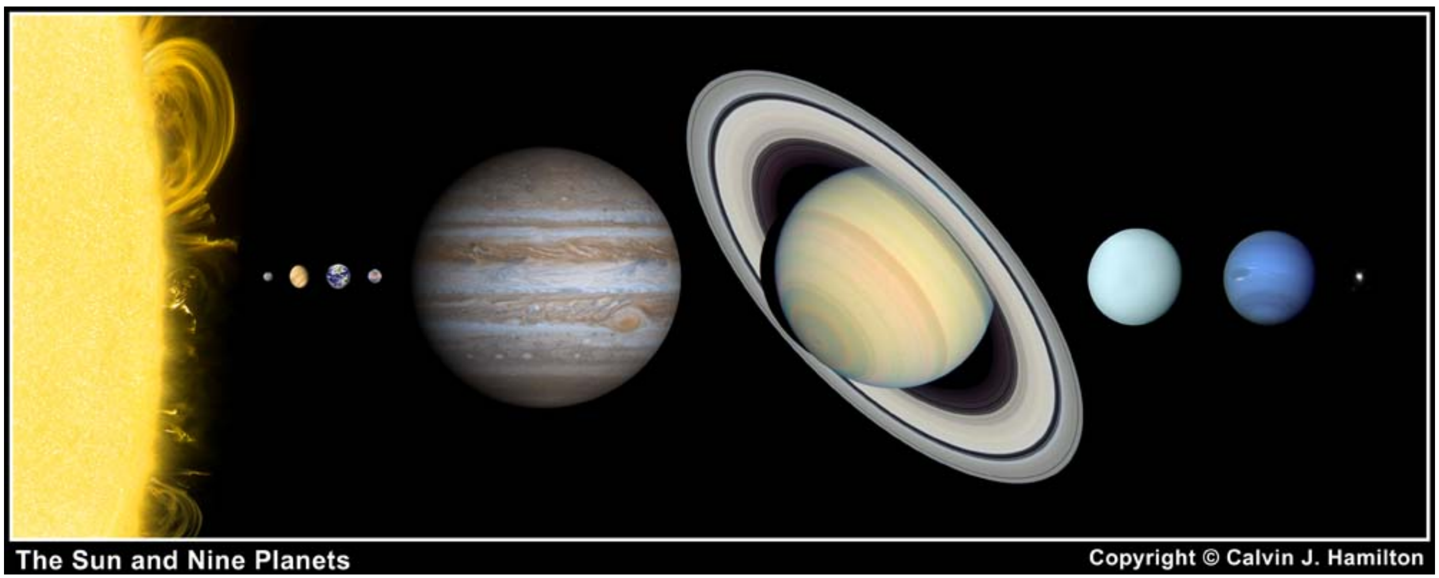
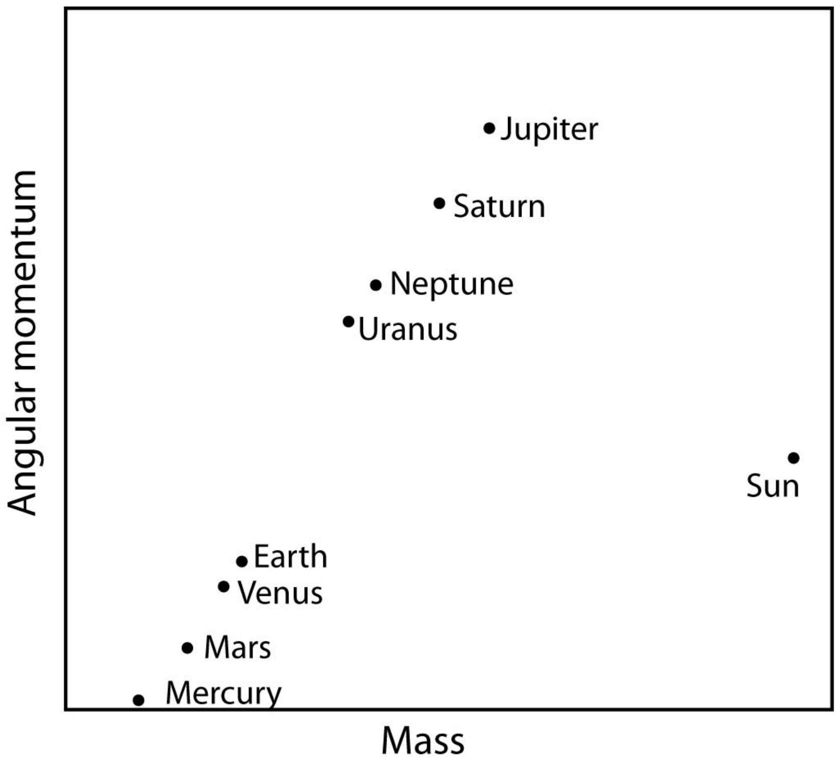
Solar System architecture



