International Radio-Telescope Project "ALMA" and Its Scientific Results

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Toward nuclear fusion
核融合に向かって

• We, astronomers, are studying how stars form (starts nuclear fusion)
Orion at optical  at radio wavelengths

Seiichi Sakamoto et al.
Visual Universe and Radio電波 Universe

• We can see “visible light 可視光” (wavelength $\lambda = 0.4-0.8 \, \mu m$)
  – our eyes are designed to see light of the sun whose surface temperature is 6000K, (reflected by matters around us)
  – Therefore, in the night sky, we see adult stars having very hot surface temperature like our sun

• Radio signal of millimeterミリ波 ($\lambda = 1-10 \, mm$) and submillimeter wave サブミリ波 ($\lambda = 0.1-1 \, mm$)
  – We can see “Cold Universe” of $< -150 \, ^\circ C$ or 10-100 K
Life Cycle in the Universe –ecosystem–

Universe to be observed with ALMA

Radio: millimeter

Interstellar Medium

Molecular Clouds

Protostars, Protoplanets

Stars, Planets

Red Giants

Planetary Nebulae

Protostars, Protoplanets

Low-mass Stars

Massive Stars

Supernovae

Stars, Planets

Infrared

Visual Light

Radio: centimeter

Radio: submillimeter

X-rays

Pulsars

X-ray Satellite like “Suzaku”

Optical Telescopes like “Subaru”

Infrared Satellite like “Akari”
Radio Telescope “ALMA”

- International radio telescope project by 20 countries lead by NAOJ, NRAO and ESO to construct and operate the telescope in Chile.
- Taiwan and Korea participate ALMA through collaboration with NAOJ.
- Atacama Large Millimeter/submillimeter Array.
- ALMA means “soul 魂” in Spanish used in Chile.
Photo of the ALMA antennas
“Morita Arrayモリタアレイ” built by Japan
credit: ALMA (ESO/NAOJ/NRAO)
Atacama Large Millimeter/submillimeter Array

• 66 parabolas in 16 km diameter campus
• Spatial Resolution ~ telescope size/wavelength
• Vision 視力 of 6000, which is 10 times better than Hubble (vision of 600)
**Sciences with ALMA**

Our promise for the government (e.g. MEXT 文科省)

We cannot break it!!!

**Target 1**
Formation of Planets

**Target 2**
Formation and Evolution of Galaxies

**Target 3**
Evolution of matter in the Universe – prebiotic molecules (e.g. amid acid)

By utilizing ALMA’s great spatial resolution and sensitivity
Formation of Planetart System

- Radio: millimeter
- Radio: submillimeter
- Molecular Clouds
- Protostars, Protoplanets
- Stars, Planets
- Red Giants
- Planetary Nebulae
- Interstellar Medium
- Black Holes
- Pulsars
- Supernovae
- Low-mass Stars
- Massive Stars
- Infrared
- Visual Light
- X-rays
- X-ray Satellite like “Suzaku”
- Radio: Centimeter
- Optical Telescopes like “Subaru”
- Infrared Satellite like “Akari”
- Universe to be observed with ALMA
- ALMA
Our Solar System

Until 1995, this has been the sole planetary system we knew.
Discovery of thousands exoplanets
Variety of exoplanets
Our solar system may not be typical
ALMA was expected to be the first telescope to see planet formation.

Observation with Hubble ©STScI
Silhouette disk (protoplanetary disk) against the Orion Nebula. Red star is a protostar.

Computer simulation (Bryden et al. 1999)
Protoplanets are formed by accreting gas. ALMA will be used to investigate which model is correct.
“Kyoto model” C. Hayashi et al.)

planetesimal accretion

- Explained the formation of our solar system rather than “Cameron model” (gravitational instability)
- However, exoplanets observations show variety of systems
  - Some cases are hard to explain with Kyoto model. Cameron model?
- Planet migration? Planets move from the birth site.
Kyoto model

Core Accretion

Planetesimals

C. Hayashi 1977 PASJ 29,163

Cameron model

Gravitational Instability

A protoplanetary disk of gas and dust forms around a young star.

Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.

Dust grains coagulate and sediment to the center of the protoplanet, forming a core.

The planet sweeps out a wide gap as it continues to feed on gas in the disk.

Credit: NASA/ESA and A. Feild (STScI)
Protoplanetary Disk around HL Tau

T Tau star $\sim 10^6$ yr old

vision=2000; 0.035 arcsec resolution
HL Tau (10^6 yr) formed planets so quickly!! (C. Hayashi+85, PII)

<table>
<thead>
<tr>
<th>Time (yr)</th>
<th>Event Description</th>
</tr>
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<tbody>
<tr>
<td>-10^6 - 5</td>
<td>Collapse &amp; fragmentation of a giant molecular cloud</td>
</tr>
<tr>
<td>-10^5 - 4</td>
<td>Collapse of a rotating presolar cloud</td>
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| 0         | Formation of protosun and solar nebula  
            (Growth & sedimentation of dust-grains) |
| 10^4      | Fragmentation of dust layer into planetesimals |
| 10^5      | (Accumulation of planetesimals) |
| 10^6      | Formation of the Earth |
| 10^7      | Formation of Jupiter’s core & accretion of gas onto it  
            Dissipation of nebular gas |
| 10^8      | Formation of Saturn’s core & capture of remaining gas  
            Formation of Asteroid Belt |
| 10^9      | Formation of Uranus(?) |
| 10^10     | Formation of Neptune(?) |
Resonance between three satellites of Saturn

