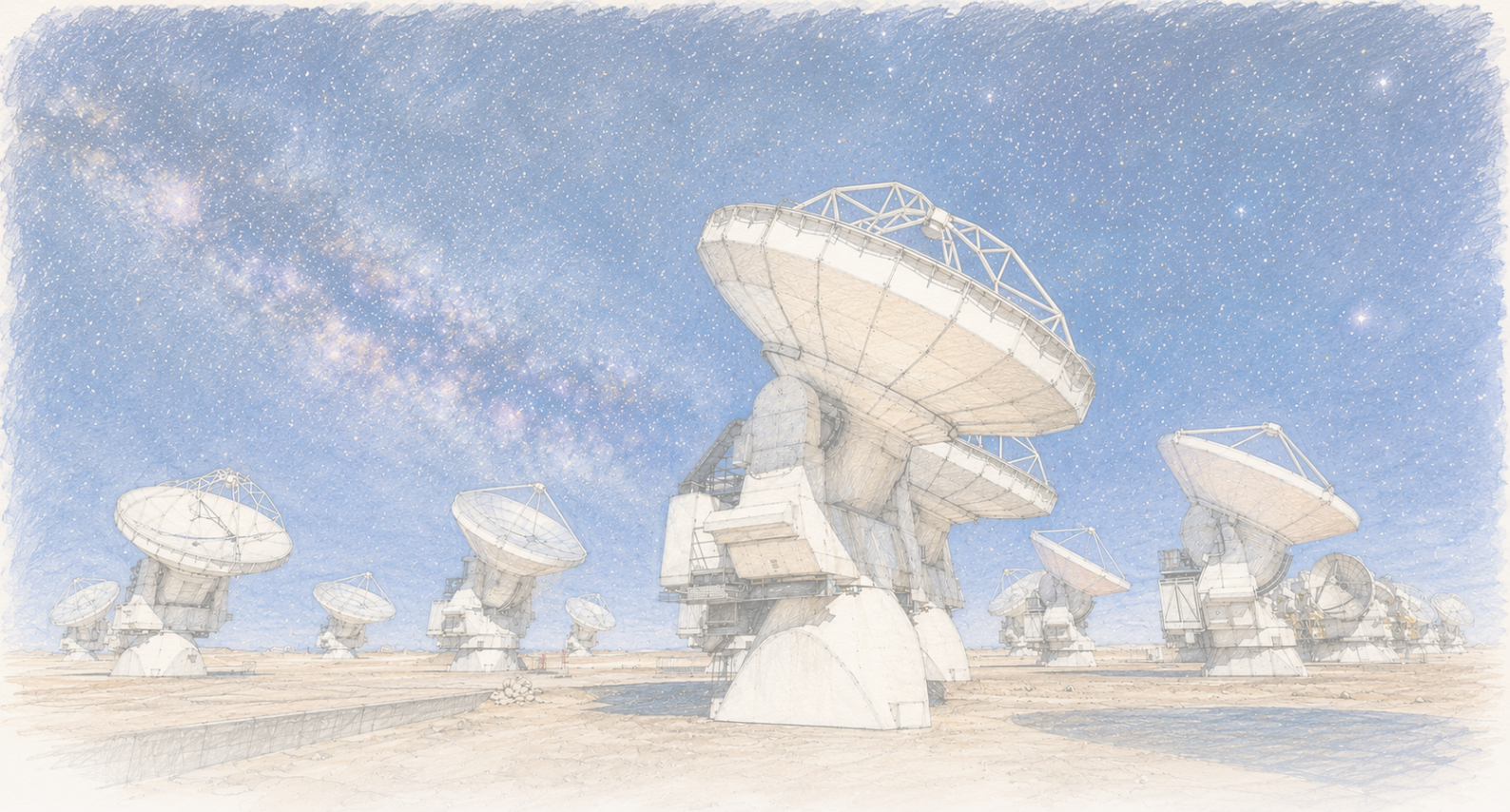




The CLEAN PAPER

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Comet interstellar 3I/ATLAS bishaan comet keenya caalaa qorra keessatti uumame qaba — yeroo jalqabaaf keemistirii planetary system biraa dubbisuu

ALMA fayyadamuun, astronomers ratio hydrogen “ulfaataa” fi idilee bishaan 3I/ATLAS — wanta interstellar beekame sadaffaa — keessatti daangessanii, deuterium’n baay’ee badhaadhe argan: yoo xiqqaate galaanota Lafaa tilmaamaan dachaa 40 fi comet Sirna Aduu idilee dachaa 30. Kun bishaan haala comet keenya caalaa qorra keessatti uumame akeeka. Bu’aan lower limit karaa al-kallattiin argame dha (bishaan mataan isaa kallattiidhaan hin argamne); jireenya yookaan technology irratti homaa hin jedhu — keemistirii fi qorra qofa.