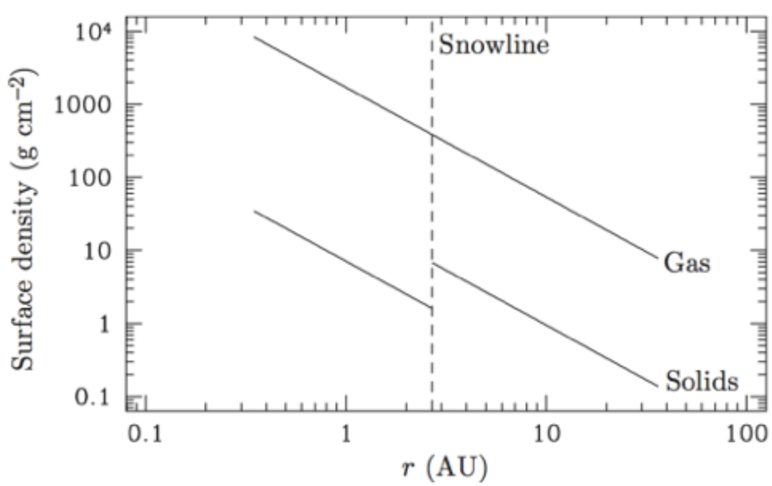
Mass - Angular Momentum Segregation

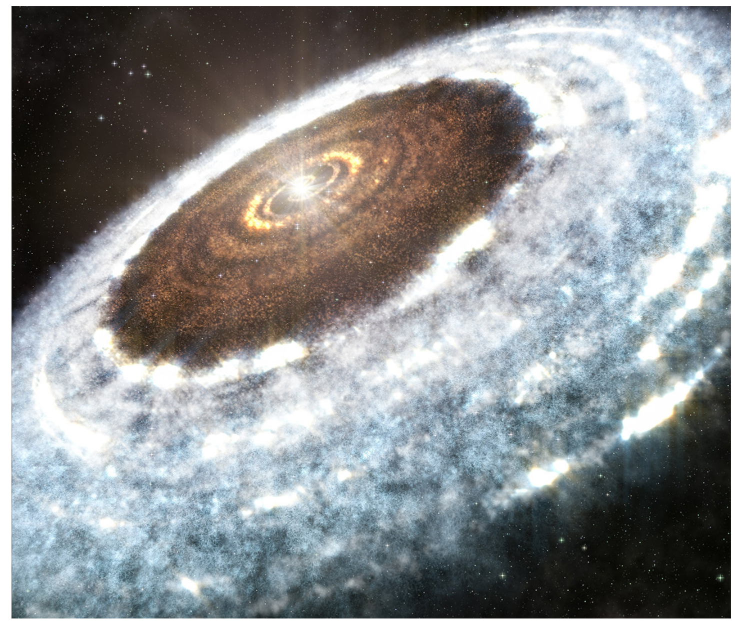


Mass: The planets sum up to less than 0.2% of the mass of the Sun

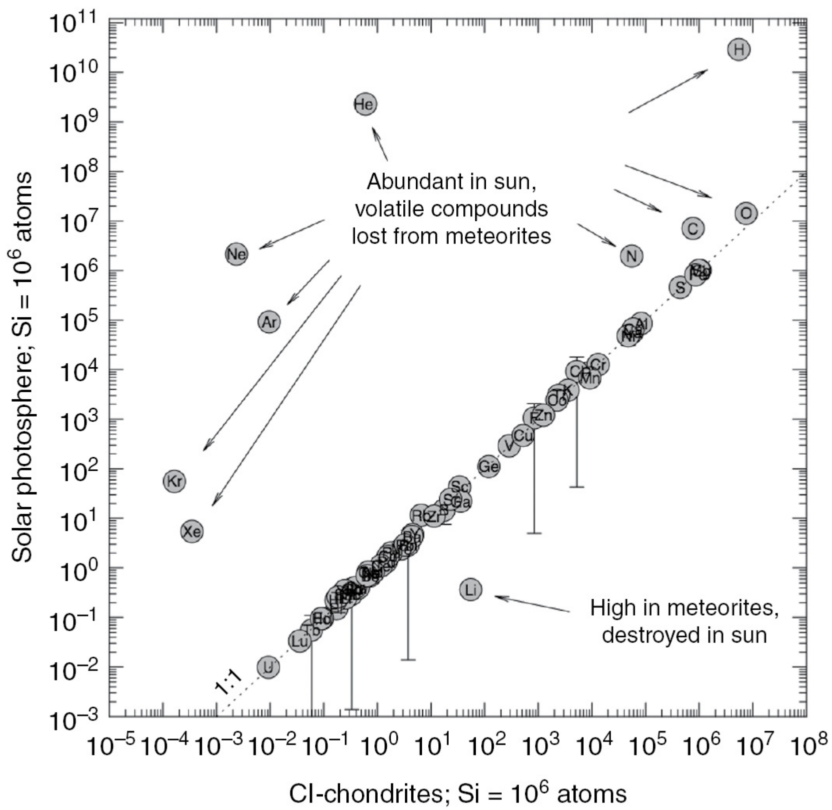
Angular Momentum: The planets (mostly Jupiter) have about 100 times the angular momentum of the Sun.

