Curriculum Vitae — Richard Teague

Contact Information

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Employment

Massachusetts Institute of Technology — July 2022
Department of Earth, Atmospheric and Planetary Sciences
Assistant Professor

Center for Astrophysics | Harvard & Smithsonian — Sep. 2019 – June 2022
Submillimeter Array Fellow

University of Michigan — May 2017 – Jul. 2019
Postdoctoral Researcher

Max-Planck-Institute for Astronomy — Jan. 2017 – Apr. 2017
Postdoctoral Researcher

Education

Max-Planck-Institute for Astronomy, Heidelberg, Germany
Ph.D. in Astronomy (Magna Cum Laude) — Oct. 2013 – Jan. 2017

University of Edinburgh, Edinburgh, United Kingdom
MPhys Astrophysics (First Class Honours) — Sep. 2008 – May 2013

Honours & Awards

Harvard Data Science Initiative Research Fund ($9,700) — Mar. 2020
Regularized Maximum Likelihood Imaging: A New Method for Detecting Planets

Ernst Patzer Award — Nov. 2016
Awarded for the best refereed publication by a young scientist.

Pre-Honours Certificate of Merit — May 2011
Awarded for top 5% performance in pre-honours exams.

Pre-Honours Certificate of Merit — May 2010
Awarded for top 5% performance in pre-honours exams.

Publication Summary

17 lead author papers, including one published in *Nature*, and 66 co-author papers, totaling **1723 citations** (ADS). A full publication list can be found at the end of the CV.

Observational Time Summary

I have been awarded over **265 hours** (335 hours) of time on **ALMA** as PI (co-I), including as the `exoALMA` Large Program of which I am PI, **20 hours** (165 hours) on **IRAM** telescopes as PI (co-I), **16 hours** (30 hours) on the **SMA** as PI (co-I) and **8 hours** (18 hours) on **JWST** as co-PI (co-I). I have also been a co-investigator on projects for the **VLA**, the **VLT** and the **Magellan** telescopes, with awards of 50 hours, 25 hour and 2 nights, respectively. A break down of PI proposals can be found at the end of the CV.

Professional Services

SMA Interferometry School SOC — Mar. 2021
SMA, Hilo, Hawaii, USA

Advanced Data Analysis Techniques for ALMA SOC — Oct. 2020
NRAO, Charlottesville, Virginia, USA [postponed due to Covid-19]

SMA Seminar Organizer — 2020 - 2021
Departmental Seminar Series

Visualizing the Kinematics of Planet Formation SOC — Oct. 2019
Flatiron Institute, New York City, USA

Postdoc and Research Scientist DEI Representative — 2018 – 2019
Department Diversity, Equity and Inclusion Committee Member

Equi-Tea Organizer — 2018 – 2019
Diversity, Equity and Inclusion Journal Club

	Stars, Planets and Formation Seminar Organizer *Departmental Seminar Series*	2018 – 2019
	Conversations on Equity and Inclusion Co-organizer *Joint Physics / Astronomy / Space Sciences DEI Colloquium Series*	2018 – 2019
	NESSF External Reviewer	2018, 2020
	Heidelberg MPG Student Workshop Organizer	2016
	PSF Coffee Organizer *Departmental Seminar Series*	2015 – 2017
	MPIA Student Representative	2015 – 2017
	MPIA Student Workshop Organizer	2015, 2016
	IMPRS Graduate Student Representative	2013 – 2017
	Referee for AAS, A&A, MNRAS and Nature journals	

SUPERVISION

Haochuan Yu Beijing Normal University *Undergraduate student.*	2020 -
Alessandra Canta Harvard University *Undergraduate student. Co-supervised with Karin Öberg, Harvard*	2020 -
Felipe Alcaron University of Michigan *Graduate student. Co-supervised with Ted Bergin and Ke Zhang, UMich.*	2019 – 2020
Jenny Calahan University of Michigan *Graduate student. Co-supervised with Ted Bergin and Ke Zhang, UMich.*	2019 – 2020
Deryl Long University of Michigan *Undergraduate student. Co-supervised with Ted Bergin and Ke Zhang, UMich.*	2019
Case Hazewinkel University of Michigan *Undergraduate student. Co-supervised with Ted Bergin, UMich.*	2019
Jeanne Kwon University of Michigan *Undergraduate Research Opportunity Program*	2018 – 2019
Julian Penzinger Ludwig Maximilian University *Summer student. Co-supervised with Dmitry Semenov, MPIA.*	2016, 2018

