Planet Formation in Star-Forming Regions: from the Solar System to Other Worlds

Yasuhiro Hasegawa
JPL Postdoc -> JPL Staff Scientist
Jet Propulsion Laboratory, California Institute of Technology
1. Evolution in Astronomical Disk Observations

We can see planet-forming regions

First Stage

~ micron  ~ mm  ~ m  ~ km  ~ $10^3$ km  Size

JWST is coming soon

ALMA Partnership et al 2015

ALMA in mm

Kwon et al 2011
2. Evolution in Space Engineering & Lab Experiments

We can touch planet-forming materials

Second Stage

~ micron  ~ mm  ~ m  ~ km  ~ $10^3$ km  Size

Rosetta  OSIRIS-REx  Hayabusa  Meteorites
3. Evolution in the Number of Known (exo)Planets

We can characterize (exo)planetary systems.

Total = 4,696

Super-Earths

Third Stage

\[ \sim \text{micron} \quad \sim \text{mm} \quad \sim \text{m} \quad \sim \text{km} \quad \sim 10^3 \text{km} \]

Size
A Comprehensive Examination of Planet Formation

Grain Growth in Star-forming Clouds and Protoplanetary Disks

Chondrules & Origins of Asteroids

Planet Formation and Exoplanet Populations
: Hasegawa & Pudritz 2010a,b, 2011a,b, 2012, 2013, Hasegawa & Ida 2013,

Protoplanetary Disks
: Takami et al 2014, Galvan-Madrid et al 2014,
Hasegawa & Takeuchi 2015, Akiyama et al 2016a,b,
Hasegawa et al 2017 submitted

Origins of Presolar Grains
: Nozawa et al 2015, Wakita et al 2017

First Stage

Second Stage

Third Stage

~ micron ~ mm ~ m ~ km ~ 10³ km

Size
A Comprehensive Examination of Planet Formation

JPL/Caltech, USA: Neal Turner, Joseph Masiero, Mario Flock, Mark Swain, Gautam Vasisht, Pin Chen
Caltech, USA: Konstantin Batygin, Roberta Paladini
Univ of Delaware, USA: Debanjan Sengupta, Sally Dodson-Robinson
McMaster, Canada: Ralph Pudritz
NAOJ, Japan: Eiji Akiyama, Shigeru Wakita, Takaya Nozawa, Yuji Matsumoto, Shouichi Oshino, Jun Hashimoto
TokyoTech, Japan: Satoshi Okuzumi, Shigeru Ida
ASIAA, Taiwan: Naomi Hirano, Hiroyuki, Hirashita, I-Hsiu Li, Pin-Gao Gu, Nanase Harada
ESO, Germany: Hauyu Baobab Liu
Univ. of Dundee, UK: Soko Matsumumura

First Stage
~ micron ~ mm

Second Stage
~ m ~ km

Third Stage
~ $10^3$ km

Size
Chondrules: the primitive material in the solar system

Chondrules are abundant in chondrites that are one class of meteorites kept forming for 3-5 Myr after CAI formation began, which is 4.567 Gyr ago.
Onset of Star Formation

3-5 Myr

Chondrule formation

First Stage
Second Stage
Third Stage

~ micron
~ mm
~ m
~ km
~ $10^3$ km

Size
Now
Onset of Star Formation

Now

3-5 Myr

Time

First Stage

Second Stage

Third Stage

Chondrule formation

Onset of Star Formation

Meteorites

Planetesimals

~ micron

~ mm

~ m

~ km

~ $10^3$ km

Size
Onset of Star Formation

First Stage

Second Stage

Chondrule formation

Third Stage

Planetesimals

Fragments

Asteroids

Meteorites

Time

3-5 Myr

Now

~ micron

~ mm

~ m

~ km

~ $10^3$ km

Size
Chondrules enable tracing back the long journey of planet formation in both time and size.
Current Picture of Planet Formation

NIR image of Hubble Space Telescope

Molecular Clouds

Gravitational collapse

The Eagle Nebula (d \sim 2000~pc)

1~pc = 3 \times 10^{18}~cm

Circumstellar Disks
Current Picture of Planet Formation

e.g., Hayashi 1981

\[ M_{\text{disk}} \sim 10^{-2} M_\odot \]

\( (: \sim 99\% \text{ of gas and } \sim 1\% \text{ of dust}) \)

\[ \tau_{\text{disk}} \sim 10^6 - 10^7 \text{ yr} \]

