Cold Clouds as Cosmic Ray Detectors

Shmuel Bialy

Technion - Israel Institute of Technology
Haifa, Israel

Paola Caselli, Alexei Ivlev, Katya Makarenko (MPE)
Brandt Gaches (Uni DUE)

AstroBialy.com/

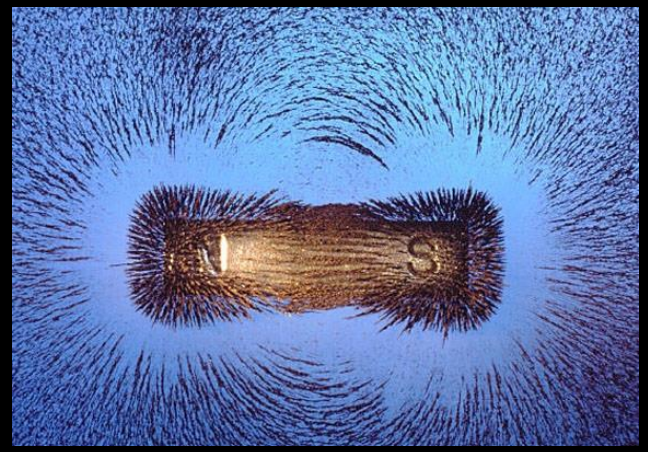
M51 - JWST

Cosmic-Rays set the stage for star formation

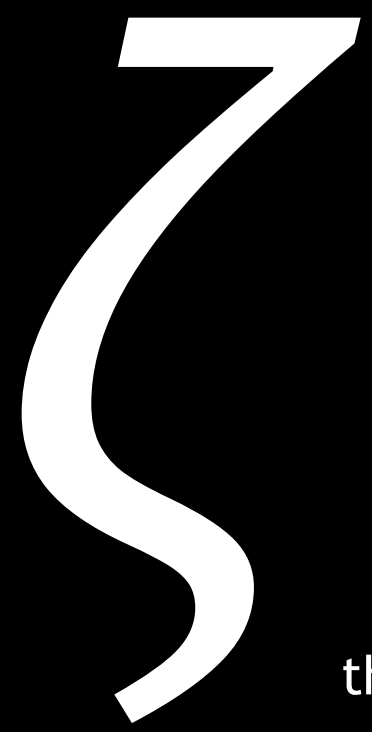
Ionization (primary + secondary)

chemistry

heating



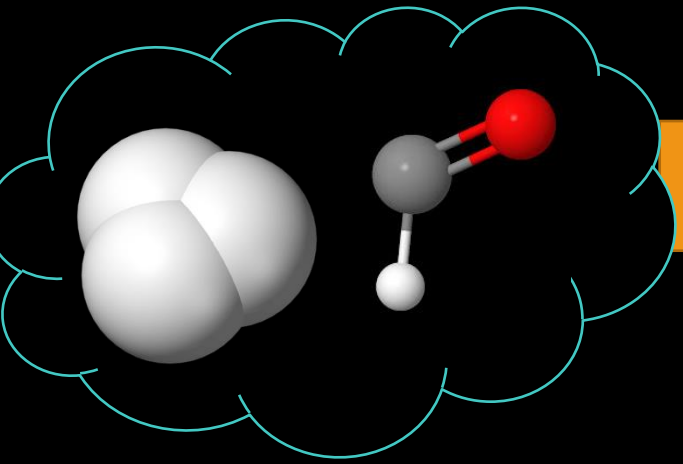
Coupling to B fields



the CR ionization rate (s^{-1})

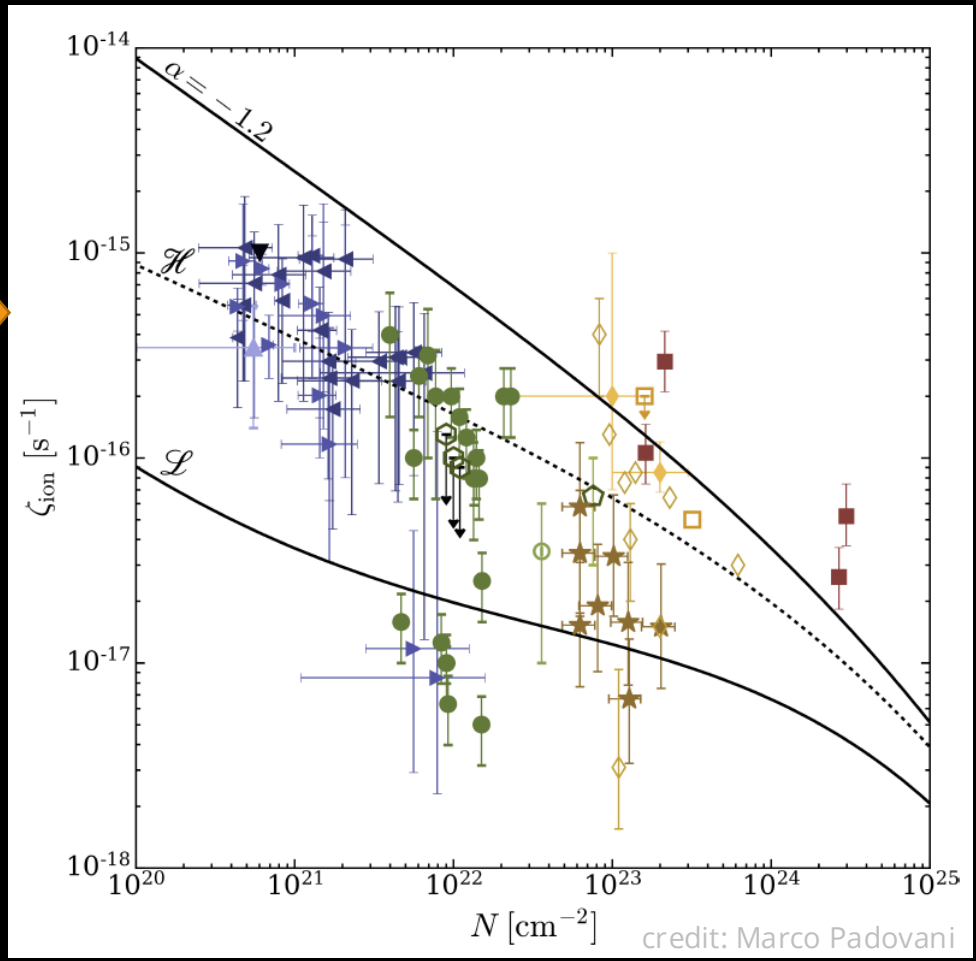
What is the CR ionization rate ζ ?