Snowline


Snowline
Gas
Solids
Surface density (g cm^{-2})
10^4
1000
100
10
1
0.1
0.1
1
10
100
r (AU)



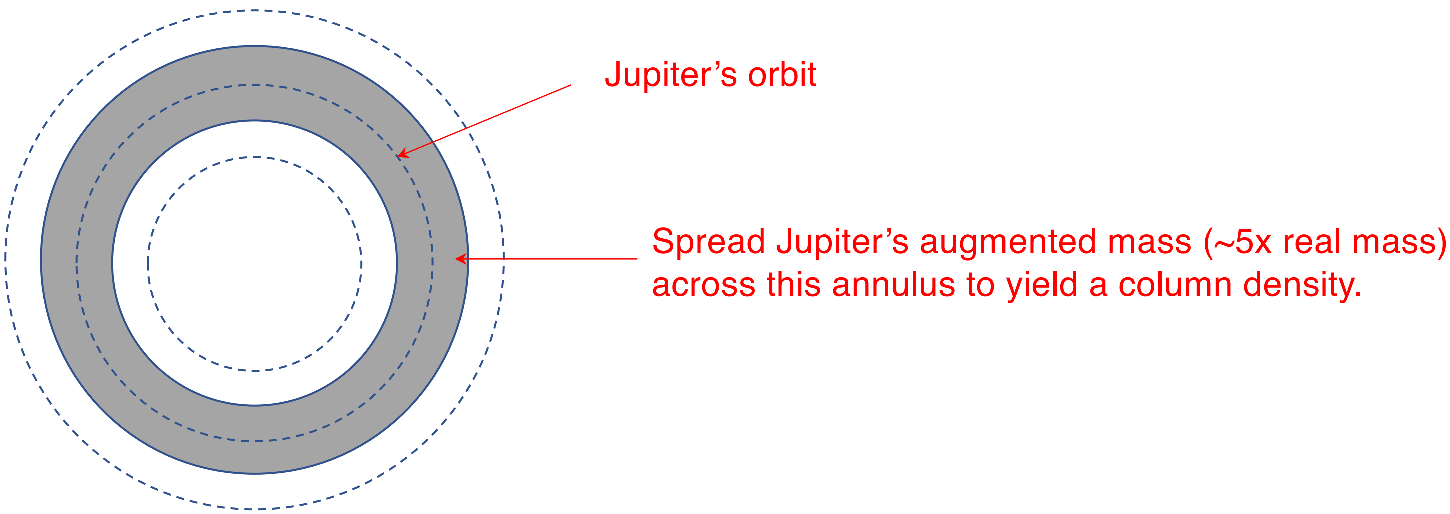
Refractories in meteorites: Solar Composition



The Minimum Mass Solar Nebula (MMSN)

How much mass was needed to form the planets?