Disks are turbulent possibly by magnetic fields
Current Picture of Planet Formation

e.g., Hayashi 1981

\[ M_{\text{disk}} \sim 10^{-2} M_\odot \]

(\sim 99\% of gas and \sim 1\% of dust)

\[ \tau_{\text{disk}} \sim 10^6 - 10^7 \text{ yr} \]

Disks are turbulent possibly by magnetic fields

At 1 au, \( n \sim 10^{14} \text{ cm}^{-3} \)

\[ T \sim 300 K \]

cf) the atmosphere of the Earth,

At 1 bar, \( n \sim 10^{19} \text{ cm}^{-3} \)
Current Picture of Planet Formation

\[ M_{\text{disk}} \sim 10^{-2} M_\odot \]
\( (: \sim 99\% \text{ of gas and } \sim 1\% \text{ of dust}) \)

\[ \tau_{\text{disk}} \sim 10^6 - 10^7 \text{ yr} \]

Disks are turbulent possibly by magnetic fields

\(10 - 100 \text{ Myr} \)

At 1 au, \( n \sim 10^{14} \text{ cm}^{-3} \)
\( T \sim 300 K \)

cf) the atmosphere of the Earth,
At 1 bar, \( n \sim 10^{19} \text{ cm}^{-3} \)

Gillon et al 2017
Chondrules: the primitive material formed in the Solar Nebula (disk)

abundant in chondrites (up to 80 % by volume)

~1mm sized spherical particles formed as molten droplets of silicate (T ~ 1800K)

the cooling rate is ~ 10 - 1000 K per hour (the nebular gas is needed)

kept forming for 3-5 Myr after CAI formation began, which is 4.567 Gyr ago

cf) Mars formed at ~2 Myr after CAI formation
New information from lab experiments: magnetic fields in the nebula (disk)

Semarkona meteorite: primitive, ordinary chondrite

Both thermoremanent magnetization & its direction => olivine-bearing chondrules were magnetized in the solar nebula

Fu et al 2014

B-fields in the solar nebula were ~ 50 - 540 mG

=> Level of turbulence in the nebula can be estimated!!
Chondrule Formation
& Accretion

Thermal History

Abundance

Timescale

B-fields
Chondrule Formation & Accretion

Chondrule Formation = Impact Jetting

Chondrule Accretion = Pebble Accretion

Thermal History

Abundance

Timescale

B-fields
Key idea: impact jetting

A planetesimal with $r = 5\text{km}$ collides with a planetesimal or a protoplanet

Some materials melt, and are ejected from the system

Such ejected materials may be a progenitor of chondrules

Total ejected mass is about 1% of impactors’ mass when $v > 2.5 \text{ km/s}$
Lots of collisions occur when protoplanets form.

Protoplanets form via runaway/oligarchic growth.

Impact velocity of 2.5 km/s is achieved in the oligarchic phase.

Chondrule-forming collisions occur at the hatched region.

The total chondrule abundance is 1% of the protoplanet mass.

MMSN = the Minimum Mass of the Solar Nebula.
Lots of collisions occur when protoplanets form.

Protoplanets form via runaway/oligarchic growth. Impact velocity of 2.5 km/s is achieved in the oligarchic phase. Chondrule-forming collisions occur at the hatched region. Hasegawa et al. 2016a

Both the resulting abundance and the formation timescale of chondrules seem reasonable!!
(Note that the thermal history of chondrules is also probably fine)

The total chondrule abundance is 1% of the protoplanet mass.

MMSN = the Minimum Mass of the Solar Nebula
Chondrule Formation & Accretion

Chondrule Formation = Impact Jetting

Chondrule Accretion = Pebble Accretion
Lab results (magnetic fields) come into play!!!
Lab results (magnetic fields) come into play!!!

**B-fields**

**MagnetoRotational Instability (MRI) can operate**

Disks become turbulent

Flock et al 2011
Lab results (magnetic fields) come into play!!!

- MagnetoRotational Instability (MRI) can operate

- $h$ depends on level of turbulence, so the B-field strength

- Disks become turbulent

- Chondrules

- Flock et al 2011
2-3AU
H increases with disk mass and planetesimal mass (protoplanet)
Chondrule accretion onto planetesimals occurs when $H < h$

$h$ increases with *vertical magnetic flux*

$H$ increases with *disk mass and planetesimal mass (protoplanet)*

Lesion et al 2015

Dullemond & Monnier 2010

2-3AU
$m_{pl} = 10^{23} \text{ g}$

Hasegawa et al. 2016b
Disk mass (MMSN) $m_{pl} = 10^{23} \text{g}$

A large number of chondrules form in massive disks

No chondrule formation due to a low disk mass

Hasegawa et al 2016b
A large number of chondrules form in massive disks.

