EXOPLANET EXPLORATION
Planets Beyond Our Solar System

https://exoplanets.nasa.gov


NASA/JPL-Caltech

Roadmap to the 2021 Sagan Summer Workshop

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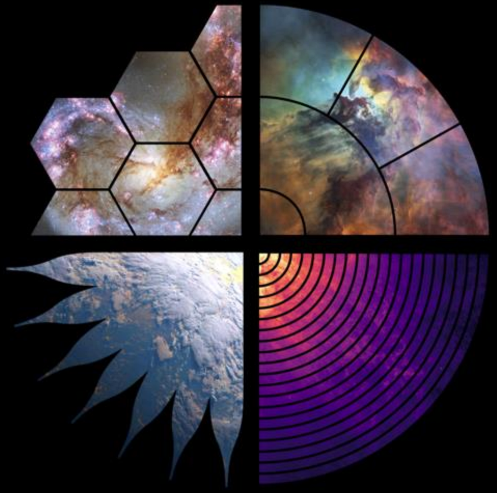

https://www.greatobservatories.org

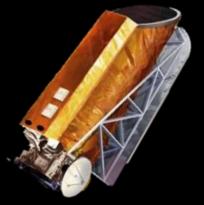
Talk overview

- Why now for a workshop on disks and young planets
- Another word from our sponsor
- Inventory of circumstellar disks and young planets
- Context for the workshop agenda
  - Key topics and research highlights for each day
- Concluding thoughts

NASA Exoplanet Exploration Program (ExEP)

Space Missions and Concept Studies

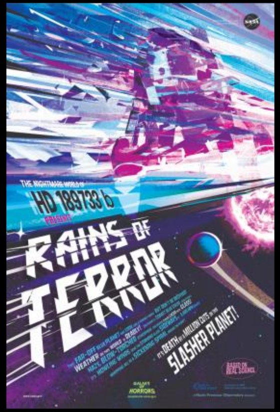
Large- and Probe-Scale
Mission Concepts



Coronagraph

Starshade

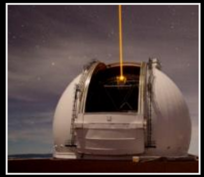
Exoplanet Communications



Supporting Research & Technology

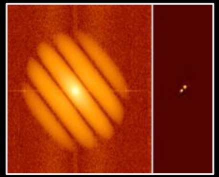
Key Sustaining Research

NN-EXPLORE



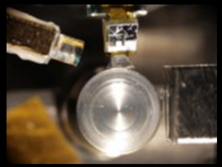
Keck Observatory

Large Binocular Telescope Interferometer

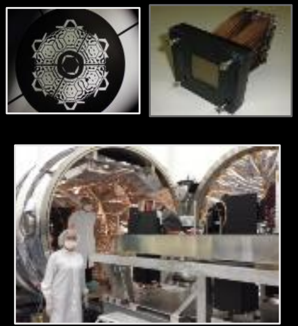


High Resolution Imaging

Technology Development



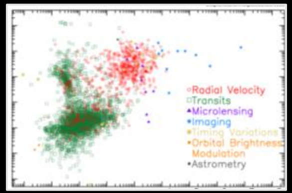
Extreme Precision Radial Velocity Technology Development

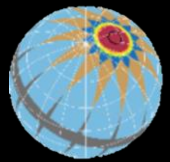


Coronagraph Technology Development

Starshade Technology Development (S5)

NASA Exoplanet Science Institute (NExScI)