Indirect observations:
astrochemistry in interstellar clouds



Uncertainty:
-chemical models
- n
- observational

credit: Marco Padovani

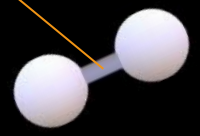


credit: Marco Padovani

The idea

Use H2 excitation
to probe cosmic-rays

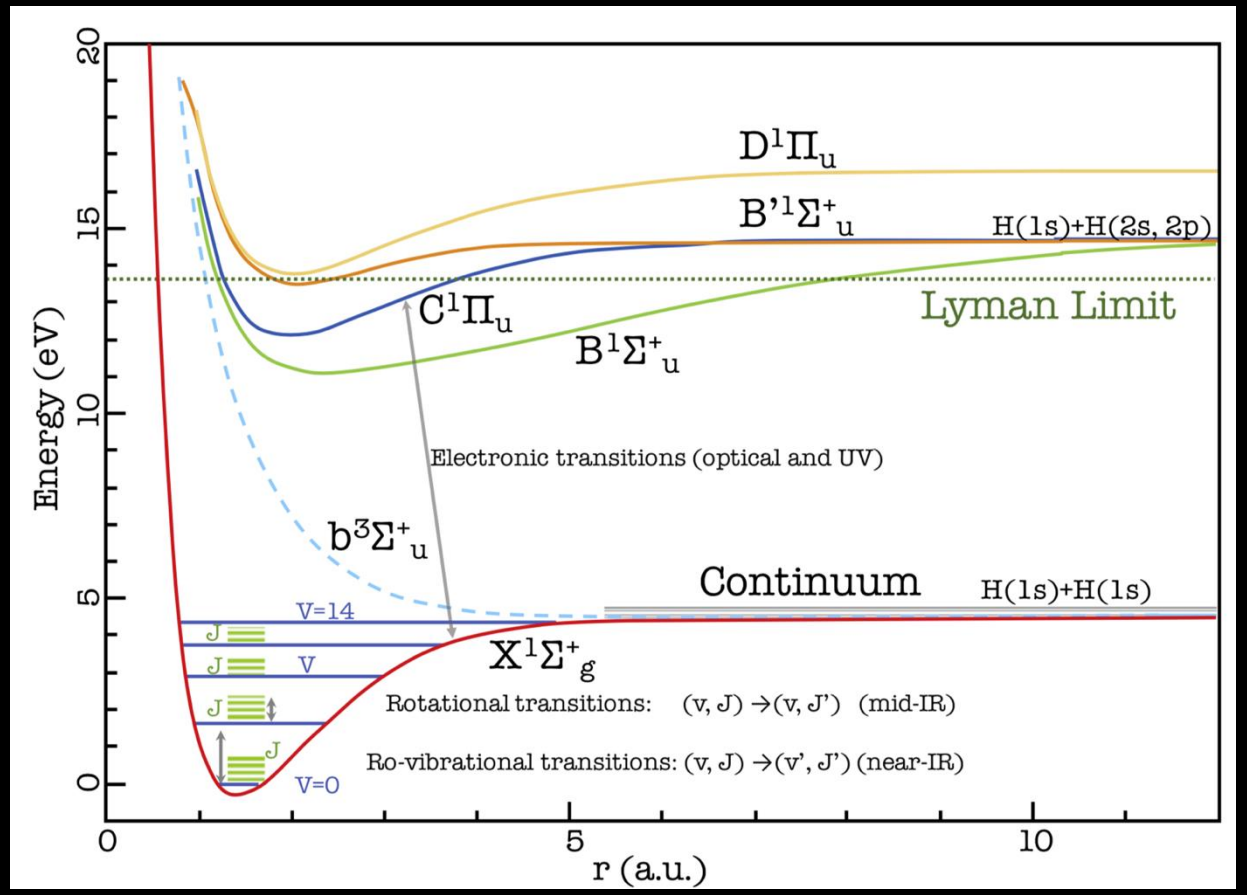
Cosmic ray
(secondary e-)



Gredel & Dalgarno 1995

Bialy 2020

H2 energy level diagram



The idea

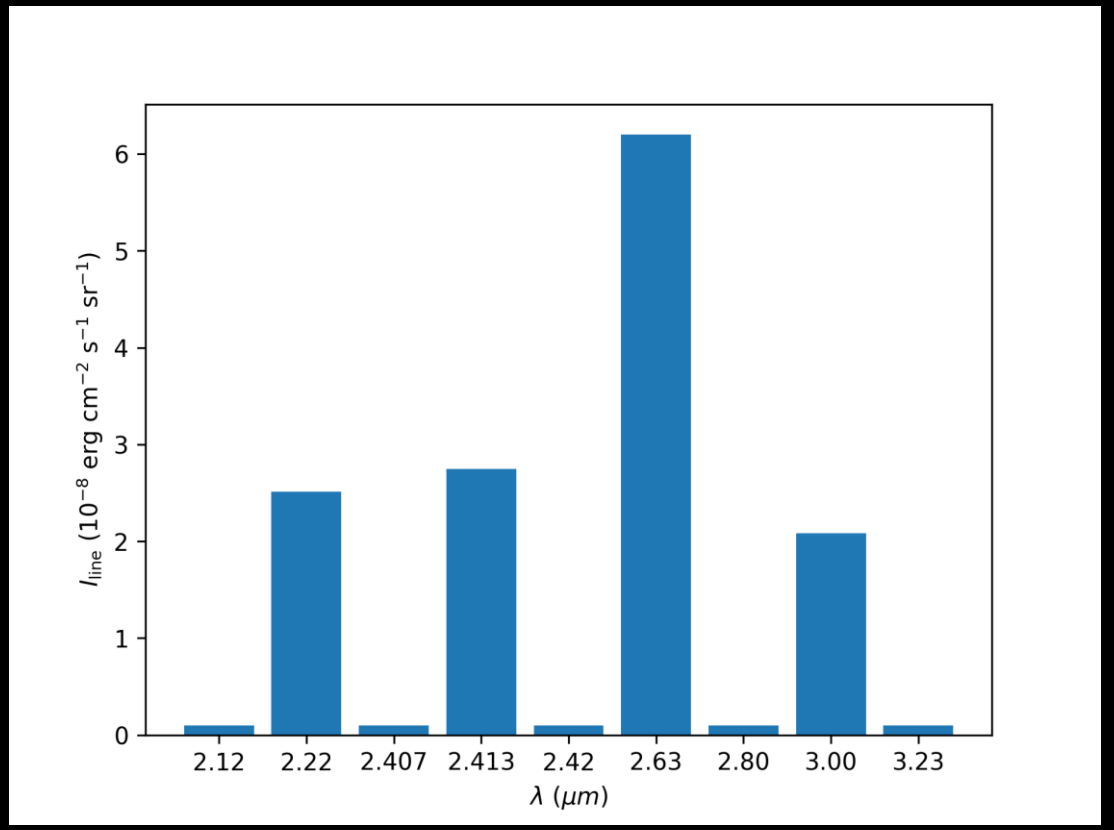
CRs excite mainly:
v=1, J=0
and
v=1, J=2

giving rise to 4 transitions
with known line ratios

Line intensity ~ ζ

$$I_{ul,(\mathrm{cr})} = \frac{1}{4\pi} g N_{\mathrm{H}_2} \zeta_{\mathrm{ex}} p_{u,(\mathrm{cr})} \alpha_{(u)l} E_{ul},$$

