Progress in and prospects for understanding of planet formation

Late Stage Accretion of Gas Giants

Masahiro IKOMA (Univ. Tokyo)

Shibata, Helled, & Ikoma (2019, A&A)
1995

23 November (Mayor & Queloz 1995)
Discovery of Exoplanet

7 December
Probe Entry into Jupiter’s Atmosphere

51 Pegasi b

Galileo
In situ measurement of element abundances in Jupiter’s atmosphere

Jupiter’s atmosphere is enriched with heavy elements relative to the solar abundances, similarly to its interior.

Oxygen and thus water was missing.

Did the probe happen to enter a dry region? Was oxygen fixed in the core in the form of ice?
2005

Detection of RV variation for HD149026 with Subaru (Sato+ 2005)

Mass = 0.36 Jupiter
Radius = 0.73 Jupiter
Semimajor axis = 0.042 AU
2005

Detection of RV variation for HD149026 with Subaru (Sato+ 2005)

HD149026b
A surprisingly dense close-in gas giant

Core 60-80 M$_{\text{Earth}}$
Envelope 30-50 M$_{\text{Earth}}$

Give support, but a challenge to the core accretion model for giant planet formation

$\leftarrow$ Thermal evolution models (Ikoma+ 2006)

Critical core mass is at most $30 \, M_{\text{Earth}}$.

Recent theories favor smaller cores.

Additional heavy elements must be captured during and/or after the runaway gas accretion phase.
**Giant Collision Hypothesis**

SPH simulation of collision of two gas giants
(Ikoma+ 2006; Courtesy of H. Genda)

Merger of the cores + Loss of the envelopes
→ Formation of HD149026b-like planets

Impact velocity [escape = 1]

Envelope loss rate [%]

Ikoma+ (2006)
Retrograde or Highly Tilted Planets

Detection of the RM effect with **Subaru HDS** (Narita et al. 2009)

→ Retrograde-orbit giant planet, HAT-P-7b

Detection of another gas giant HAT-P-7c with **Subaru HDS** & a stellar companion 7B with **Subaru HiCIAO** (Narita et al. 2012)

A piece of the evidence of dynamical interaction & migration of gas giants.
Metallicity of Warm Gas Giants

Most of the known warm Jupiters are enriched with heavy elements relative to their host star.

> ~50 Earth masses!

Late-stage addition of heavy elements may be a common process.
In situ Capture of Planetesimals

Pushing Out of Feeding Zone

Planetesimals are pushed out of the feeding zone by the combined effect of gravitational scattering and eccentricity damping via gas drag.

Planet Growth Helps

The mass growth of the protoplanet via gas accretion leads to expanding the feeding zone and engulfing some of the surrounding planetesimals.

Low Capture Efficiency

However, the capture efficiency is low: ~ 0% for planetesimal size of $10^4$ & $10^5$cm, < 5% for $10^6$cm, ~20% for $10^7$cm
Capture of Planetesimals by a **Migrating Planet**

Disc-assisted migration helps the planet capture planetesimals.

For > 50-100 M\(_{\text{Earth}}\) of planetesimals to be captured, **Long-distance migration** is needed.

The planet captures planetesimals **From limited regions.**

→ important for atmospheric composition

*Shibata+ (2019, A&A)*
Atmospheric Composition of Hot Jupiters

Transmission Spectroscopy for Transiting Planets

Detect H$_2$O and some other molecules in atmospheres of hot Jupiters.

Atmospheric spectra are diverse.
Almost half of the HJ atmospheres are subsolar-H$_2$O (and thus substellar H$_2$O) abundances. Haze/clouds possibly obscure the H$_2$O features.
Growing, Infant Giant Planets

Detection of a giant gap in a circumstellar disk around PDS 70 with Subaru HiCIAO (Hashimoto+ 2012; Dong+ 2012)

Existence of gas giant planets which are massive enough to open the gap were predicted.
Hα emission from Objects in PDS70 Disk

MagAO Hα SDI on 6.5 Mag-Clay telescope

Two Hα emitters

Observed constraints

Intensities

Line shapes

Appear to be near 2:1 MMR \rightarrow migration?

What is the origin of Hα emission?

- LTAO-HRSDI in MUSE@VLT
  Haffert et al. (2019, Nat.Astron.)