TALKS & SEMINARS

Munich Join Astronomical Colloquium *Mapping the Assembly of Planetary Systems in 6 Dimensions*	Oct. 2021 *(invited)*
Center for Astrophysics Colloquium *Mapping the Assembly of Planetary Systems in 6 Dimensions*	Sep. 2021 *(invited)*
ETH Zurich Exoplanets & Habitability Seminar *Witnessing the Assembly of Planetary Systems*	May 2021 *(invited)*
Cambridge Exoplanet Center Seminar *Witnessing the Assembly of Planetary Systems*	May 2021 *(invited)*
Towards the Comprehensive Characterization of Exoplanets: Science at the Interface of Multiple Measurement Techniques *Transforming ALMA into a Planet Hunting Facility*	Apr. 2021
McMaster University Astrophysics Seminar *Witnessing the Assembly of Planetary Systems*	Apr. 2021 *(invited)*
Circumplanetary Disks II *Observations and Observational Predictions*	Mar. 2021 *(invited)*
Max Planck Research Group Selection Symposium *Witnessing the Assembly of Planetary Systems*	Feb. 2021 *(invited)*
Caltech Dix Planetary Science Department Seminar *Planet Formation in Six Dimensions*	Feb. 2021 *(invited)*
Five Years After HL Tau: A New Era in Planet Formation *Observing the Kinematics of Gaseous Substructures*	Dec. 2020

Research Unit Transition Disks (RUTD) Conference Oct. 2020
Observing the Dynamics of Planet Disk Interactions *(invited)*

From Clouds to Planets II: The Astrochemical Link Oct. 2020
ALMA's 3D View of Planet Formation [postponed due to Covid-19] *(invited)*

Exoplanets III July 2020
Kinematical Detection and Characterizing of Protoplanets with ALMA

MPIA Königstuhl Colloquium July 2020
Visualizing the Assembly of Planetary Systems *(invited)*

JPL Astrophysics Colloqium Nov. 2019
Witnessing the Dynamics of Planetary Assembly *(invited)*

Visualizing the Kinematics of Planet Formation Oct. 2019
Exploiting ALMA's Potential for Planet Hunting

Gordon Research Seminar June 2019
Unveiling the Dynamics of Planet Formation

IAU Symposium 350: Laboratory Astrophysics Apr. 2019
The Physical Conditions of Planet Formation with Molecular Excitation (invited)

Planet-Forming Disks Mar. 2019
Unveiling the Dynamics of Planet Formation (invited)

NAOJ Theoretical Astronomy Seminar Oct. 2018
Observing the Kinematics of Planet-Disk Interactions with ALMA (invited)

LMU Munich Astronomy Colloquium Aug. 2018
Using Kinematics to Search for Embedded Protoplanets (invited)

University of Tübingen Astronomy Seminar Aug. 2018
Kinematical Detections of Embedded Protoplanets (invited)

Astrophysical Frontiers in the Next Decade and Beyond Apr. 2018
The First Kinematical Detection of Embedded Protoplanets

Magnetic Fields or Turbulence Feb. 2018
A Spatially Resolved Search for Turbulence in TW Hya

MPIA Patzer Awards Colloquium Nov. 2016
Measuring Turbulence in TW Hya with ALMA: Methods and Limitations (invited)

MPIA Königstuhl Colloquium Nov. 2016
Observing the Earliest Stages of Planet Formation (invited)

Astrochemistry with ALMA Cycle 4 Jun. 2016
Detecting Turbulence in Protoplanetary Disks (invited)

Sant-Cugat Forum on Astrophysics Apr. 2016
Turbulence in Protoplanetary Disks: Methods and Limitations

Protoplanetary Discussions Mar. 2016
Turbulence in TW Hya

Chemical Diagnostics of Star and Planet Formation Jan. 2015
Deuterium Fraction in Protoplanetary Disks (invited)

ZAG - IPAG - MPIA Workshop on Planet Formation Jan. 2015
Deuterium Fraction in DM Tau (invited)

Successful Telescope Proposals (as PI)

ALMA PI: **Teague, R.**, 183 hours, 2021.1.01123.L, A ranked 2021
co-PIs: Bensity, M., Facchini, S., Fukagawa, M. & Pinte, C.
exoALMA Large Program