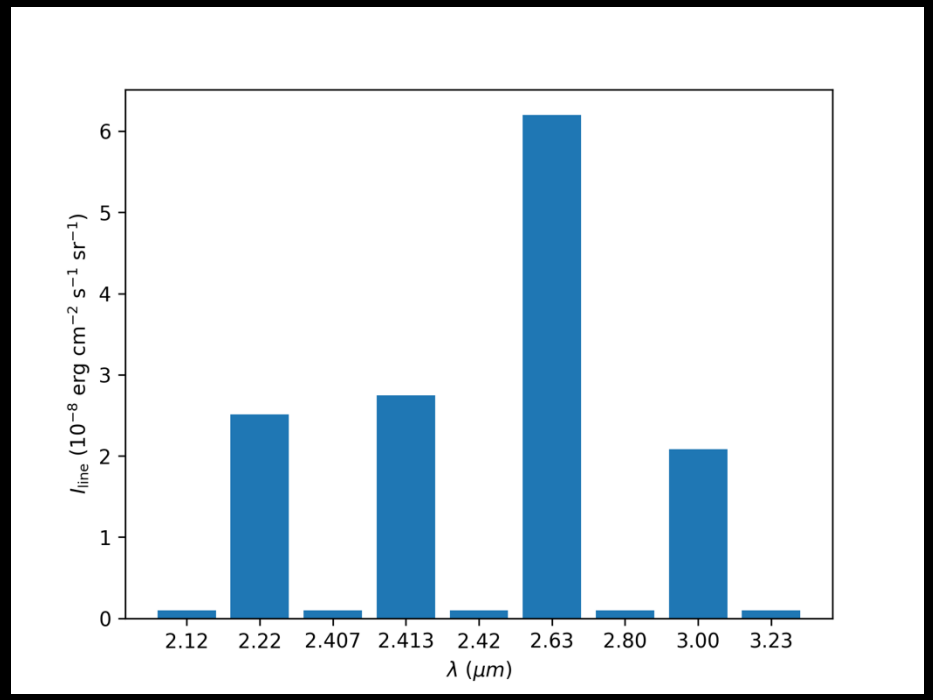
CR excitation



Bialy 2020

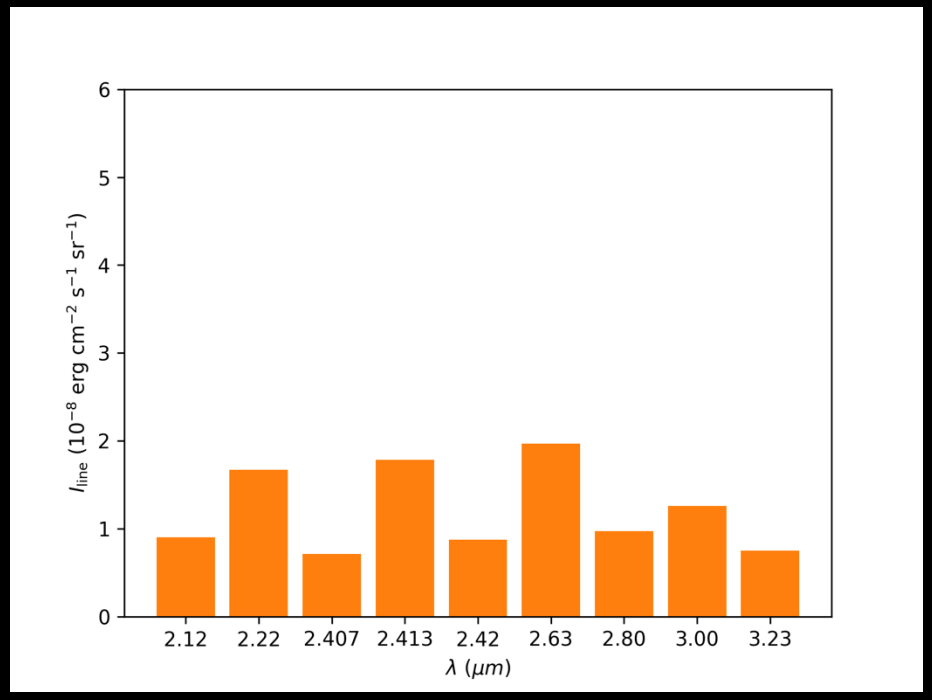
Unique Emission patterns

CR excitation



Bialy 2020

UV excitation



Observations

Observing CR-excited H2 – from the ground

MMT 6.5m Arizona

Atmosphere is too noisy

No detection

Upper limits on $\zeta = 2 \times 10^{-16}\ s^{-1}$

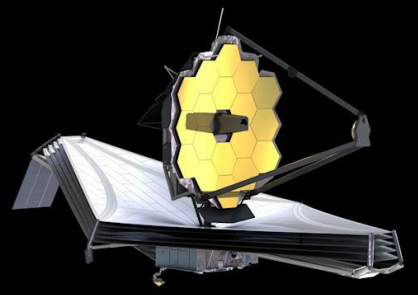
Observing CR-excited H2 with JWST