A very strong magnetic field is needed for chondrules to have the same height as planetesimals.

Planetesimals can reside in the chondrule sea, but no chondrules indeed.

No chondrule formation due to a low disk mass.

$m_{pl} = 10^{23} \text{g}$

Hasegawa et al. 2016b
All the currently available meteorite data can be satisfied when the disk mass is $< 5 \, \text{MMSN}$ and the planetesimal mass is $< 10^{24} \, \text{g}$. 

Hasegawa et al. 2016b
Our model needs a first generation of planetesimals that trigger impact jetting and serve as parent bodies to accrete chondrules.

Hasegawa et al 2016b

Planetaryesimal mass

\[10^{24} \text{ g}\]

Vesta/Ceres

Chondrule-rich surface layer:
\(~ 0.3 \text{ km for 230km-sized planetesimals}\)

Matsumoto et al 2017
Chondrule Formation & Accretion

Chondrule Formation = Impact Jetting

Chondrule Accretion = Pebble Accretion
Chondrule Formation & Accretion

Thermal History & Abundance

Chondrule Formation = Impact Jetting
Chondrule Accretion = Pebble Accretion

A great mixture of lab experiments, numerical simulations of collisions, theory of planet formation, & disk physics = the heart of (exo)planetary sciences
Planetesimal Formation & Origins of Asteroids

Scenario 1: Chondrule accretion

Scenario 2: Chondrule accumulation

We will identify formation mechanism(s) of planetesimals

Applications to debris disks
Chondrule formation

Onset of Star Formation

3-5 Myr

Time

Now

~ micron

~ mm

~ m

~ km

~ $10^3$ km

Size

First Stage

Second Stage

Third Stage

Meteorites

Asteroids

Fragments

Planetesimals

Chondrule formation

Chondrule formation

???
Chondrule formation ~ micron ~ mm ~ m ~ km

Onset of Star Formation 3-5 Myr

First Stage

Meteorites

Asteroids

Chondrule formation

Fragments

Planetesimals

Size

~ micron ~ mm ~ m ~ km ~ $10^3$ km

3-5 Myr
Magnetically Induced Disk Winds and Transport in the HL Tau Disk

Key Observed Features:
- a high disk accretion rate
- efficient dust settling

Our Disk Model:
- magnetized turbulence and magnetically induced disk winds

First Stage

Size:
- ~ micron
- ~ mm
- ~ m
- ~ km
- ~ $10^3$ km
Numerical Modeling of Dust Growth in Turbulent Disks

Flock et al 2011   Sengupta et al 2017 in prep

We will specify the distribution of planet-forming materials in disks

Applications to cloud/haze particles in planetary atmospheres
Chondrule formation

~ micron ~ mm ~ m ~ km

Onset of Star Formation

3-5 Myr

Meteorites

Asteroids

Planetesimals

Fragments

Third Stage
Link formation mechanisms of (exo)planets to their atmosphere

Close-in Super-Earths: failed cores of gas giants

Population Synthesis: a statistical understanding

Mass-Radius Diagram: useful for tracing down the formation history

Hasegawa 2016

~ micron ~ mm ~ m ~ km ~ $10^3$ km

Third Stage
We will link formation mechanisms of (exo)planets to their atmosphere applications to the origin of the solar system.

Gas Accretion onto Cores & Origins of Super-Earths

Hasegawa & Pudritz 2012
Kreidberg et al 2014

Third Stage

~ km

~ 10^3 km

Size

Applications to the Origin of the Solar System
Planet Formation is the Central in (exo)Planetary Sciences!!!

- Exoplanets
- Solar System
- Current & Future Missions, New Technologies
- Interdisciplinary
- Comprehensive

Super Fun!!!
Summary

• Planet formation is the long journey from small dust grains to large planets

• A number of astonishing progresses allow a comprehensive examination of planet formation, covering the fill size range

• As an example, chondrule formation and accretion are discussed, focusing on the impact jetting scenario

• This scenario can account for a number of the currently available meteorite data, and may be useful for the sample return missions

• Further synergies between planetary and exoplanetary sciences will be undertaken to draw a better picture of planet formation and examine the origin of the solar and extrasolar planetary systems