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Antenaa DV-59 fuuldura, antenaawwan ALMA hedduun samii halkanii ifa ji'aan mul'atu ilaalaa jiru. Credit: Alex Pérez / ALMA Observatory.

Alex Pérez / ALMA Observatory CC BY 4.0

Comet urjii biraa irraa, fi mallattoo qubaa bishaan isaa keessaa

Yeroo tokko tokko wanti matumaa keenya hin turre Sirna Aduu keessa darba. Dhagaa asteroid belt irraa bade miti; comet funyoo dheeraa isaa irratti Oort cloud irraa deebi'u miti; wanta daandii hyperbolic banaa irra jiru — hawaa urjiilee gidduu irraa dhufe, Aduu marsaa tokko naanna'ee, bara baraan deemu. Amma sadii argineerra. Kan jalqabaa, 'Oumuamua 2017 keessatti, namni hundi maal akka ture irratti walii galuu dura jechuun ni danda'ama bade. Kan lammaffaa, 2I/Borisov 2019 keessatti, comet ta'uun isaa ifa ture. Kan sadaffaa, July 2025 keessatti argame, 3I/ATLAS dha — coma keemistarii dhugaa irratti hojjechuuf gahaa socho'u keessatti marfamee dhufe.

Ariitiin oduu osoo hin jalqabin kutaan qabachuun gatii qabu kana. Comet interstellar jechuun, hiika kallattiin, ciccitaa planetary system biraa ti: cabbii fi awwaara urjii biraa naannoo keessatti jabaate, tarii humna gravityn yeroo dheeraa dura alatti darbame, Galaxy keessa yaa'e, cabbii isaa sirriitti bakka teleskooppiin keenya ilaalu danda'utti danfuu jalqabuuf Aduu keenyatti gahaa dhihaatee darbe. Dhugaan dhugumaan nama ajaa'ibu kana; inni gargaarsa tokko malee gahaa nama ajaa'iba.

Ta'us yeroo baay'ee gargaarsa argata. Wantoonni interstellar oduu garmalee hafuura fudhatu gosa tokko — ifa dukkaneessuu, *garuu namni tokko yoo isa ijaare hoo* — hawwatu; 3I/ATLAS qooda isaa argate. Deebiin amanamaan gaaffii sanaaf kan nama nuffisiisu dha; kan nama nuffisiisu ammoo caalaatti nama hawwata: comet dha. Gaaffiin dhugaa namni tokko isa tolchee turee miti. Gaaffii tasgabbaa'aa kana ture — keemistirii wanta urjii biraa naannoo keessatti walitti qabame tokkoo dubbisuu yoo dandeesse, waa'ee maatii urjii sanaa maal sitti hima? Akkamitti dubbista?

Meeshaan dubbisuu yeroo kana bishaan dha. Bishaan hydrogens lama fi oxygen tokko dha; garuu hydrogen isaa keessaa qoodni xiqqaan *deuterium* — obboleessa isaa ulfaataa, atom hydrogen idilee neutron tokko dabalataa baatu — dha. Ratio hydrogen ulfaataa fi hydrogen idilee bishaan keessatti, D/H jedhamee barreeffamu, tasaa miti. Keemistiriidhaan, irra caalaa bakka bishaan jalqaba uumame hammam qorra akka tureen murtaa'a: bakka dhalootaa sanatti qorra fi tasgabbiin yoo baay'ate, deuterium baay'een keessa hidhamuu danda'a. Comet akka deep-freezer — cabbii isaa waggoota biliyoon-aaf qorra keessatti kuusuu danda'u — waan ta'eef, ratio D/H bishaan isaa haala bishaan sun keessatti uumame mallattoo qubaa ta'ee tursiisuu danda'a.