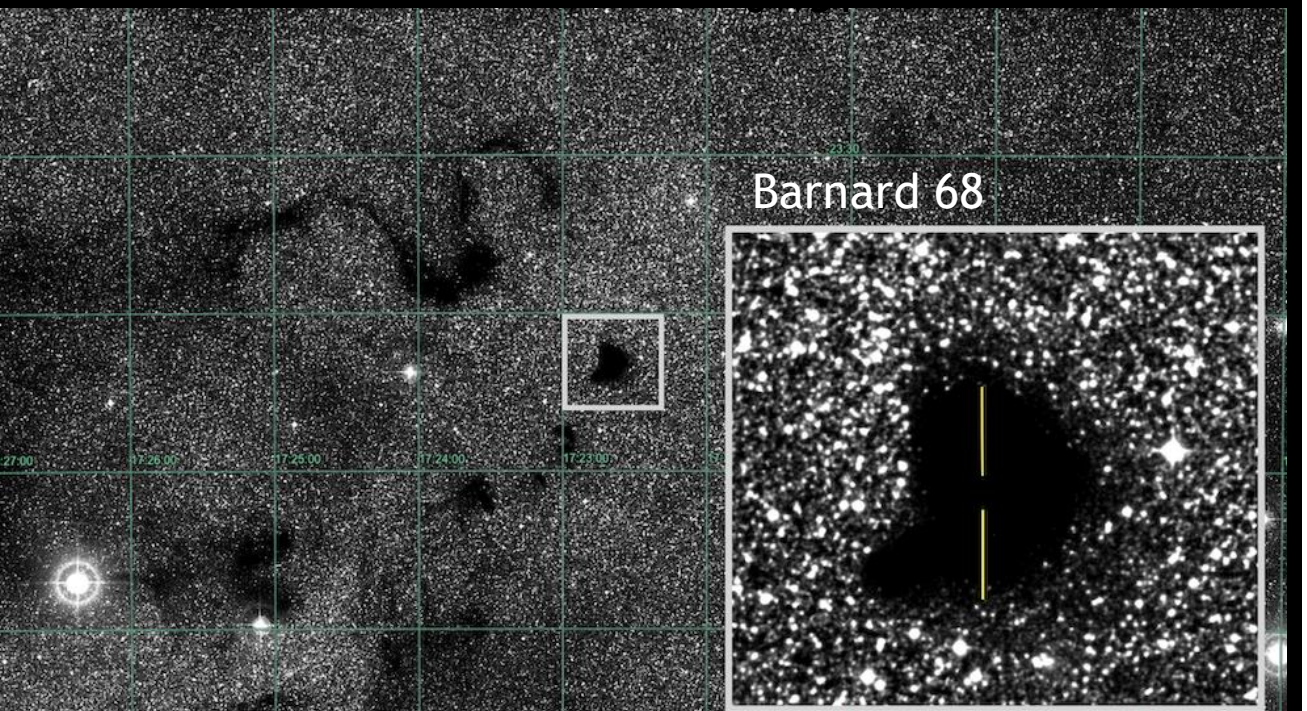
Observing CR-excited H2 with JWST

Observing CR-excited H2 with JWST

Observing CR-excited H2 with JWST

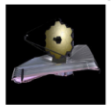
Barnard 68





8 hour program

JWST Proposal 5064 (Created: Thursday, February 29, 2024 at 7:01:35 PM Eastern Standard Time) - Overview

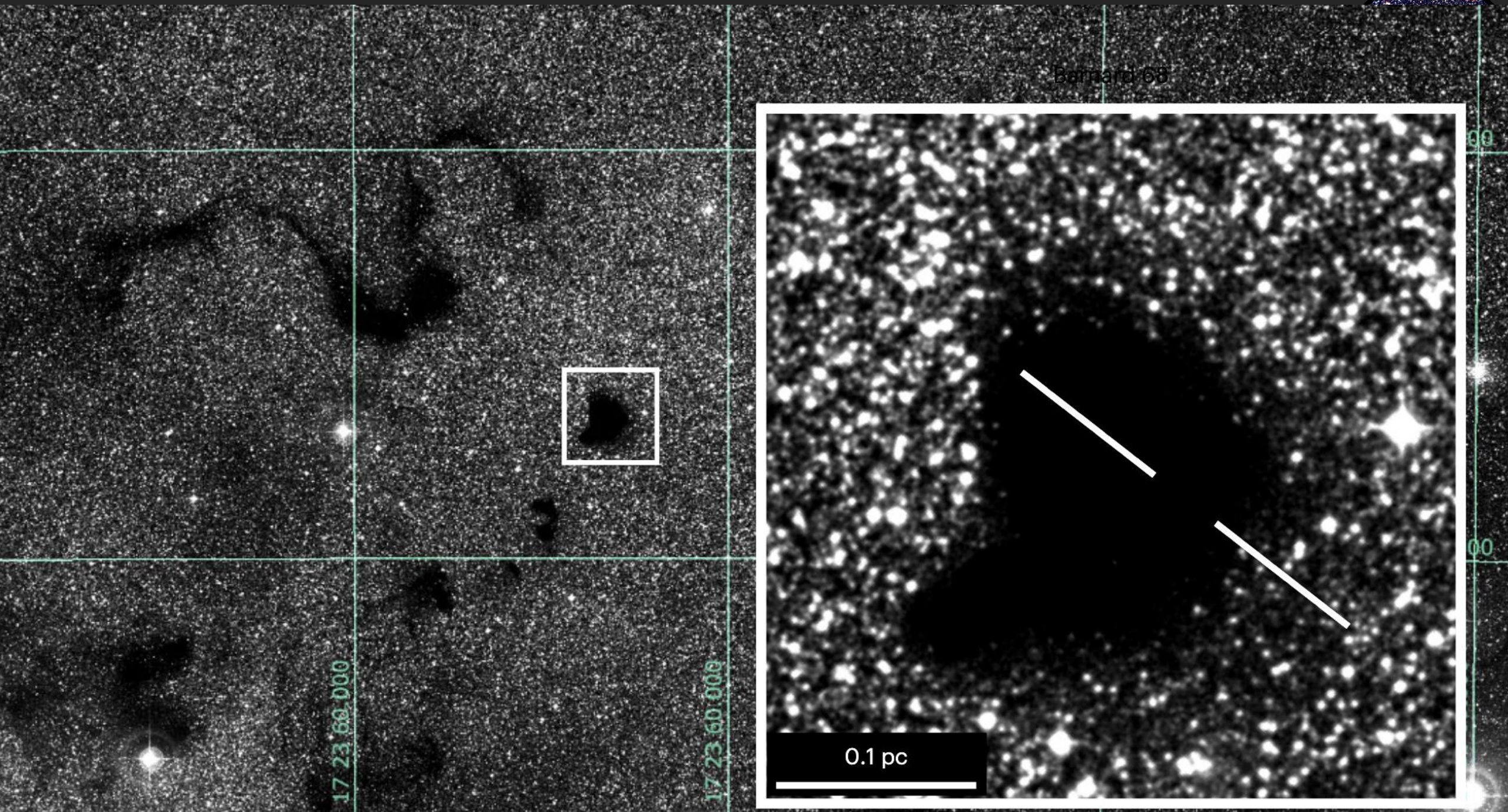


5064 - Constraining Cosmic Rays with H2 Ro-Vibrational Excitation in Dense Clouds