1. Take the mass in each planet
2. Increase H/He to solar composition
3. Spread the mass into an annulus around each orbit



The Minimum Mass Solar Nebula (MMSN)

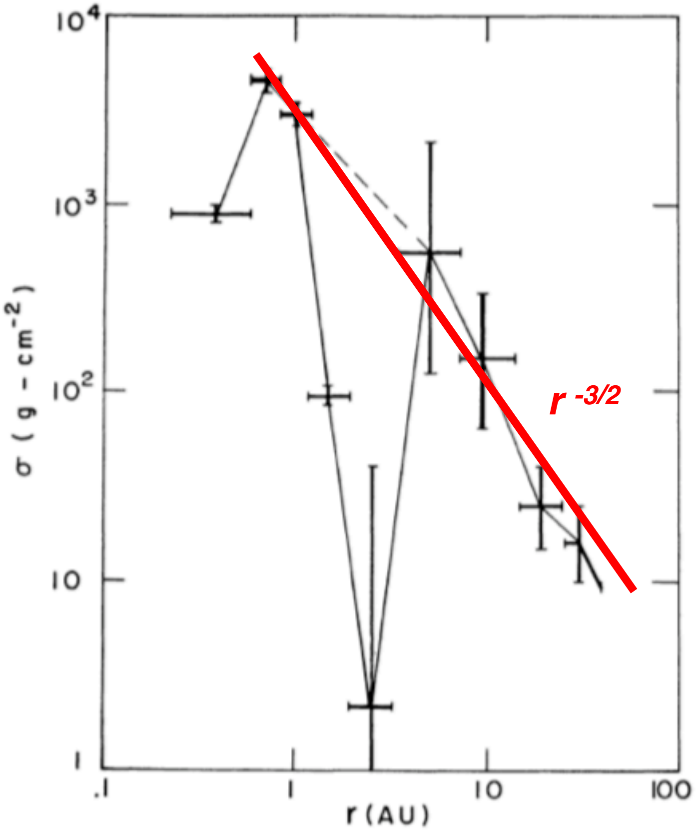


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.

The Minimum Mass Solar Nebula (MMSN)

Planetary zones: masses and surface densities

	Mass ($M_\oplus$)	Fe mass fraction	Solar comp. mass ($M_\oplus$)	Zone limits (AU)	Surface density (g cm^{-2})
Mercury	0.053	0.62	27	0.22	880
Venus	0.815	0.35	235	0.56	4750
Earth	1	0.38	320	0.86	3200
Mars	0.107	0.30	27	1.26	95
Asteroids					
present	0.0005	0.25	0.1	2.0	0.13
original	0.15?		30		40
				3.3	
Jupiter	318	–	600–12 000	7.4	120–2400
Saturn	95	–	1000–6000	14.4	55–330
Uranus	14.6	–	700–2000	24.7	15–40
Neptune	17.2	–	800–2000	35.5	10–25

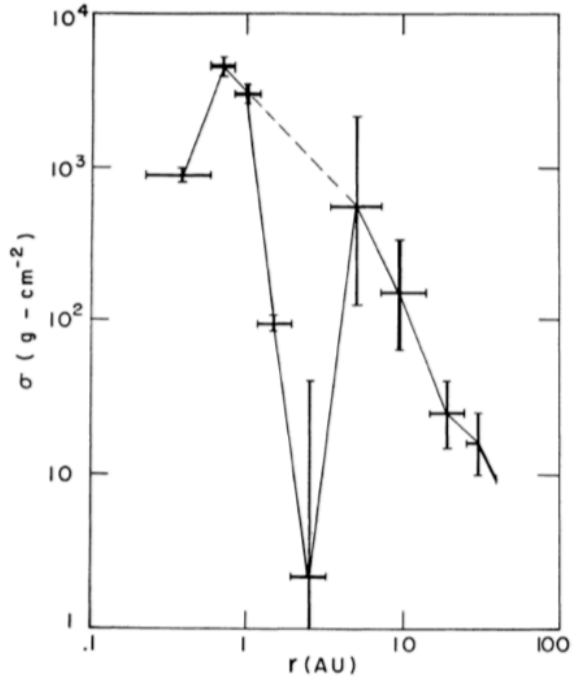


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.

VIEW

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The Distribution of Mass in the Planetary System and Solar Nebula

Show affiliations

Weidenschilling, S. J.