### Observations

- PDS 70: Hα SDI on 6.5 Mag-Clay telescope
- Two Hα emitters observed

### Results

- Distances:
  - PDS 70b: 113.43 ± 0.52 pc
  - Mass: 5.4 ± 1.0 Myr

### Discussion

- Two Hα emitters with different intensities and line shapes
- Appearance near 2:1 MMR may suggest migration
- Origin of Hα emission needs further investigation
Late Stage Accretion

Three different pictures

2D

3D

3D + Magnetic field

Accretion through a circum-planetary disk (CPD)

Vertical infall + Accretion through CPD

Vertical infall + Deccretion through CPD

Shock heating + Line emission
1D Radiation Hydrodynamic Model


1) Hydrodynamics
   - Eq. of continuity
   - Eq. of motion
   - Eq. of energy

2) Chemical reactions
   - H, He, C, O, N, e
   - 60 species & 246 reactions

3) Electron transitions
   - Collisional excitation
   - Radiative absorption & emission

initial velocity $u_0$
$H_2$ number density $n_0$
Shock front

Line emission
The shock-heated gas is hot (\sim 7 \times 10^4 K) enough to dissociate and also ionize hydrogen, producing a number of electrons.
Post-shock Process


Those free electrons collide with and excite hydrogen atoms, resulting in hydrogen line emission.

\[ n_{H,0} = 10^{17} \text{m}^{-3} \]

\[ v_0 = 40 \text{ km/s} \]
Hydrogen Line Emission


Increase with preshock velocity

$\rightarrow$ Decrease with radial distance to the planet

Increase with number density

$F(H_\alpha) \propto v_0^3 n_0$
Comparison with Observed Line Widths

Line Profile

Our theoretical model reproduces observation.

Higher velocity yields larger width (Doppler broadening)

Higher density yields larger width (Absorption)

Constraints to Accretion Flow Properties

- Estimated properties in previous studies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protoplanet mass</td>
<td>~12 ( M_\oplus )</td>
</tr>
<tr>
<td>Mass accretion rate</td>
<td>~1 ( \times 10^{-5} ) ( M_\oplus / \text{yr} )</td>
</tr>
<tr>
<td>Filling factor</td>
<td>~5 ( \times 10^{-4} )</td>
</tr>
</tbody>
</table>

- \( L_{\text{H}_\alpha} = 4\pi R_p^2 f \text{F}_{\text{H}_\alpha} \) for PDS 70 b and/or c, respectively. Also, the resultant value of \( \alpha \) is \((10 \pm 5)\) \( \times 10^{-3} \).

- To convert \((10 \pm 5)\) \( \times 10^{-3} \) to \((3 \pm 1)\) \( \times 10^{-3} \) (e.g. 2018 Ha

- The intersection point of the two lines of the maximum likelihood reproduces observed H\( \alpha \) lines.

- The black lines correspond to the maximum likelihood (see Eq. [1]).

- The white line is \((12 \pm 10)\) \( \times 10^{-3} \).

- However, given the imprecision of the theoretical modeling of TTS accretion shock with \( \nu_{\text{preshock}}\), we show again \((12 \pm 10)\) \( \times 10^{-3} \).

- Also, the resultant value of \( \alpha \) is \((10 \pm 5)\) \( \times 10^{-3} \).

- To convert \((10 \pm 5)\) \( \times 10^{-3} \) to \((3 \pm 1)\) \( \times 10^{-3} \) (e.g. 2018 Ha

- The black lines correspond to the maximum likelihood (see Eq. [1]).

- The white line is \((12 \pm 10)\) \( \times 10^{-3} \).

- However, given the imprecision of the theoretical modeling of TTS accretion shock with \( \nu_{\text{preshock}}\), we show again \((12 \pm 10)\) \( \times 10^{-3} \).
Vertical Flow onto Protoplanet
Most of the accreting gas flows vertically and directly onto the central protoplanet with the help of the protoplanet’s intrinsic magnetic field.

Convergence of Accretion Flow
The accretion flow converges to quite narrow regions of the protoplanetary surface and experiences strong shock heating, resulting in hydrogen line emission.

Issues to Be Examined
- No detailed model of such accretion flow
- More samples other than PDS70 is needed.
Summary

- Subaru has made important contributions to understanding of the formation of giant planets through exoplanet observations.
- The bulk and atmospheric composition of giant exoplanets have been observationally constrained.
- The origin of heavy elements in gas giant planets remains a mystery, which is related to the late-stage accretion and migration.
- Recent observation is capable of accreting gas giants both indirectly and directly, which is of great help in understanding the formation of gas giants.
- Characterization of the atmospheres of gas giants and direct detection of infant gas giants by Subaru are expected.