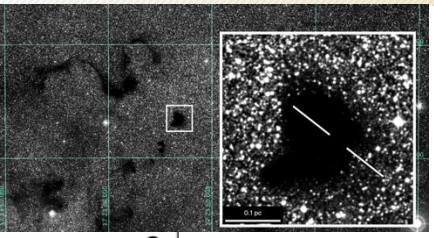
Cycle: 3, Proposal Category: GO

INVESTIGATORS

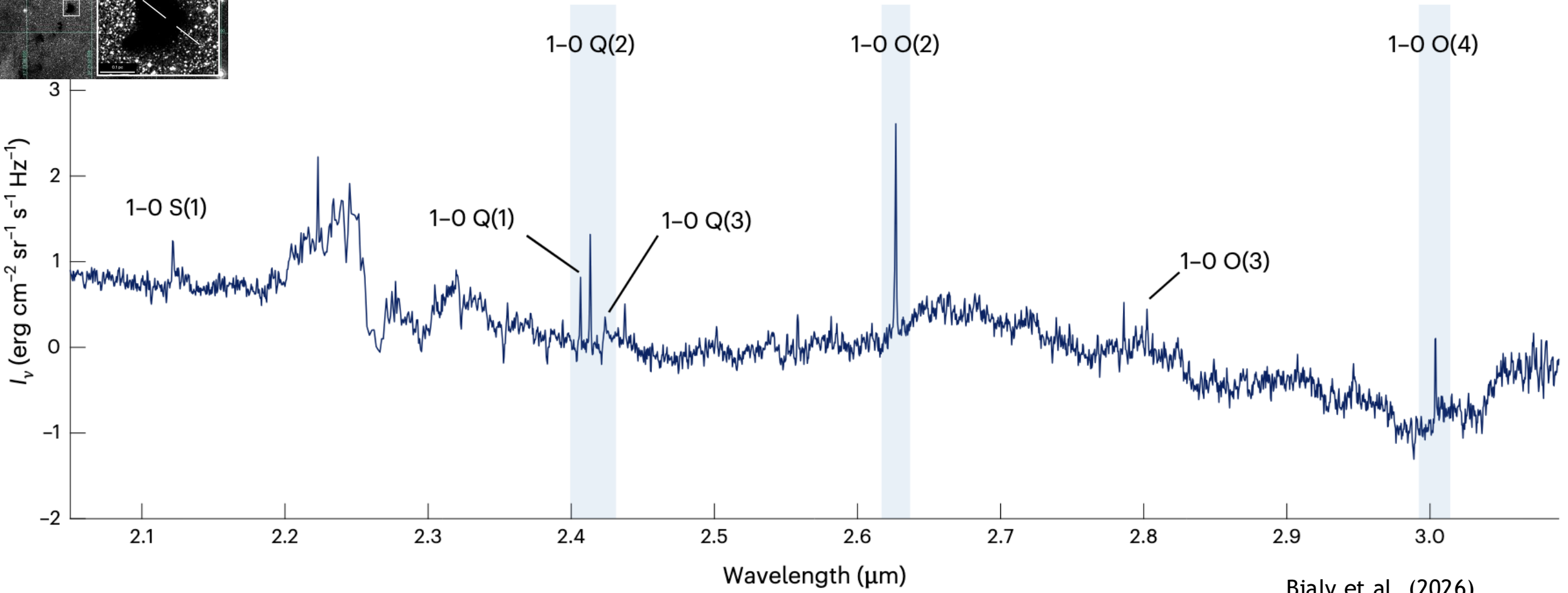
Name	*Institution*
Dr. Shmuel Bialy (PI)	**Technion-Israel Institute of Technology**
Dr. Marco Padovani (CoI) (ESA Member)	INAF-Osservatorio Astrofisico di Arcetri
Prof. Sirio Belli (CoI) (ESA Member)	Universita di Bologna
Dr. Benjamin Godard (CoI) (ESA Member)	Observatoire de Paris
Dr. Arshia Maria Jacob (CoI)	The Johns Hopkins University
Prof. David Neufeld (CoI) (US Admin CoI)	The Johns Hopkins University
Dr. Thomas G Bisbas (CoI) (ESA Member)	Universitat zu Koln
Dr. Brandt Alfred Lloyd Gaches (CoI) (ESA Member)	Chalmers University of Technology
Paola Caselli (CoI) (ESA Member)	Max-Planck-Institut fur extraterrestrische Physik
Christian Rab (CoI) (ESA Member)	Ludwig Maximilian Universitat of Munich
Dr. Alexei Ivlev (CoI) (ESA Member)	Max-Planck-Institut fur extraterrestrische Physik
Kedron Pyle Silsbee (CoI)	University of Texas at El Paso
Troy Porter (CoI)	Stanford University