JWST co-PIs: Cugno, G. & **Teague, R.**, 8 hours, 2153, Cycle 1
Detecting a Young 2 Jupiter Mass Planet Embedded in the Disk of HD 163296

SMA PI: **Teague, R.**, 6 hours, 2020A-S033, B ranked 2020b
A 3D Exploration of an Edge-On Self-Gravitating Disk

SMA PI: **Teague, R.**, 10 hours, 2020A-S033, A ranked 2020a
A 3D Exploration of an Edge-On Self-Gravitating Disk

ALMA PI: **Teague, R.**, 13.8 hours, 2019.1.01357.S, A ranked — 2019
Constraining the H2 Surface Density Profile in IM Lup

ALMA PI: **Teague, R.**, 3.0 hours, 2019.1.00794.S, B ranked — 2019
Detecting the Photoevaporative Wind in IM Lup

ALMA PI: **Teague, R.**, 33.2 hours, 2019.1.00419.S, B ranked — 2019
Mapping the 3D Kinematic Structure of Planet Formation

ALMA PI: **Teague, R.**, 20.2 hours, 2018.A.00021.S, DDT — 2019
Confirmation of an Embedded Planet in the Disk of TW Hya

Magellan/MagAO PI: **Teague, R.**, 6 hours — 2018
Searching for Wide Separation Planets in AS 209

ALMA PI: **Teague, R.**, 6.7 hours, 2018.1.00980.S, A ranked — 2018
An Unambiguous Detection of a Magnetic Field in a Protoplanetary Disk

ALMA PI: **Teague, R.**, 5.3 hours, 2016.1.00440.S, A ranked — 2016
Model Independent Study of Turbulence and Temperature in TW Hya

IRAM PdBI PI: **Teague, R.**, 19.9 hours, W14BI, C ranked — 2014
Disk Diagnostics with Deuteration

(AS CO-I) Including over 355 hours with **ALMA**, 150 hours with **IRAM** telescopes, 30 hours with the **SMA**, 50 hours with the **VLA**, 50 hours with **VLT** (X-SHOOTER, SPHERE and CRIRES), 2 nights with **Magellan** (MagAO/MagAOx) and 18 hours with **JWST**.

OUTREACH

University of Michigan Lowbrow Astronomers — Nov. 2020
How to Find Baby Planets

SCHOOL PARTICIPATION

45th Saas-Fee Course — 2015
From Protoplanetary Disks to Planet Formation

Heidelberg Graduate School on Fundamental Physics — 2015

DIANA Protoplanetary Disk School — 2014

OBSERVING EXPERIENCE

Sub-Millimeter Array — Sep. 2019 –
Monthly rota

MPG/ESO 2.2m — 2016
14 nights

TEACHING

Wavefront Analysis Laboratory Instructor — 2014

PUBLICATIONS (LEAD AUTHOR)

Teague, R., Law, C. J., Huang, J. et al., JOSS, submitted
`disksurf`*: Extracting the 3D Structure of Protoplanetary Disks*

Teague, R., Bae, J., Aikawa, Y., et al., ApJS, in press
MAPS XVIII: Kinematic Substructure in the Disks of HD 163296 and MWC 480

Teague, R., Hull, C. L. H., Bergin, E. A., et al., ApJ, in press
Discovery of Molecular Line Polarization in the Disk of TW Hya

Teague, R. & Loomis, R. A., ApJ, 899
The Excitation Conditions of CN in TW Hya

Teague, R., Jankovic, M. R., Haworth, T. J., et al., MNRAS, 495
A Three Dimensional View of Gomez's Hamburger

Teague, R., 2019, IAU Proceedings Series, 350
Tracing The Physical Conditions of Planet Formation with Molecular Excitation

Teague, R., Bae, J., Huang, J., Bergin, E. 2019, ApJL, 884
Spiral Structure in the Gas Disk of TW Hya

Teague, R., Bae, J., Bergin, E. 2019, Nature, 574
Meridional Flows in the Disk Around a Young Star

Teague, R., 2019, Journal of Open Source Software, 4
GoFish: Fishing for Line Observations in Protoplanetary Disks

Teague, R., 2019, RNAAS, 3
[non-refereed] Statistical Uncertainties in Moment Maps of Line Emission