Mallattoolee sirna keenya haala gaariin beekna: galaanota Lafaa fi maatii comet Sirna Aduu adda addaa daangaa dhiphaa tokko keessatti walitti qabamu. Wanti namni tokko illee hin murteessin mallattoo wal fakkaatu kan bishaan urjii *biraa* naannoo keessatti uumamee dha. Barruun kun 3I/ATLAS keessatti sana dubbisuuf ka'e.

Barreessitoonni maal godhan?

ALMA — array guddaa dishes raadiyoo gammoojjii Chile keessa jiru — gara 3I/ATLAS 4 November 2025, comet sun Aduu erga naanna'ee guyyaa ja'a booda, qajeelchan. Glow wavelength millimetre laafaa molecules sadii coma keessaa qabuuf qindeessan: bishaan idilee (H_2O), bishaan *ulfaataa* (HDO, bakka hydrogen tokko deuterium ta'e), fi methanol (CH_3OH).

Ratio D/H barbaadan, bu'uurumaan, ratio bishaan ulfaataa fi bishaan idilee ti. Kanaaf lamaan barbaadan. Achiin booda spectra sana radiative-transfer model atmosphere comet babal'achaa jiru (code SUBLIME jedhamu) keessa galchani, gosa statistical machinery atmosphere exoplanet keessa maal akka jiru deebisee argachuuf fayyadamuun fit godhan; temperature, yaa'a alaa fi comet molecule tokkoon tokkoo hammam akka oomishu baasuuf.

Rakkoon tokko waan itti aanu hunda murteessa: **bishaan sana dhugumaan hin argine**. HDO fi methanol mul'atan; H_2O mataan isaa noise gadi hafe. Kun bishaan idilee dhabamuu isaatiif miti — kan ulfaataa caalaa baay'ee jira. Line tokko mul'achuun molecule hammam akka jiru qofa irratti miti; line addaa sun hammam ilaalamuu akka danda'u irratti hundaa'a, wantoonni lama line bishaanii asitti mormu. Tokkoffaan atmosphere dha: line H_2O isaan qajeelfachuu danda'an (183 GHz naannoo) bakka qilleensi Lafa kan bishaan qabu cimaa xuuxutti argama; kanaaf bishaan comet achitti lafa irraa dubbisuun akkuma dukkana hurrii keessa shamaa ilaaluuf yaaluu ti — barruun bands bishaan energy gadi-aanaa kun atmospheric absorption cimaa akka qaban, line bishaan ulfaataa (HDO) 241 GHz naannoo jiru ammoo window qulqulluu keessa akka kufu ibsa. Lammaffaan sensitivity dha: channel bishaanii baay'ee noise qaba — beam tokkoof tilmaamaan 500 mJy, HDO'f 21 wajjin wal bira

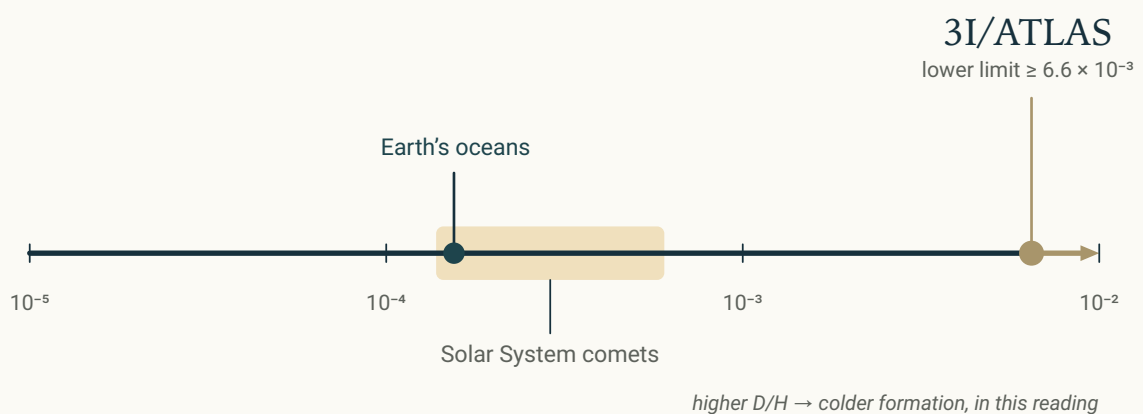
qabamee — kanaaf mallattoon baay’een illee isa jala hafuu danda’a. Hurrii fi noise gidduutti, bishaan idilee baay’een threshold gadi hafe; bishaan ulfaataa baay’ee muraasa ta’e ammoo window qulqulluu fi tasgabbaa’aa keessatti qabamee ifatti mul’ate. (Atmosphere gubbaa, hawaa keessaa, bishaan wal fakkaatu arguun baay’ee salphaa dha: JWST booda infrared keessatti, perihelion booda, bishaan comet sanaa argate — kanaaf ALMA’n arguu dhabuun line tokko qilleensa Lafaa keessa darbuu sana irratti, bishaan dhabamuu irratti miti.) Kanaaf baay’inni bishaan idilee *karaa al-kallattiin* tilmaamamuu qaba ture — irra caalaa akkaataan lines methanol itti kaka’an irraa; kunis molecules methanol bishaan wajjin yeroo meeqa walitti bu’an irratti hundaa’a. Kun safartuu dhugaa dha, garuu moodeela irratti hundaa’a; barreessitoonnis ifatti ibsu.