Barnard 68
0.1 pc
17 23 60.000
17 23 60.000

First detection of CR-excited H_2

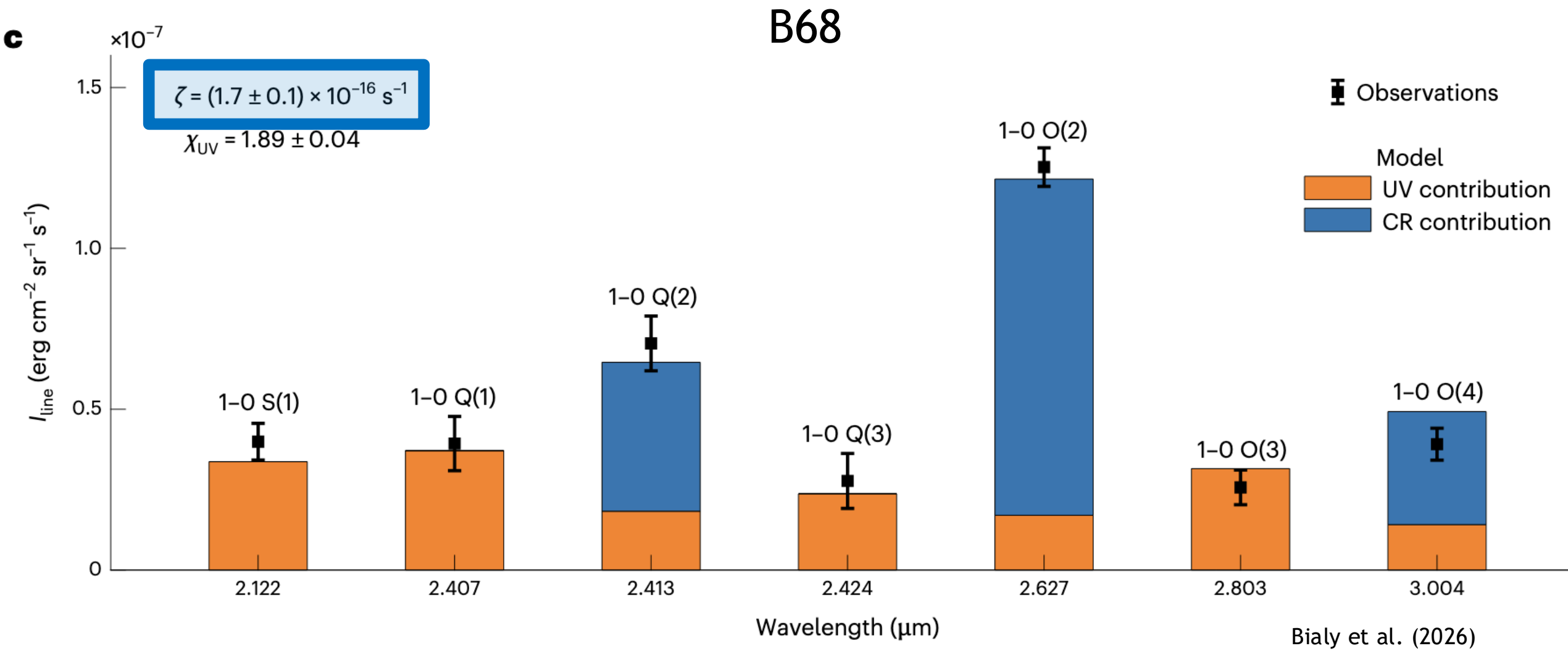


B68



Bialy et al. (2026)

First detection of CR-excited H_2



Bialy et al. (2026)

First detection of CR-excited H_2

nature astronomy

Article

https://doi.org/10.1038/s41550-025-02771-9

Direct detection of cosmic-ray-excited H_2 in interstellar space

Received: 24 July 2025

Accepted: 22 December 2025

Published online: 03 February 2026

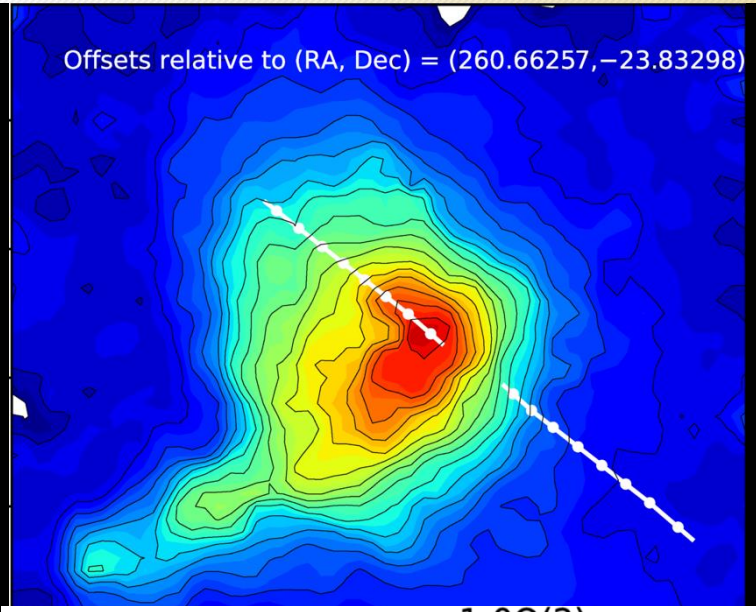
Check for updates

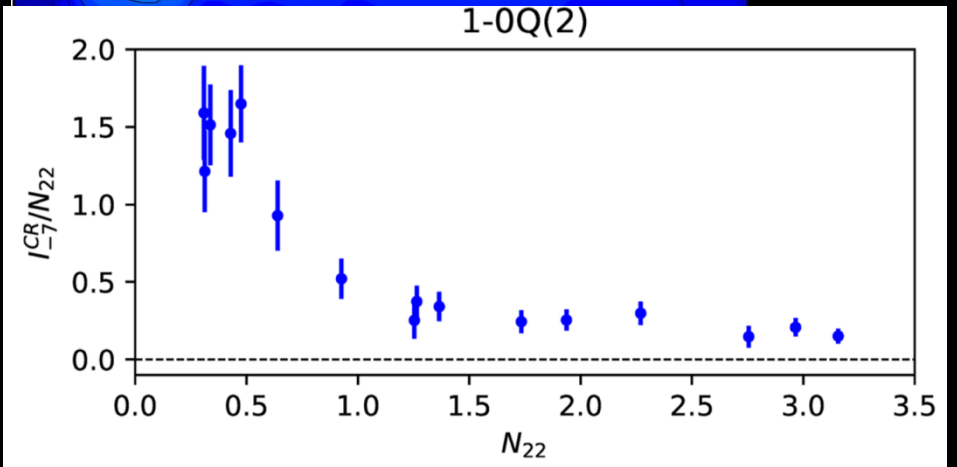
Shmuel Bialy[1], Amit Chemke[1], David A. Neufeld[2], James Muzerolle Page[3], Alexei V. Ivlev[4], Sirio Belli[5], Brandt A. L. Gaches[6], Benjamin Godard[7,8], Thomas G. Bisbas[9], Paola Caselli[4], Arshia M. Jacob[10,11], Marco Padovani[12], Christian Rab[4,13], Kedron Silsbee[14], Troy A. Porter[15] & Ekaterina I. Makarenko[4]