Teague, R., 2019, Journal of Open Source Software, 4
eddy: Extracting Protoplanetary Disk Dynamics with Python

Teague, R., Bae, J., Birnstiel, T. & Bergin, E., 2018, ApJ, 868
Evidence For A Vertical Dependence on the Pressure Structure in AS 209

Teague, R. & Foreman-Mackey, D., 2018, RNAAS, 2
[non-refereed] A Robust Method to Measure Centroids of Spectral Lines

Teague, R., Henning, T., Guilloteau, S., et al., 2018, ApJ, 864
Temperature, Mass, and Turbulence: A Spatially Resolved Multiband Non-LTE Analysis of CS in TW Hya

Teague, R., Bae, J., Bergin, E. A., et al., 2018, ApJL, 860
A Kinematical Detection of Two Embedded Jupiter-mass Planets in HD 163296

Teague, R., Semenov, D., Gorti, U., et al., 2017, ApJ, 835
Surface Density Perturbations in the TW Hydrae Disk at 95 au Traced by Molecular Emission

Teague, R., Guilloteau, S., Semenov, D., et al., 2016, A&A, 592
Measuring turbulence in TW Hya with ALMA: methods and limitations

Teague, R., Semenov, D., Guilloteau, S., et al., 2015, A&A, 574
Chemistry in disks. IX. Observations and modelling of HCO^+ and DCO^+ in DM Tauri

(CO-AUTHOR) All papers with a substantial component of student supervision are marked.

Yu, H., **Teague, R.**, Bae, J. & Öberg, K., ApJL, in press
[student paper] Mapping the 3D Kinematical Structure of the Gas Disk of HD 169142

Öberg, K. I., Guzmán, V. V., Walsh, C., et al., ApJS, in press
MAPS I: Program Overview and Highlights

Czekala, I., Loomis, R. A., **Teague, R.**, et al., ApJS, in press
MAPS II: CLEAN Strategies for Synthesizing Images of Molecular Line Emission in Protoplanetary Disks

Law C. J., Loomis, R. A., **Teague, R.**, et al., ApJS, in press
[student paper] MAPS III: Characteristics of Radial Chemical Substructures

Law C. J., **Teague, R.**, Loomis, R. A., et al., ApJS, in press
[student paper] MAPS IV: Vertical Disk Chemical Structures

Zhang, K., Booth, A. S., Law, C. J., et al., ApJS, in press
MAPS V: CO Gas Distributions

Guzmán, V., Ö, K. I., Aikawa, Y., et al., ApJS, in press
MAPS VI: Distribution of the small organics HCN, C_2H and H_2CO

Bosman, A., Alarcon, F., Bergin, E. A., et al., ApJS, in press
MAPS VII: Sub-stellar O/H and C/H and Super-stellar C/O in Planet Feeding Gas

Alarcon, F., Bosman, A., Bergin, E. A., et al., ApJS, in press
MAPS VIII: Gap chemistry in AS 209 – Gas Depletion or Chemical Processing?

Ilee, J. D., Walsh, C., Booth, A. S., et al., ApJS, in press
MAPS IX: Distribution and properties of the Large Organic molecules HC_3N, CH_3CN and c-C_3H_2

Cataldi, G., Yamato, Y., Aikawa, Y., et al., ApJS, in press
MAPS X: Distributions of Deuterated Molecules

Bergner, J., Öberg, K. I., Bosman, A., et al., ApJS, in press
MAPS XI: CN and HCN as Tracers of Photochemistry in Disks

Le Gal, R., Öberg, K. I., Aikawa, Y., et al., ApJS, in press
MAPS XII: Inferring the C/O and S/H ratios in Protoplanetary Disks with Sulfur Molecules

Aikawa, Y., Cataldi, G., Yamato, Y., et al., ApJS, in press
MAPS XIII: HCO^+ and Disk Ionization

Sierra, A., Peréz, L. M., Guzmán, V. V., et al., ApJS, in press
MAPS XIV: Revealing Dust Disks Substructures From Nulti-wavelength Continuum Emission

Bosman, A., Bergin, E. A., Öberg, K. I., et al., ApJS, in press
MAPS XV: Tracing Protoplanetary Disk Structure Within 20 AU