Maal argan?

- **Bishaan ulfaataa, garuu bishaan idilee hin jiru.** HDO fi lines methanol hedduun ifatti argaman; H_2O hin argamne. Ratio D/H *upper limit* rate oomisha bishaan idilee irratti hundaa’u — line bishaanii noise gadi waan hafeef itti yaadanii akkasitti ilaalu — waan ta’eef, ratio deuterium akka **lower limit** bahaa, value tokko miti.
- **Deuterium baay’ee badhaadhe.** Scenario of eeggannoo isaanii keessatti ratio D/H bishaanii 6.6×10^{-3} **caala** — value galaanota Lafaa caalaa tilmaamaan **dachaa 40**, comet Sirna Aduu idilee caalaa tilmaamaan **dachaa 30**. Tilmaama isaanii lamaan keessatti, 3I/ATLAS safartuu D/H bishaanii hanga ammaatti godhame hunda keessaa dhuma baay’ee ol’aanaa irra jira.
- **Halkan tokko qofa tasaa ta’uun isaa hin fakkaatu.** Safartuun epoch tokko irraa dha; garuu daataa ALMA naannoo isaa jiru dursee ilaaluun guyyaa irraa gara guyyaatti jijjiirama guddaa hin agarsiisu; xiinxalli JWST of danda’e kan 3I/ATLAS, ji’a tokkoo ol booda fudhatames gara walfakkaatu akeeka — bishaan deuterium’n badhaadhe.

Where 3I/ATLAS’s water sits on the deuterium scale

Water D/H ratio — logarithmic scale



Bishaan 3I/ATLAS scale deuterium irratti bakka taa’u: gara dhuma deuterium’n baay’ee badhaadhe, galaanota

Lafaa fi comet population Sirna Aduu guutuu bira darbee (asitti approximate range ta'ee agarsiifame). Xiyyi sun *lower limit* agarsiisa — value dhugaa ol ta'uu danda'a. Ratio D/H ol'aanaan mallattoo *haala uumamuu qorraa* dha, teessoo mana isaa miti.

Original diagram — The Clean Paper CC BY 4.0

Kun maal jechuu ta'uu danda'a?

Ratio D/H bishaanii ol'aanaan mallattoo bishaan bakka baay'ee qorraa (30 K gadi naannoo) keessatti jabaatee, booda ho'aan baay'ee hin jijjiiramne ti. Kanaaf dubbisni qulqulluun bishaan 3I/ATLAS haala comet Sirna Aduu keenya caalaa *qorra fi tasgabbaa'aa* keessatti uumame — kanaaf parental planetary system isaa cabbii karaa keenya irraa adda ta'een ijaare — jechuu dha.

