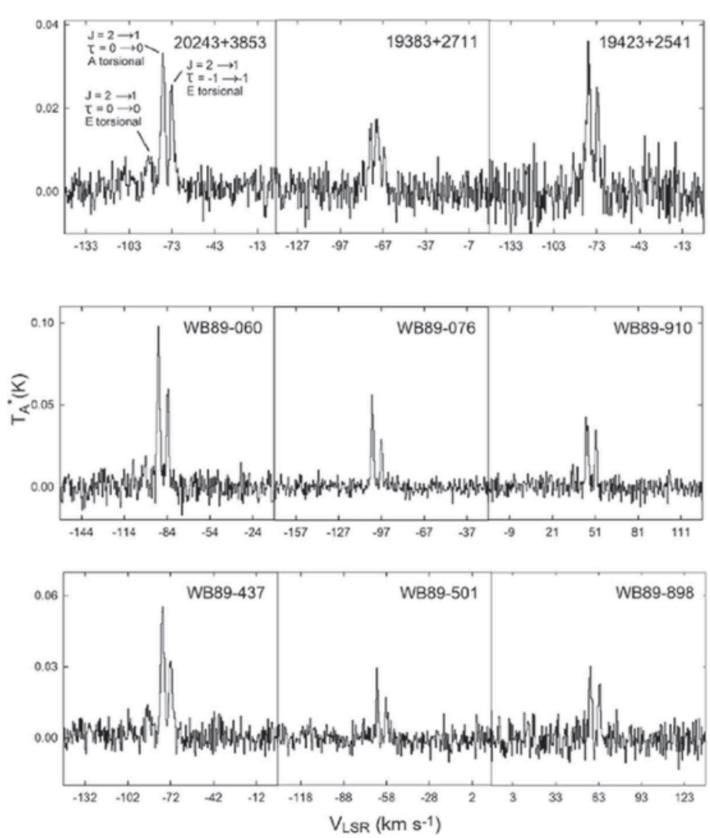

Figure 1. Spectra of asymmetry and torsional (E and A) components of the J = 2 → 1 transition of ethanol, observed at 96.7 GHz with the ARO 12 m telescope toward a sample of dense molecular clouds with RGC = 12.9–16.4 kpc. Transitions are labeled in the upper left panel. All spectra are centered on the Jτ = 2−1−1−1 line at 96,739.4 MHz. The intensity scale is TA *(K). Spectral resolution is 156 kHz (0.48 km s−1). CH3OH is clearly detected in all sources.