Booth, A. S., Tabone, B., Aikawa, Y., et al., ApJS, in press
MAPS XVI: Zooming in on the HD 163296 Disk Wind with CO Isotopologues

Calahan, J., Bergin, E. A., Zhang, K., et al., ApJS, in press
MAPS XVII: Uncovering the 2D Thermal Structure of HD 163296

Huang, J., Bergin, E. A., Öberg, K. I., et al., ApJS, in press
MAPS XIX: Spiral Arms, a Tail, and Diffuse Structures Traced by CO Toward the GM Aur Disk

Schwarz, K., Calahan, J., Zhang, K., et al., ApJS, in press
MAPS XX: The Massive Disk Around GM Aurigae

Canta, A., **Teague, R.**, le Gal., R., et al., ApJ, submitted
[student paper] The first detection of CH_2CN in a protoplanetary disk

Benisty, M., Bae, J., Facchini, S., et al., ApJL, 916
A Circumplanetary Disk Around PDS 70c

Andrews, S. M., Elder, W., Zhang, S., et al., ApJ, in press
Limits on Millimeter Continuum Emission from Circumplanetary Material in the DSHARP Disks

Long, F., Andrews, S. M., Vega, J., et al., ApJ, in press
The Architecture of the V892 Tau System: the Binary and its Circumbinary Disk

Rich, E., **Teague, R.**, Monnier, J., et al. ApJ, 913
Are Small Dust Grains actually coupled to the Gas in Protoplanetary Disks?

Pegues, J., Öberg, K. I., Bergner, J. B., et al., ApJ, 911
An ALMA Survey of Chemistry in Disks around Late-Type M-Stars

Facchini, S., **Teague, R.**, Bae, J., et al. ApJ, in press
The chemical inventory of the planet-hosting disk PDS 70

Boehler, Y., Ménard, F., Robert, C. M. T., et al. A&A, 650
Vortex-like kinematic signal, spirals, and beam smearing effect in the HD 142527 disk

Bae, J., **Teague, R.**, Zhu, Z., ApJ, 912
Tightly-Wound Spirals Driven by Buoyancy Resonance in Protoplanetary Disks

Cleeves, L. I., Loomis, R. A., **Teague, R.**, et al., ApJ, 911
The TW Hya Rosetta Stone Project IV: A hydrocarbon rich disk atmosphere

Pegues, J., Czekala, I., Andrews, S. M., ApJ, 908
Dynamical Masses and Stellar Evolutionary Model Predictions of Low-Mass M-Stars

Harrison, R. E., Looney, L. W., Stephens, I. W., et al., ApJ, 908
ALMA CN Zeeman Observations of AS 209: Limits on Magnetic Field Strength and Magnetically Driven Accretion Rate

Garufi, A., Podio, L., Codella, C., et al., A&A, 645
ALMA chemical survey of disk-outflow sources in Taurus (ALMA-DOT V)

Calahan, J., Bergin, E. A., Zhang, K., et al., ApJ, 908
[student paper] Uncovering the Thermal Profile of a Typical Gaseous Protoplanetary Disk

Wölfer, L., Facchini, S., Kurtovic, N. T., et al. A&A, 648
A highly non-Keplerian protoplanetary disc

Terwisscha, J. v. S., Hogerheijde, M. R., Cleeves, L. I., et al., ApJ, 906
Spatially resolved emission of formaldehyde hints at low-temperature gas-phase formation

Öberg, K., Cleeves, L. I., Bergner, J., et al., AJ, 161
Radial and vertical distributions of DCN and DCO^+ in the TW Hya disk

Podio, L., Garufi, A., Codella, C., et al., A&A, 644
ALMA chemical survey of disk-outflow sources in Taurus (ALMA-DOT II)

Alarcón, F., **Teague, R.**, Zhang, K., et al., ApJ, 905
[student paper] Chemical Evolution in a Protoplanetary Disk with Dust Substructures

White, J. A., Kóspál, Á, Hughes, A. G. Hughes, et al., 2020, ApJ, 904
ALMA and VLA Observations of EX Lupi in its Quiescent State

Stephens, I. W., Fernández-López, M., Li, Z.-H., et al., 2020, ApJ, 901
Low Level Carbon Monoxide Line Polarization in two Protoplanetary Disks

Hall, C., Dong, R., **Teague, R.,**, et al., ApJ, 904
Kinematic Evidence for Gravitational Instability