Archives, Tools, Sagan Program, Professional Engagement

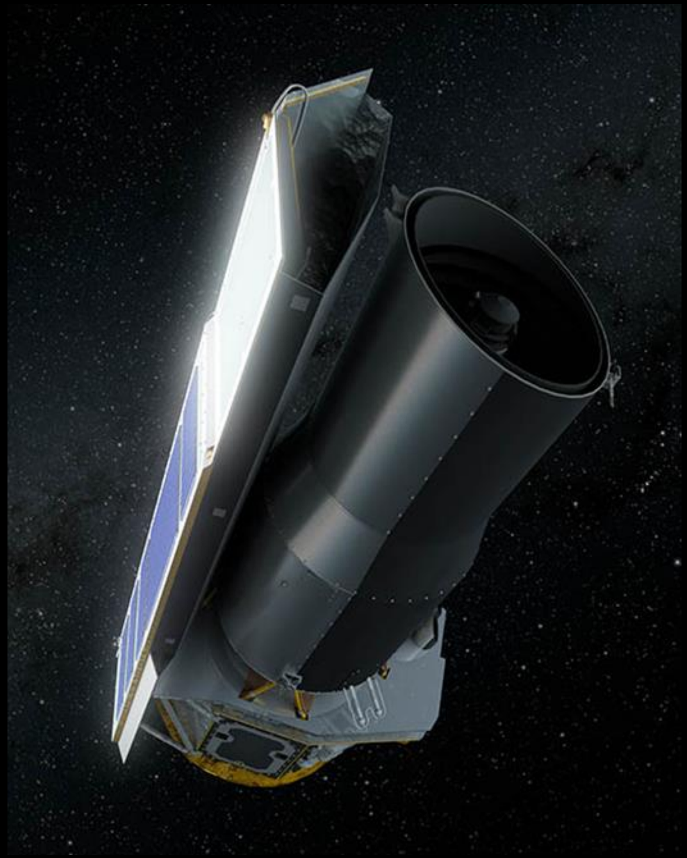
Staying connected to NASA Exoplanet Programs

- Public website: https://exoplanets.nasa.gov
- For researchers: https://exoplanets.nasa.gov/exep
- NASA Exoplanet Science Institute: https://nexsci.caltech.edu
- Community stakeholders: Exoplanet Program Analysis Goup (ExoPAG) https://exoplanets.nasa.gov/exep/exopag/overview includes info on how to subscribe to our mailing list

- NASA Exoplanet habitability research coordination network "NExSS": https://nexss.info

Circumstellar disk surveys: Mostly complete for bright/nearby targets

- Spitzer and Herschel surveyed low-mass star-forming regions within 500 pc, identifying > 6,500 young stars with disks and/or envelopes in various evolutionary stages (Dunham et al. 2015, Rebull et al. 2010, Andre et al. 2010, Megeath et al. 2012)
- Both missions surveyed main sequence stars within 25-50 pc, and young moving groups at greater distances, to find older debris disks (Eiroa et al. 2013, Sibthorpe et al. 2018)
- WISE all-sky survey found warm debris disks in areas not mapped by Spitzer/Herschel, for overall total of 1,750 (Cotton & Song 2016)
- Altogether, the local disk population and the best disk targets for individual studies have largely been identified by far-IR space telescopes over 2004-2016 – We know where to look for observational studies of planetary system evolution



How many young planets are known today ?

https://exoplanetarchive.ipac.caltech.edu

NASA Exoplanet Archive
NASA Exoplanet Science Institute

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Planetary Systems

Planet Name	Discovery Method	Discovery Year	Stellar Age [Gyr]	Planet Mass or Mass*sin(i) [Jupiter Mass]	Planet Radius [Jupiter Radius]	Orbit Semi-Major Axis [au]
			< 0.03	< 13		
2MASS J04414489+23015	Imaging	2010	0.001	7.5±2.5		15.0
DH Tau b	Imaging	2004	0.001	11^{+10}_{-3}		330
CHXR 73 b	Imaging	2006	0.002	$12.569^{+8.379}_{-5.23}$		210
V830 Tau b	Radial Velocit	2016	0.0022	0.70±0.12		0.057±0.001
CFHTWIR-Oph 98 b	Imaging	2021	0.003	$7.8^{+0.7}_{-0.8}$	1.86±0.05	200±6
CI Tau b	Radial Velocit	2019	0.0025±0.0005	$11.6^{+2.9}_{-2.7}$		
HD 97048 b	Disk Kinemat	2019	0.003	2.5±0.5		130
1RXS J160929.1-210524 b	Imaging	2008	0.005	8±1		330
PDS 70 b	Imaging	2018	0.0054±0.0010	3±1	$2.72^{+0.20}_{-0.17}$	20±2
PDS 70 c	Imaging	2019	0.0054±0.0010	2±1	$2.04^{+0.61}_{-0.45}$	34^{+6}_{-3}
2MASS J12073346-393253	Imaging	2004	$0.008^{+0.004}_{-0.003}$	5±2		55
K2-33 b	Transit	2016	$0.00930^{+0.00110}_{-0.00130}$	<3.7	$0.450^{+0.030}_{-0.033}$	
HD 106906 b	Imaging	2013	0.013±0.002	11±2		650
HIP 65426 b	Imaging	2017	0.014±0.004	9.0±3.0	1.5±0.1	92
YSES 2 b	Imaging	2021	0.0139±0.0023	$6.3^{+1.6}_{-0.9}$		115
HD 95086 b	Imaging	2013	0.017±0.004	5±2		55.7±2.5
TAP 26 b	Radial Velocit	2017	0.017	1.66±0.31		0.0968±0.0032
TYC 8998-760-1 c	Imaging	2020	0.0167±0.0014	6±1	$1.1^{+0.6}_{-0.3}$	320
AU Mic b	Transit	2020	0.022±0.003	<0.18	0.375±0.018	$0.066^{+0.007}_{-0.006}$
bet Pic c	Radial Velocit	2019	0.023	9		2.7