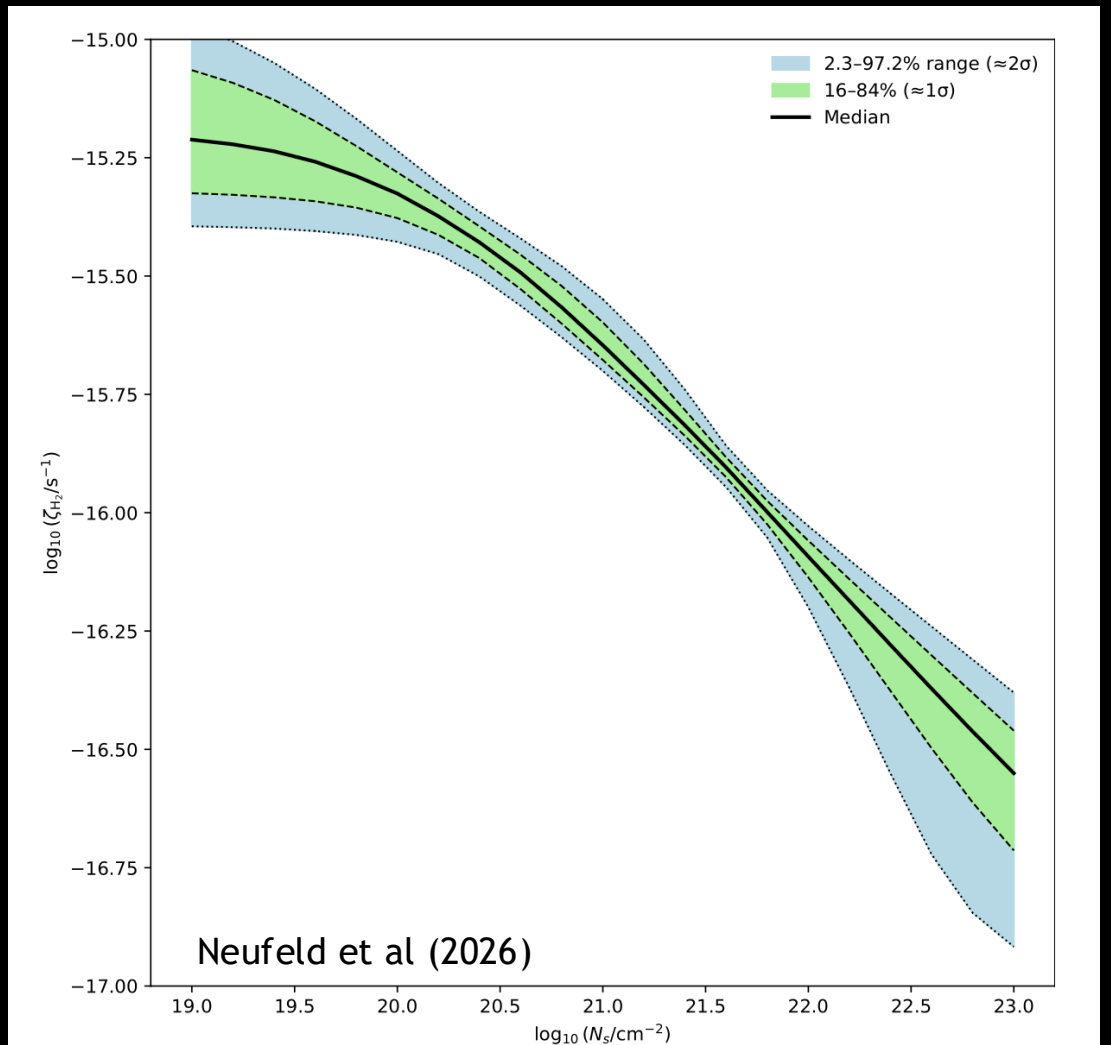
Stars and planets form within cold, dark molecular clouds. In these dense regions, where starlight cannot penetrate, cosmic rays (CRs) are the dominant source of ionization—driving interstellar chemistry, setting the gas temperature and enabling coupling to magnetic fields. Together, these effects regulate the collapse of clouds and the onset of star formation. Despite this importance, the CR ionization rate, ζ, has never been measured directly. Instead, this fundamental parameter has been loosely inferred from indirect chemical tracers and uncertain assumptions, limiting our understanding of star formation physics. Here we report the direct detection of CR-excited vibrational H_2 emission, using James Webb Space Telescope observations of the starless core Barnard 68 (B68). The observed emission pattern matches theoretical predictions for CR excitation

Bialy et al. (2026)

First direct observation of CR attenuation







First detection of CR-excited H_2

The Astrophysical Journal, 998:71 (15pp), 2026 February 10 https://doi.org/10.3847/1538-4357/ae22cd
© 2026. The Author(s). Published by the American Astronomical Society.
OPEN ACCESS

JWST Observations of Cosmic-Ray-excited H_2 in Barnard 68: Spatial Variations and Constraints on Cosmic-Ray Attenuation

David A. Neufeld[1], Kedron Silsbee[2], Alexei V. Ivlev[3], Shmuel Bialy[4], Brandt A. L. Gaches[5], Marco Padovani[6], Sirio Belli[7], Thomas G. Bisbas[8], Amit Chemke[4], Benjamin Godard[9,10], James Muzerolle Page[11], and Christian Rab[3,12]
[1] William H. Miller Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
[2] Physics Department, University of Texas at El Paso, El Paso 79968, USA
[3] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse 1, 85748 Garching, Germany
[4] Technion—Israel Institute of Technology, Haifa, 3200003, Israel
[5] Faculty of Physics, University of Duisburg-Essen, Lotharstraße 1, 47057 Duisburg, Germany
[6] INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy
[7] Dipartimento di Fisica e Astronomia, Università di Bologna, 40125 Bologna, Italy
[8] Research Center for Astronomical Computing, Zhejiang Laboratory, Hangzhou, 311000, People's Republic of China
[9] Observatoire de Paris, Université PSL, Sorbonne Université, LERMA, 75014 Paris, France
[10] Laboratoire de Physique de l'Ecole Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université de Paris, 75005 Paris, France
[11] Space Telescope Science Institute, Baltimore, MD 21218, USA
[12] University Observatory, Faculty of Physics, Ludwig-Maximilians-Universität München, Scheinerstr. 1, 81679 Munich, Germany
Received 2025 October 10; revised 2025 November 17; accepted 2025 November 19; published 2026 February 3