Long, D. E., Zhang, K., **Teague, R.**, et al., 2020, ApJL, 895
[student paper] Hints of a Population of Solar System Analog Planets from ALMA

Facchini, S., Benisty, M., Bae, J., et al., 2020, A&A, 639
Annular substructures in the transition disks around LkCa 15 and J1610

Garufi, A., Codella, C., Rygl, K., et al., 2020, A&A, 636
ALMA chemical survey of disk-outflow sources in Taurus (ALMA-DOT I)

Rosotti, G., **Teague, R.**, Dullemond, C., et al., 2020, MNRAS, 495
The Efficiency of Dust Trapping in Ringed Protoplanetary Discs

Semenov, D. & **Teague, R.** 2020, Europhysics News, 51
Accretion disks around young stars: the cradles of planet formation

Huang, J., Andrews, S. M., Dullemond, C. P., et al., 2020, ApJ, 891
A multi-frequency ALMA characterization of substructures in the GM Aur protoplanetary disk

Rosotti., G., Benisty, M., Juhazs, A., et al., 2020, MNRAS, 491.
Spiral arms in the proto-planetary disc HD100453 detected with ALMA

Bae, J., Zhu, Z., Baruteau, C., et al., 2019, ApJL, 884
An Ideal Testbed for Planet-disk Interaction: Two Giant Protoplanets in Resonance Shaping the PDS 70 Disk

Isella, A., Benisty, M., **Teague, R.**, et al., 2019, ApJL, 879
Detection of Continuum Submillimeter Emission Associated with Candidate Protoplanets

Cleeves, L. I., Loomis, R. A., **Teague, R.**, et al., 2019, BAAS, 51
Realizing the Unique Potential of ALMA to Probe the Gas Reservoir of Planet Formation

Lyra, W., Haworth, T., Bitsch, B., et al., 2019, BAAS, 51
Planet formation âĂŤ The case for large efforts on the computational side

Gallo, E., **Teague, R.**, Plotkin, R. M., et al., 2019, MNRAS, 488
ALMA observations of A0620-00: fresh clues on the nature of quiescent black hole X-ray binary jets

Schwarz, K., **Teague, R.**, Bergin, E., et al., 2019, ApJL, 876.
Line Ratios Reveal N2H+ Emission Originates above the Midplane in TW Hydrae

Keppler, M., **Teague, R.**, Bae, J., et al., 2019, A&A, 625
[student paper] Highly structured disk around the planet host PDS 70 revealed by high-angular resolution observations

Semenov, D., Favre, C., Fedele, D., et al., 2018, A&A, 617
Chemistry in disks. XI. Sulfur-bearing species as tracers of protoplanetary disk physics and chemistry: the DM Tau case

Flaherty, K. M., Hughes, A. M., **Teague, R.**, et al., 2018, ApJ, 856
Turbulence in the TW Hya Disk

Fedele, D., Tazzari, M., Booth, R., et al., 2018, A&A, 610
ALMA continuum observations of the protoplanetary disk AS 209. Evidence of multiple gaps opened by a single planet

Flock, M., Nelson, R. P., Turner, N. J., et al., 2017, ApJ, 850
Radiation Hydrodynamical Turbulence in Protoplanetary Disks: Numerical Models and Observational Constraints

Dutrey, A., Guilloteau, S., Piétu, V., et al., 2017, A&A, 607
The Flying Saucer: Tomography of the thermal and density gas structure of an edge-on protoplanetary disk

Beuther, H., Linz, H., Henning, T., et al., 2017, A&A, 605
Multiplicity and disks within the high-mass core NGC 7538IRS1.

Parfenov, S. Y., Semenov, D. A., Henning, T., et al., 2017, MNRAS, 468
On the methanol emission detection in the TW Hya disc: the role of grain surface chemistry and non-LTE excitation

van Boekel, R., Henning, T., Menu, J., et al., 2017, ApJ, 837
Three Radial Gaps in the Disk of TW Hydrae Imaged with SPHERE

Haworth, T. J., Ilee, J. D., Forgan, D. H., et al., 2016, PASA, 33
Grand Challenges in Protoplanetary Disc Modelling

Feng, S., Beuther, H., Semenov, D., et al., 2016, A&A, 593
Inferring the evolutionary stages of the internal structures of NGC 7538 S and IRS1 with chemistry