A model 'solar nebula' is constructed by adding the solar complement of light elements to each planet, using recent models of planetary compositions. Uncertainties in this approach are estimated. The computed surface density varies approximately as $r^{-3/2}$. Mercury, Mars and the asteroid belt are anomalously low in mass, but processes exist which would preferentially remove matter from these regions. Planetary masses and compositions are generally consistent with a monotonic density distribution in the primordial solar nebula.

Publication: Astrophysics and Space Science, Volume 51, Issue 1, pp.153-158

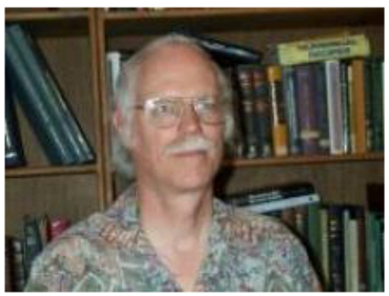
Pub Date: September 1977

DOI: 10.1007/BF00642464

Bibcode: 1977Ap&SS..51..153W

Keywords: Astronomical Models; Mass Distribution; Planetary Composition; Planetary Mass; Solar System; Asteroids; Cosmology; Nebulae; Space Density; Astrophysics

Dr. Stu Weidenschilling



Senior Scientist Emeritus

Currently resides in Tucson, AZ

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Areas of Expertise

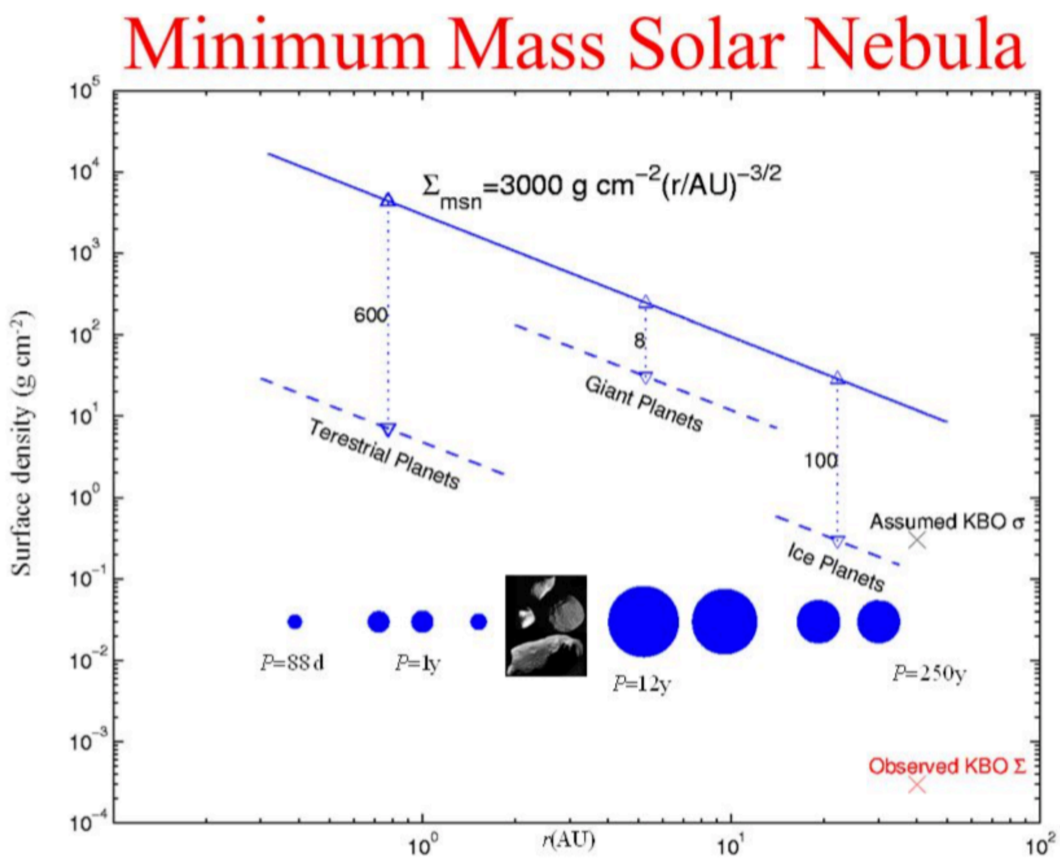
Targets: Asteroids, Comets, Exoplanets, Meteorites, Small satellites, Trans-Neptunian objects