Statistics of young planets vs. age and detection method (all "planet" masses)

	< 10 Myrs	< 30 Myrs	< 100 Myrs	< 300 Myrs
Imaging	16	27	32	38
Transit	1	8	12	28
Transit timing	0	0	0	1
Radial velocity	2	4	4	6
Disk kinematics	2	2	2	2

Statistics of young planets vs. age and detection method ($M_p < 13\ M_J$ to exclude brown dwarfs)

	< 10 Myrs	< 30 Myrs	< 100 Myrs	< 300 Myrs
Imaging	8	17	18	23
Transit	1	3	6	13
Transit timing	0	0	0	1
Radial velocity	2	4	4	5
Disk kinematics	2	2	2	2

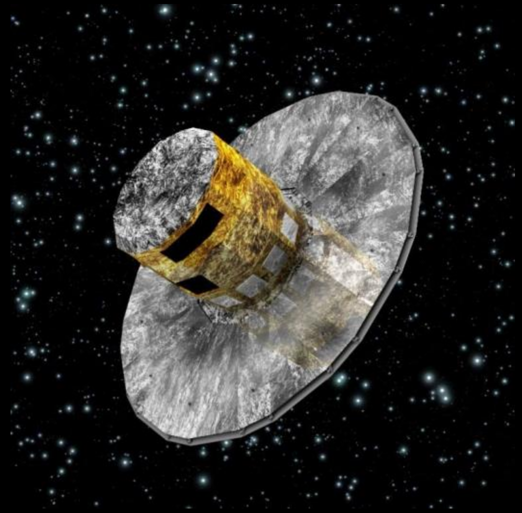
Summary of young planet statistics:

- Still a very small population: only ~ 44 with age < 100 Myrs out of 4434 known exoplanets, 1% of the total
- Imaging provides the largest number of detections, but uncertain stellar parameters & evolutionary tracks makes the ages (and thus masses) of these planets uncertain as well

Monday: Populations & Properties of Young Stars

- Why they matter: These are the stars around which we find circumstellar disks and young planets
- Beginners should remember:
  - Young stars (ages < 100 Million years) are only a fraction of all the stars in the galaxy and have distinctive properties.
  - We classify them according to both what the star and its surrounding material are doing, and arrange them in an evolutionary sequence (Megeath, Hillenbrand, & Baraffe talks)

Research highlight: In 2018 the ESA Gaia mission (right) provided highly accurate distance and space motion measurements for young stars, reducing the uncertainty in stellar ages and adding to our understanding of which stars are members of young associations (Gagné talk)