Wikipedia
Dipierro et al. (2015)
three planets with 0.2, 0.27, 0.55 x Jupiter mass

• Left: ALMA image; right: simulation

Figure 4. Comparison between the ALMA image of HL Tau (left) with simulated observations of our disc model (right) at band 6 (continuum emission at 233 GHz). Note that the colour bars are different. The white colour in the filled ellipse in the lower left corner indicates the size of the half-power contour of the synthesized beam: (left) 0.035 arcsec × 0.022 arcsec, P.A. 11°; (right) 0.032 arcsec × 0.027 arcsec, P.A. 12°.
氷結モデル
焼結

• Sintering (焼結)
model
Alternative explanation (Okuzumi+ Titech)

• Gap is not evidence of planet formation
• However, it is evidence that small solid grains are forming from gas???
Sintering 焼結 model
Okuzumi (Titech)+2015

- More packing of fluffy snow at slightly lower temperature of sublimation temperature (fluffy snow to more solid snow)
Okuzumi+2015
Gap due to sintering will disappear in 2 Myr

ALMA Observation

Obs

Model

中心星からの距離（天文単位）
HL Tau (100万歳) では惑星が早く形成!! 太陽系の木星は1000万年で形成。

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Habitable planets
生命居住可能惑星

• Planets suitable for life
  – Terrestrial planets 地球型惑星（having the ground）
  – Existence of liquid water 液体の水が存在
  – Greenhouse effect 温室効果（二酸化炭素が凍ってドライアイスになってしまうほどの遠くない）
  – 右の図
    • Top: Solar system
    • Bottom: exo-planets with low mass star
    • Light blue: habitable zone

Credit: ESO
Importance of the snow line

- Paper by Okuzumi may indicate snow line-sintering line
Gravitational lens SDP.81(z~3.04) with vision 2000

- Mass of lensing point source is $> 3 \times 10^8 \, M_\odot$
Lensed galaxy  \( Z = 3.042 \)

Redshift and age (after Big Bang)

- \( z = (\lambda_{\text{obs}} - \lambda_0)/\lambda_0 \) \( \lambda_0 \) = rest wavelength
- \( 1+z= \lambda_{\text{obs}}/\lambda_0 \)
- \( z = ((1+v/c)/(1-v/c))^{1/2} - 1 \approx v/c \) (if \( v<<c \))
- \( z = 0 \rightarrow \text{age} \ 13.8 \ \text{Gyr (present)} \)
- \( z = 1 \rightarrow \text{age} \ 5.8 \ \text{Gyr} \)
- \( z = 3 \rightarrow \text{age} \ 2.14 \ \text{Gyr} \)
- \( z = 6 \rightarrow \text{age} \ 0.9 \ \text{Gyr} \)
- \( z = 10 \rightarrow \text{age} \ 0.5 \ \text{Gyr} \)
- \( z = 1000 \rightarrow \text{age} \ 380 \ \text{kyr} \)
Gravitational lens

Credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.
SDP.81 ALMA CO emission
Dye et al. (2015)

- Left: observed Einstein ring
- Middle: best-fit model
- Right: restored CO original distribution
SDP.81 radio and near infrared
ALMA (white contour) vs Hubble (color)
Dye et al. (2015)

- Left: obs, Middle: restored distribution, Right: enlarged. Cloud seen in radio is located next to star system seen in near infrared. Interacting

**Figure 2.** Source reconstruction of the HST F160W data. Panels show the observed image (left; black ellipse masks out residual noise left from lens galaxy light subtraction and the inset panel shows the lensed image of the reconstructed source), the full scale of the reconstructed source that fits the tidal debris-like emission seen in the observed image (middle) and a zoomed-in section of the source overlaid with band 6 continuum contours (right).
SDP.81: restored image
Dye et al. (2015)

- Color: ALMA, CO
- White: ALMA, dust
- Yellow: Hubble
Case that lensing gal is point-symmetric

http://gravitationallensing.pbworks.com/
Gravitational lens (lensing gal: elliptical)

caustic 焦線（blue）、critical curve 臨界線（red）

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Solid will be mapped to solid. Broken will be mapped to broken. Magnification becomes...

http://gravitationallensing.pbworks.com/
Gravitational lense PG1115+080

資料提供：米原厚憲（筑波大学）
Measure kinematics by using Doppler effect.

Dye et al. (2015)

- Rotating disk
Toomre’s Q

\[ Q = \frac{\kappa C_s}{\pi G \Sigma_0}, \]

- \( G \): gravitational constant
- \( \Sigma \): surface density
- If \( Q > 1 \), disk is stable
- If \( Q < 1 \), disk is unstable

- \( C_s \): sound speed \( \propto \sqrt{\text{temperature}} \)
- \( \kappa \): epicyclic frequency = angular speed (Kepler rotation)
Gravitational lens SDP.81

• Q=0.2 from CO observation
• Molecular gas disk is unstable
• Star forming rate = 500 Mo/y
  (cf. 3 Mo/yr in our Milky Way Galaxy)

Lensed galaxy is forming stars very actively
(hundred times more than our Galaxy)
Conclusion

• We have achieved two of three promises we made for the Government
• However, one model claims that the gaps do not represent planet formation!!!
• Very high resolution image by using gravitational lenses
• We should like to achieve the third promise (amid acid detection beyond the solar system)
Thank you for your attention!