Disciplines/Techniques: High-Throughput Computing (HTC), Numerical modeling

---

Research Interests

Dr. Stuart Weidenschilling conducts theoretical research on the origin of the solar system. He is particularly interested in the aerodynamic interactions of solid paricles and gas in the primordial solar nebula, and their implications for the formation of planetesimals from microscopic dust grains.. He has developed a numerical code that models coagulation of grains into larger bodies, taking account their mechanical properties and motions induced by gas drag and turbulence. He uses this code to investigate the


Minimum Mass Solar Nebula
Σmsn=3000 g cm−2(r/AU)−3/2
600
8
100
Terestrial Planets
Giant Planets
Ice Planets
Assumed KBO σ
Observed KBO Σ
P=88d
P=1y
P=12y
P=250y
Surface density (g cm−2)
r(AU)
10^5
10^4
10^3
10^2
10^1
10^0
10^−1
10^−2
10^−3
10^−4
10^0
10^1
10^2

Disk Masses

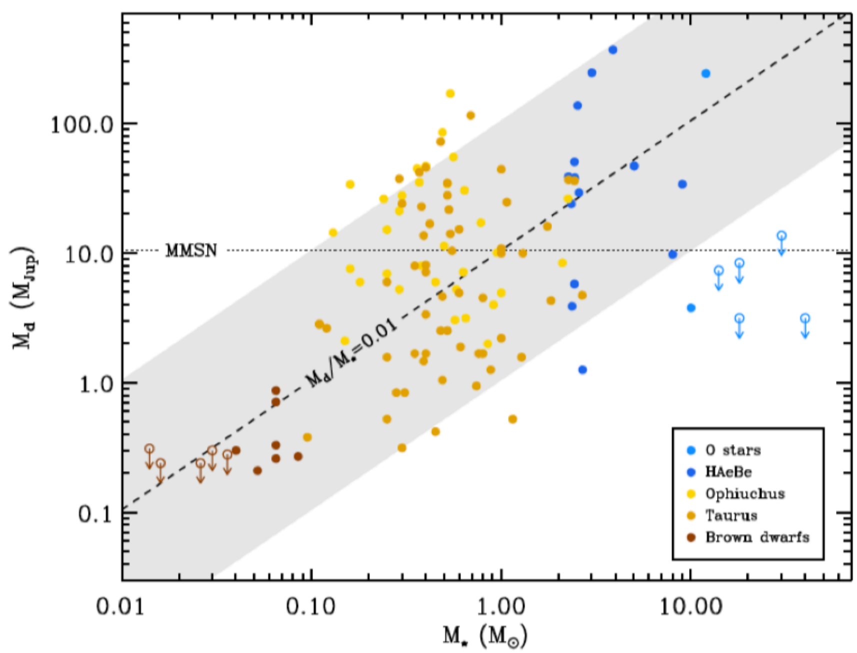
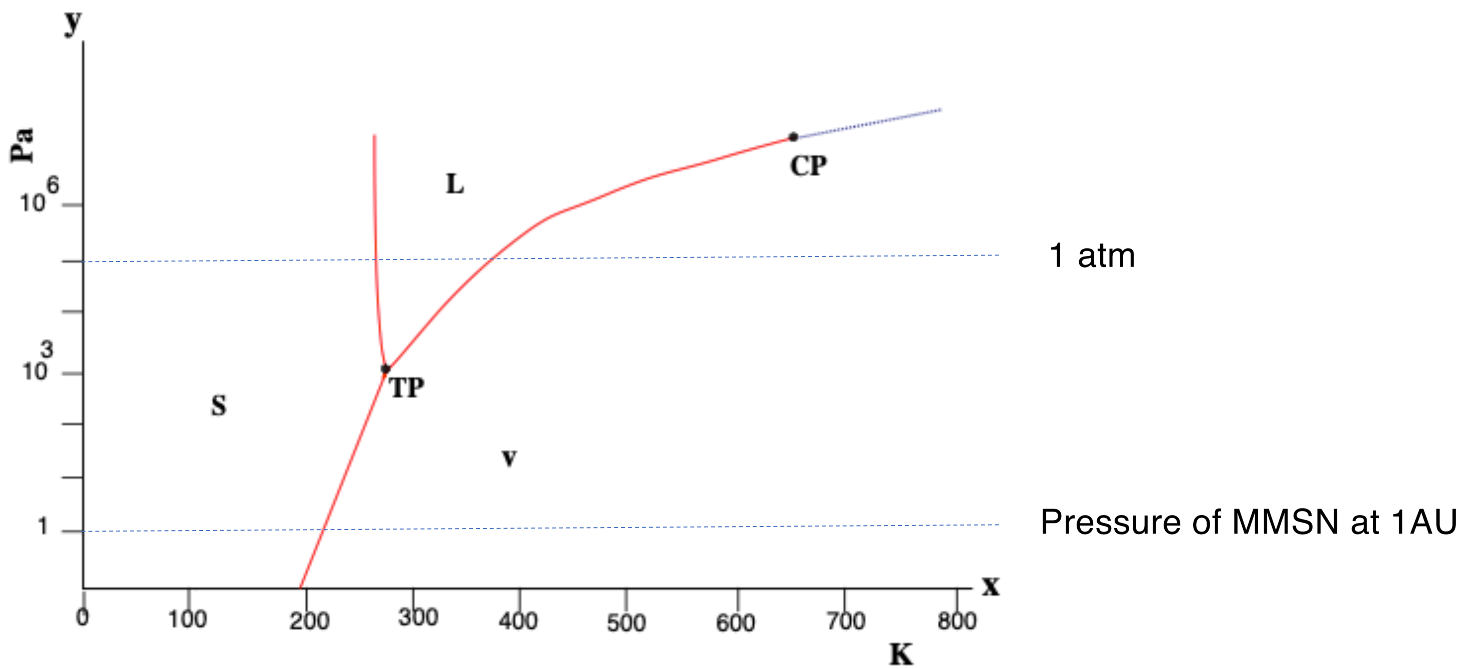