Barreessitoonni tarkaanfii itti aanu irratti of eeggatu; nutis akkasuma ta'uu qabna. Bishaan deuterium'n hangana badhaadhe uumuuf karaan lama jira; safartuun kun adda isaan hin baasu: bishaan sun cold cloud sirni keessatti dhalate irraa badhaadhina isaa *dhaaluu* danda'a; yookaan yeroo comet cold outer disk keessatti uumamu booda murtaa'uu danda'a. Karaa lamaan, xumuri barbaachisaan ni hafa — haalli 3I/ATLAS bocu haala comets keenya bocu hin turre — garuu *maaliif* jedhu banaa dha.

Kanaaf kun yeroo jalqabaaf namni tokko mallattoo uumamuu bishaanii kan planetary system biraa irraa dubbisee, kan keenya wajjin akka hin simne arguu isaa ti.

Kun maal *hin mirkaneessu*?

- Waa'ee jireenya, technology yookaan akeekaa **homa** hin jedhu. “Wanti” ijaarame tokko hin jiru; “interstellar” trajectory ibsa, seenaa ka'umsa miti. Kun safartuu keemistirii bishaanii dha.
- Value D/H sirrii **miti**. *Lower limit* dha; bishaan inni irratti dubbatu kallattiidhaan matumaa hin argamne — baay'inni isaa excitation molecule biraa, methanol, irraa tilmaamame; bishaan wanta methanol irra caalaa itti bu'u jedhamee yaadame.
- 3I/ATLAS eessa akka dhalate **hin mul'isu**. Parent star amanamummaadhaan adda baasuun hin danda'amu; ratio D/H ol'aanaan mallattoo *haalaa* dha, teessoo mana miti.
- Bishaan maaliif deuterium'n badhaadhe *hin murteessu*. “Cold birth-cloud irraa dhaalame” fi “yeroo disk formation murtaa'e” lamaan daataa wajjin wal-simu; barruun tokko hin filatu.
- Wanta **tokko**, epoch **tokko** irratti safarame dha. Ragaan biraa deeggaruun nama jajjabeessa; base-line dheeraa miti.

Ragaan hammam cimaa dha?

Wantoonni lama adda addaan madaalamuu qabu: kallattii bu'aa, fi lakkoofsa sirrii.

- **Kallattiin bu’aa cimaa dha.** Bishaan 3I/ATLAS deuterium’n baay’ee badhaadhe ta’uun lower limit of eeggannoo dha; comet population Sirna Aduu guutuu ol jira; xiinxala JWST of danda’een deeg-garama. Kutaan kun laafaa miti.
- **Lakkoofsi sansalata modelling irratti hundaa’a.** H₂O waan hin argamneef, baay’inni bishaanii — kanaaf ratio D/H — excitation methanol irraa bishaan karaa al-kallattiin tilmaamu irratti hirkata. Kun bishaan coma keessatti collision partner duraa ta’uu yaada (perihelion bira ta’uu danda’a, garuu CO₂ gumaacha gochuu hin danda’u jechuun hin danda’amu); collision rates tilmaamaa fi sirriitti hin beekamnes fayyadama. Barreessitoonni kana hunda ibsanii, itti yaadanii akka limit, safartuu miti, gabaasu.
- **Hiikni sababa gaarii qaba garuu qofa miti.** Uumamni qorraa D/H ol’aanaaf ibsa uumamaa dha; qorri sun dhaalame moo booda uumame hin furamne; parent system adda baafamuu hin danda’u.

Gabaabumatti: bishaan sun qorra keessatti uumamuu isaa irratti ragaan cimaa dha; hammam *qorra* akka ture, fi *maaliif*, amanamummaadhaan banaa tursiifame.

Maaliif barbaachisaa dha?

Waggoota kudhan hedduuf, gaaffiin bishaan Lafaa eessaa dhufe — fi planetary systems uumamaa jiran keessatti mallattoo deuterium bishaanii maaltu murteessa — safartuu Sirna Aduu keenya keessaa qofa argameen deebifame. Kun yeroo jalqabaaf chart sana wanta urjii biraa naannoo keessatti uumamuu isaa ifatti beekamuutti diriirse.

Deebiin isaa “bakki hundi mana fakkaata” miti. Faallaa isaa: system biraan cabbii isaa haala gahaa qorra ta’e keessatti kaa’ee mallattoo comets keenya matumaa hin qabne dhiisuu danda’a. Kun waan guddaa tasgabbaa’aa tokkoof ragaa xiqqaa fi qabatamaa dha — keemistirii fi seenaa solids pilaaneetota ijaaran urjii tokko irraa gara biraatti adda ta’uu danda’a. Spacecraft light-years hedduu ergame irraa miti; ciccitaa system biraa darbaa jiru qabuun, osoo hin badin bishaan isaa dubbisuun dhufe.