Abstract

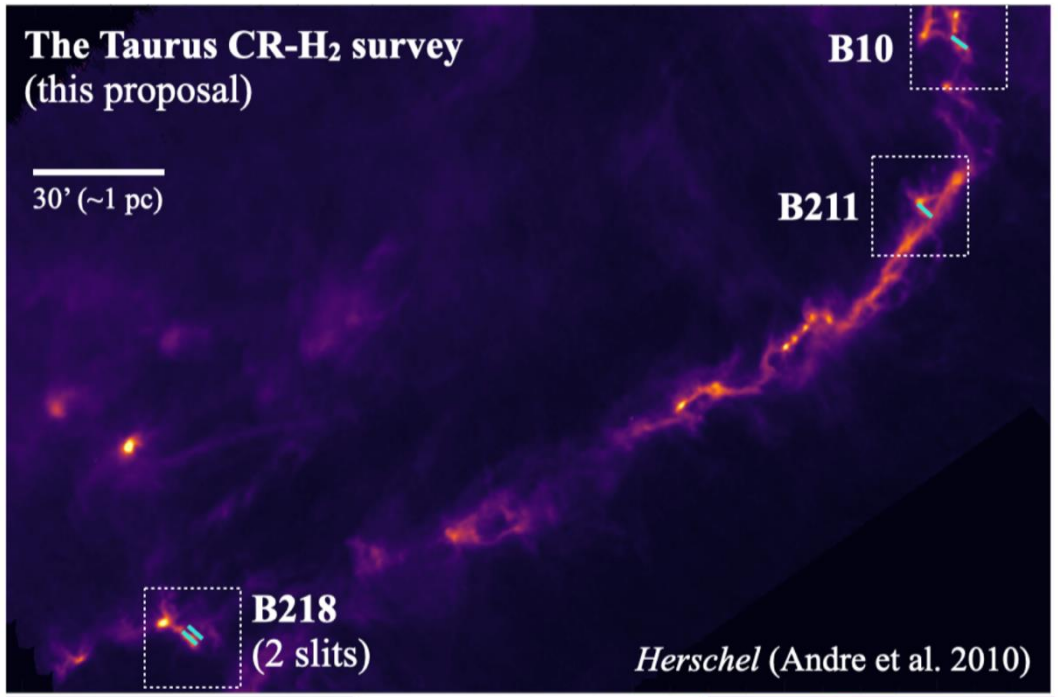
We present James Webb Space Telescope (JWST) NIRSpec observations of the starless dark cloud Barnard 68 (B68) that reveal the spatially resolved signature of cosmic-ray-excited molecular hydrogen ($CRXH_2$) emissions for the first time. Following up on our initial detection of $CRXH_2$ emissions from B68, we now exploit JWST's sensitivity and spatial multiplexing to map $CRXH_2$ rovibrational lines across 16 sight lines through the cloud. By disentangling the $CRXH_2$ and UV-pumped H_2 components, we isolate the para-H_2-dominated spectrum attributable to cosmic-ray (CR) excitation. We find that there are significant spatial variations in the ratio of the $CRXH_2$ line intensity to the line-of-sight H_2 column density; these cannot be accounted for by dust extinction alone and demonstrate a clear attenuation of the CR flux with increasing shielding column. Modeling B68 as a Bonnor–Ebert sphere, we constrain both the unshielded CR ionization rate, ζ_{H_2}, and how it decreases with shielding column. At a reference depth of $N(H_2) = 3 \times 10^{21}$ cm^{-2}, we infer $\zeta_{H_2} \approx 1.4 \times 10^{-16}$ s^{-1}, a factor of ≈3 higher than the average value derived from H_3^+ absorption studies. These results provide the most direct probe to date of CR penetration into cold, dense gas, offering new constraints on both the microphysics of CR–H_2 interactions and the attenuation of low-energy CRs in molecular clouds. Our findings establish $CRXH_2$ emission as a powerful new diagnostic of the CR environment in interstellar space.

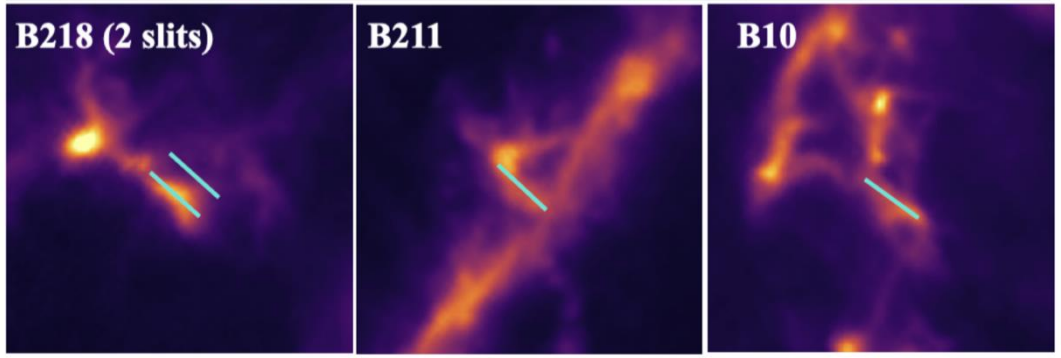
Unified Astronomy Thesaurus concepts: Cosmic rays (329); Molecular clouds (1072); Interstellar medium (847); Dark interstellar clouds (352); Infrared spectroscopy (2285); Interstellar line emission (844)

Materials only available in the online version of record: figure set

Neufeld et al. (2026)

The Future with Webb





NEW!

The Taurus survey
48 hour program

Observations have arrived!

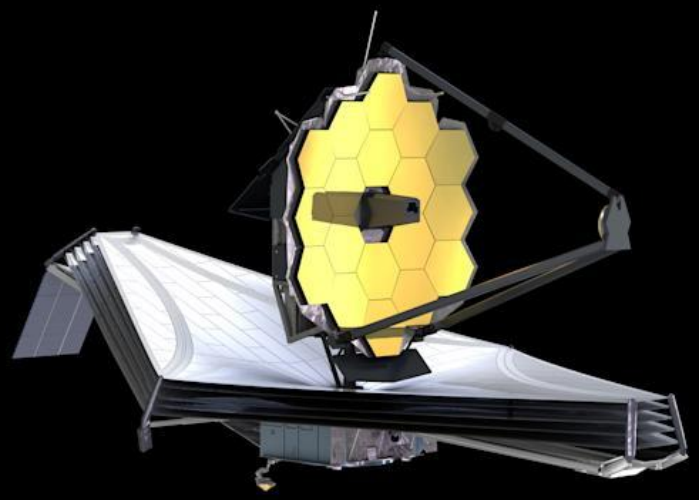
JWST Proposal 8961 (Created: Friday, February 13, 2026, 9:00:13AM Eastern Standard Time) - Overview

8961 - Probing the cosmic ray ionization rate with H2 rovibrational line emission - the Taurus survey

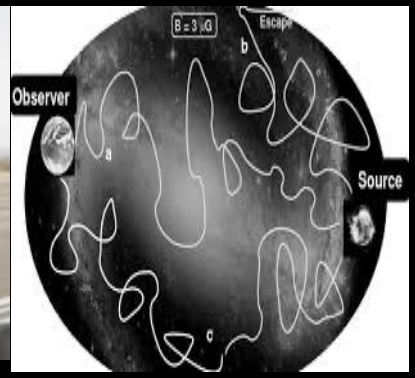
Cycle: 4, Proposal Category: GO

INVESTIGATORS

Summary



CR physics



Star formation