Direct Imaging and Spectroscopy with JWST

Aarynn L. Carter

UC SANTA CRUZ

Image Credit: Olena Shmahalo, Quanta Magazine
Direct Imaging and Spectroscopy of Exoplanets

2009-07-31

20 au

Jason Wang / Christian Marois

2013-11-15

5 au
The Exoplanet Population

- Radial Velocity
- Imaging
- Transits
- Microlensing

![Graph depicting the exoplanet population with different detection methods: Radial Velocity (blue circles), Imaging (orange squares), Transits (red crosses), and Microlensing (green triangles). The x-axis represents the semi-major axis in au, and the y-axis represents the mass in $M_J$. Different markers indicate different detection methods and their associated uncertainties.](image-url)
The Transit and Direct Imaging Populations

Transits

Mass ($M_J$)

Semi-Major Axis (au)
The New Opportunity of JWST
The New Opportunity of JWST

Sensitivity
The New Opportunity of JWST

- Sensitivity
- Wavelength Coverage

Hubble primary mirror
JWST primary mirror

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Wavelength (µm)
The New Opportunity of JWST

- Sensitivity
- Wavelength Coverage
- Versatility

JWST primary mirror
Hubble primary mirror

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Aarynn L. Carter
Sagan Summer Workshop
July 28, 2023
The Transit and Direct Imaging Populations

Transits

Imaging

Mass ($M_J$) vs. Semi-Major Axis (au)

Logarithmic scales are used for both axes.
Imaging Exoplanets with Early Release Science

HIP 65426 b
~7-9 M\text{Jup}, 1300-1600 K

Chauvin et al. 2017
Cheetham et al. 2019

IRDIS-H2H3 (Feb 7th, 2017)
Imaging Exoplanets with Early Release Science

HIP 65426 b
~7-9 M_Jup, 1300-1600 K

Chauvin et al. 2017

Cheetham et al. 2019

JWST NIRCam and MIRI Coronagraphy

Cheetham et al. 2019
Residual Stellar Light Contaminates Images

Carter et al. 2023
The First Images of an Exoplanet with JWST

Carter et al. 2023
HIP 65426b Detected from 2-16 μm

Carter et al. 2023
Precise Measurements Across the Full Spectrum

Carter et al. 2023
What Advantages will JWST Provide?
Imaging Giant Exoplanets With Independent Mass Constraints

The graph shows the relationship between the semi-major axis (in astronomical units, au) and the mass of exoplanets. The data points are color-coded to indicate different detection methods:
- Blue dots represent radial velocity detections.
- Green triangles represent imaging detections.
- Orange squares indicate transit detections.

The graph highlights the clustering of detected exoplanets in specific regions, indicating the effectiveness of each detection method across different semi-major axis and mass ranges.
Imaging Giant Exoplanets With Independent Mass Constraints
Imaging Sub-Jupiter Mass Exoplanets

The graph illustrates the distribution of planetary masses versus semi-major axes. Different markers represent various detection methods:

- **Radial Velocity** (blue dots)
- **Transit** (orange squares)
- **Imaging** (green triangles)
- **Timing Variations** (purple diamonds)
- **Microlensing** (red crosses)
- **Brightness Modulation** (black asterisks)

The data points are spread across a logarithmic scale, showing a broad range of masses and semi-major axes from $10^{-3}$ to $10^4$ au.
Sub-Jupiter Mass Sensitivity with JWST

PanCAKE Simulated Mass Sensitivity (30 Minute Exposures)

Lowest Mass Exoplanet Detected with Direct Imaging

5σ Mass Sensitivity ($M_{Jup}$)

Separation (au)
Giant Planet Hunting in the Gaps of ALMA Disks

Bae et al. 2018

New Sensitivity at Separations of Observed ALMA Disk Gaps

Sean Andrews / DSHARP / ALMA
Long Term Characterisation of New Exoplanet Benchmarks

Pathfinder Survey Observation

Coronagraphic Follow Up

Spectroscopic Follow Up

Phillips et al. 2020

$T_{\text{eff}} = 300 \text{K}$

$\sim 1 M_{\text{Saturn}}$
Spectroscopy Provides Incredible Atmospheric Detail
Spectroscopy with Early Release Science

**VHS 1256b**

- Mass: 14-24 M\(_{\text{Jup}}\)
- Temperature: 1000-1200 K

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**Gauza et al. 2015 / ESO**

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**Zhou et al. 2020**

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**Data**

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**Model**

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**VHS 1256 b**

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**Flux (10^{-20} * W/cm^2/\mu m)**

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**Wavelength (\mu m)**

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**Miles et al. 2018**
An “Exoplanet” Atmosphere In Unprecedented Detail

Miles et al. 2023
An “Exoplanet” Atmosphere In Unprecedented Detail

Miles et al. 2023
An “Exoplanet” Atmosphere In Unprecedented Detail

Miles et al. 2023
Evidence for Absorption From Silicate Clouds

Miles et al. 2023
Atmospheric Model Fitting Is Very Challenging!

Miles et al. 2023

Model -1100 K, 316 m/s², $f_{sed} = 0.6 \,(90\%) \,\text{and} \, 1.0 \,(10\%)$, $R = 1.27 \,R_J$

VHS 1256 b Data

Miles et al. 2023
Much More to Explore Beyond VHS 1256 b

- How do atmospheres evolve across different temperature regimes?
- What is the extent and prevalence of disequilibrium chemistry and clouds?
- How does atmospheric variability change across the population?
- How far can we push JWST’s spectroscopic modes?

Miles et al. 2023
JWST Spectroscopy of a ~450 K Brown Dwarf

Beiler et al. 2023
Spectroscopy at Short Angular Separations

Patapis et al. 2022
Direct Spectroscopy Observations of Exoplanets are Possible with JWST

Phillips et al. 2020

\[ T_{\text{eff}} = 300 \text{K} \]

\[ \sim 1 M_{\text{Saturn}} \]

Pathfinder Survey Observation

Coronagraphic Follow Up

Spectroscopic Follow Up
Conclusions

JWST presents an unprecedented opportunity to characterise a diverse range of exoplanets with high sensitivity and broad wavelength coverage for both direct imaging and spectroscopy observations.

JWST coronagraphic imaging is exceeding its nominal predicted performance, and opens the door to observations beyond 5 micron, and imaging observations of sub-Jupiter mass objects for the first time.

Spectroscopic observations with JWST provide an unrivaled amount of information and will greatly advance our understanding of exoplanet / brown dwarf atmospheric physics and chemistry.

These observations are only the beginning, and represent a small fraction of the exoplanet imaging science that will be performed throughout the entire lifetime of JWST. There is a wealth of discovery to look forward too!
Questions