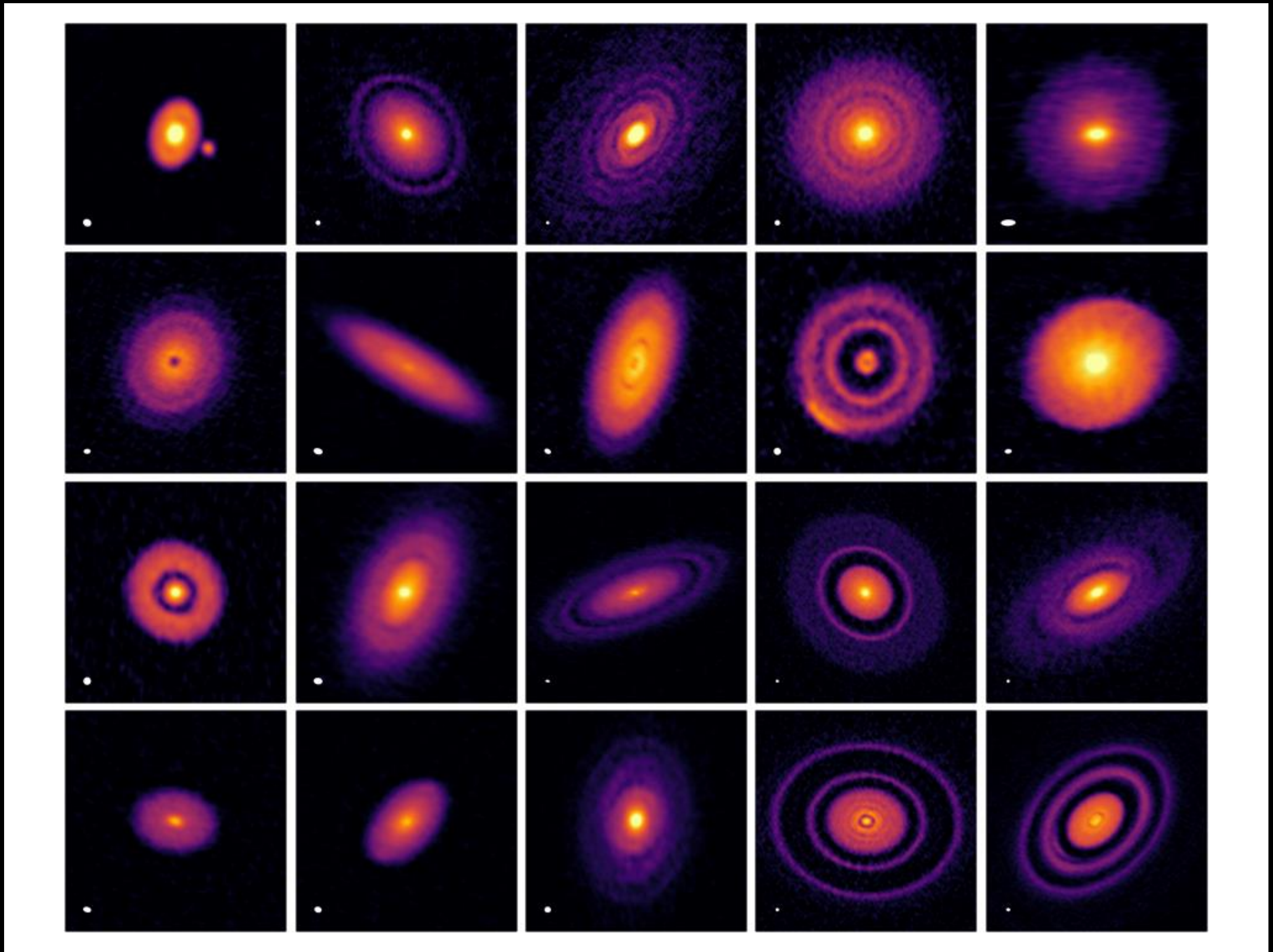
Tuesday: Properties of Circumstellar Disks

- Why they matter: Protoplanetary disks are the builders of worlds: nature's planet foundries.
- Beginners should remember:
  - Disks are clouds of gas and dust orbiting stars in a flattened configuration like the coplanar orbits of the solar system planets. Initially they feed material onto their central star (Najita talk).
  - Dust in protoplanetary disks grows into planetesimals (Benisty talk) and then into planets. Mature stars host tenuous debris disks (Weinberger talk), the "space junk" of planetary systems.
- Both types of disks can have internal structures driven by planetary perturbations (Bae, Wyatt talks)
- Research MEGA HIGHLIGHT: High resolution images of protoplanetary disks structure and composition with ALMA

Atacama Large Millimeter Array (ALMA) the penultimate disk observatory

- 50 12-m antennas located at 16,000 ft plateau in Chile
- Operating over 0.3- 9 mm wavelength range
- Offers sensitive imaging and heterodyne spectroscopy
- <u>Most competitive observatory in the world today</u> – 1,773 Cycle 7 proposals !