Cuunfaa ifaa

3I/ATLAS wanta interstellar beekame sadaffaa fi comet interstellar active ta’e lammaffaa — ciccitaa planetary system biraa kan keenya keessa yeroo tokko darbu — dha. Yeroo comet Aduu bira hunda caalaa dhihaatu ALMA fayyadamuun, astronomers bishaan ulfaataa (HDO) fi methanol coma isaa keessatti argan; bishaan idilee garuu hin argine; kana irraa ratio deuterium fi hydrogen bishaanii tilmaaman. Deuterium’n baay’ee badhaadhe — lower limit 6.6×10^{-3} ol, galaanota Lafaa tilmaamaan dachaa 40 fi comet Sirna Aduu idilee dachaa 30 — argan; kun bishaan haala comet Sirna Aduu caalaa qorra fi ho’aan xiqqoo jijjiirame keessatti uumame akeeka. Lakkoofsi lower limit moodeelaan karaa al-kallattiin argame dha, safartuu kallattii miti; badhaadhinni cold birth-cloud irraa dhaalame moo booda cold disk keessatti murtaa’e, yookaan comet eessaa dhufe, dubbachuu hin danda’u. Ta’us, kun yeroo jalqabaaf mallattoo keemistirii addaa kana bishaan urjii biraa irraa dubbisuu dha — mallattoon sun kan keenya wajjin hin simu.

Sakatta'a soba-maleessa

Barruun maal agarsiisa: Daawwannaa ALMA comet interstellar 3I/ATLAS perihelion biraa irraa, lower limit ratio D/H bishaan isaa $>6.6 \times 10^{-3}$ (scenario of eeggannoo) — galaanota Lafaa tilmaamaan $40\times$ fi comet Sirna Aduu idilee $30\times$ — kunis bishaan haala comet Sirna Aduu caalaa qorra fi thermal processing xiqqaa qabu keessatti uumame agarsiisa. Xiinxalli JWST of danda'e kallattii kana irratti walii gala.

Wanti ta'uu danda'u garuu hin mirkanoofne: Badhaadhinni cold prestellar cloud irraa kallattiidhaan dhaalame moo yeroo comet cold protoplanetary disk keessatti uumamu murtaa'e. Scenarios lamaan wal-simu; daataan adda isaan hin baasu.

Wanti inni hin agarsiisne: Waa'ee jireenya, technology yookaan ka'umsa nam-tolchee; value D/H sirrii (lower limit dha); eenyummaa yookaan bakka parent star; mechanism D/H ol'aanaa uume; yookaan bu'aan epoch tokkoo jijjiirama coma irraa walaba ta'uu.

Daangaawwan ijoo: H_2O kallattiidhaan hin argamne; kanaaf baay'inni bishaanii — fi ratio D/H — excitation methanol irraa karaa al-kallattiin tilmaamame, bishaan collider duraa ta'uu fi collision rates tilmaamaa barreessitoonni sirriitti hin beekamne jedhan irratti hundaa'e; bu'aan limit epoch tokkoo fi moodeela irratti hundaa'e dha; parent system adda baafamuu hin danda'u.

Dubbisaan waliigalaa hammam amanuu qaba? Bishaan 3I/ATLAS dhugumaan deuterium'n badhaadhe, comet keenya caalaa qorra keessatti uumame, kunis aliens irratti homaa akka hin jenne irratti amantaa guddaa. Sadarkaa badhaadhinaa sirrii, lower limit moodeela irratti hundaa'u, irratti amantaa giddu-galeessa. Sababa fi bakka dhalootaa amma iyyuu banaa irratti amantaa xiqqaa. Haala sirrii: ergaa keemistirii system urjii biraa irraa dhufe irratti dinqisiifannaa tasgabbaa'aa — iccitii miti, spaceship miti.

Maddoota

Nature Astronomy (2026)

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ALMA data archive (project 2025.A.00002.T)

<https://almascience.nrao.edu/aq/>