ALMA 0.2" resolution maps of protoplanetary disks



Perez and Oberg talks review the importance of ALMA imaging results for disk dust and gas emission

The DSHARP papers – Dec 2018 special issue of Astrophysical Journal Letters 1100 citations in only 2.5 years !

DSHARP I. Motivation, Sample, Calibration, and Overview
Andrews et al. 2018, ApJL, 869, L41

DSHARP II. Characteristics of Annular Substructures
Huang et al. 2018, ApJL, 869, L42

DSHARP III. Spiral Structures in the Millimeter Continuum of the Elias 27, IM Lup, and WaOph 6 Disks
Huang et al. 2018, ApJL, 869, L43

DSHARP IV. Characterizing Substructures and Interactions in Disks around Multiple Star Systems
Kurtovic et al. 2018, ApJL, 869, L44

DSHARP V. Interpreting ALMA Maps of Protoplanetary Disks in Terms of a Dust Model
Birnstiel et al. 2018, ApJL, 869, L45

DSHARP VI. Dust Trapping in Thin-Ringed Protoplanetary Disks
Dullemond et al. 2018, ApJL, 869, L46

DSHARP VII. The Planet-Disk Interactions Interpretation
Zhang et al. 2018, ApJL, 869, L47

DSHARP VIII. The Rich Ringed Substructures in the AS 209 Disk
Guzmán et al. 2018, ApJL, 869, L48

DSHARP IX. A High Definition Study of the HD 163296 Planet Forming Disk
Isella et al. 2018, ApJL, 869, L49

DSHARP X. Multiple Rings, a Misaligned Inner Disk, and a Bright Arc in the Disk around the T Tauri Star HD 143006
Pérez et al. 2018, ApJL, 869, L50

Wednesday: Planet Formation

- Why it matters: Use theory to understand the processes taking place inside the protoplanetary disk – astronomy's version of spinning straw into gold
- Beginners should remember:
  - We are pondering how to go from (lots of) tiny dust grains < 1 μm in size to planets that are 10 trillion times larger (Isidoro talk)
  - There are competing ideas: Theorists have found more than 1 way to form a giant planet (Helled talk), but observers have found ways to check on this (Neilsen talk)
- Important constraints are provided by the results of NASA's Kepler mission, which enabled measurements of planet sizes and orbits over a large statistical sample (Fulton talk) for comparison with models (Mordasini & Vidotto talks)
- Research highlight: Radius gap in size-frequency distribution of Kepler planets

Thursday: Finding and characterizing young planets

- Why it matters: By understanding the most newly-formed planets, we can separate the effects of initial conditions from later evolution
- Beginners should remember:
  - Young giant planets are very hot and thus easier to detect via imaging
  - Young stars vary in brightness and this can complicate indirect detections using the radial velocity and transit methods (Roy and Mann talks)
- Key facilities for direct imaging are the SPHERE, GPI, and ScExAO coronagraph instruments on the VLT, Gemini, and Subaru telescopes (Lagrange and Skemer talks)
- Research highlight is the recent high-precision astrometry and spectroscopy achieved with the VLT GRAVITY interferometer (Nowak talk)

Friday: Young Planet Evolution & the Future

- Why it matters: The story is not over once the planet has formed
- Beginners should remember:
  - The search for planets within and around protoplanetary disks is a hot topic right now
  - Planetary atmospheres can be eroded by harsh radiation & winds of their host star (Shkolnik talk)
- Research highlight: Planets have been imaged within the central cavities of a few protoplanetary disks, been observed to have their own circumplanetary disk, and to be accreting material from it ! (Follette talk)
- Upcoming & proposed telescopes will have significant new capabilities to detect greater numbers of young planets (Kasper & Chen talks), planet populations beyond the ice line (Gaudi talk), and even Earth analogs in habitable zones of nearby stars (Roberge talk)

Some questions to ponder this week

- Systems where we can localize both a planet and a disk are valuable, as they can be used to calibrate models for their dynamical interactions. Relatively few are known today.
- Circumplanetary disks may be more observable than a protoplanet itself, how can we know which source we are seeing ?
- There is so much more to do with ALMA observations of young disks, what do you think are the most important research directions to pursue ?

Best wishes for a fun and informative week !