Figure 1: The disk mass as a function of the stellar mass (adopted from [51])

Phase Diagram - Water



Where was the water iceline?

The Carbonaceous / Non-Carbonaceous Divide

Enstatite chondrites
(E-Chondrites)

Rich in $MgSiO_3$ (enstatite)

Most Fe is either metallic or sulfide,
not oxides (water-poor)

Parent bodies in **inner asteroid belt**.

Carbonaceous chondrites
(C-Chondrites)

Rich in water and volatile organic chemicals

Have *not* been exposed to
high (above water sublimation) temperatures

Parent bodies in **outer asteroid belt**.

ASTEROID TAXONOMY

The composition of the surface of an asteroid can be determined by reflectance spectroscopy at ultraviolet, visible, and infrared wavelengths.

Broad classes (Bus & Binzel 2002):

- **C group** – carbonaceous, low albedo (< 0.1)
- **S group** – silicaceous (stony), moderate albedo (0.1 – 0.25)
- **X group** – metallic, usually moderate to large albedo

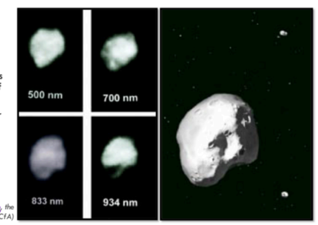
And several "assorted" groups

The first four asteroids discovered, shown on the same scale as Earth and the Moon (NASA). Together, they comprise 2/3 of the mass of the asteroid belt.

S-GROUP ASTEROIDS: S-TYPES

S-type (stony) asteroids are the second-most numerous type: about 30% of all asteroids.

- Concentrated toward the inner part of the main belt, with large albedos (~0.20); thus we may be overestimating their fraction of the total.
- Reflection bands in the infrared are similar to those from pyroxenes and olivines.
- They are either thermally processed and crystallized (like igneous rocks) or have been "space weathered" by impacts and UV.

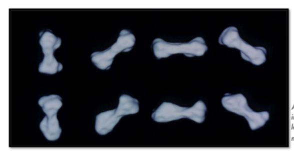


Adaptive-optical images and artist's conception of 3 Juno, the second-largest S-type asteroid (CfA)

X-GROUP ASTEROIDS: M-TYPES

M-type (metal) asteroids comprise about 10% of asteroids.

- They are shiny and relatively blue, with an albedo ~0.20, but lacking in silicate spectral features, so they are probably rich in metallic elements.
- Live mostly in the center of the main belt.

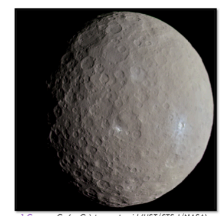


Artificially-sharpened Aricebo radar images of 216 Kleopatra, not the largest M-type but probably the most famous (Steve Ostro, JPL)

C-GROUP ASTEROIDS: C-TYPES

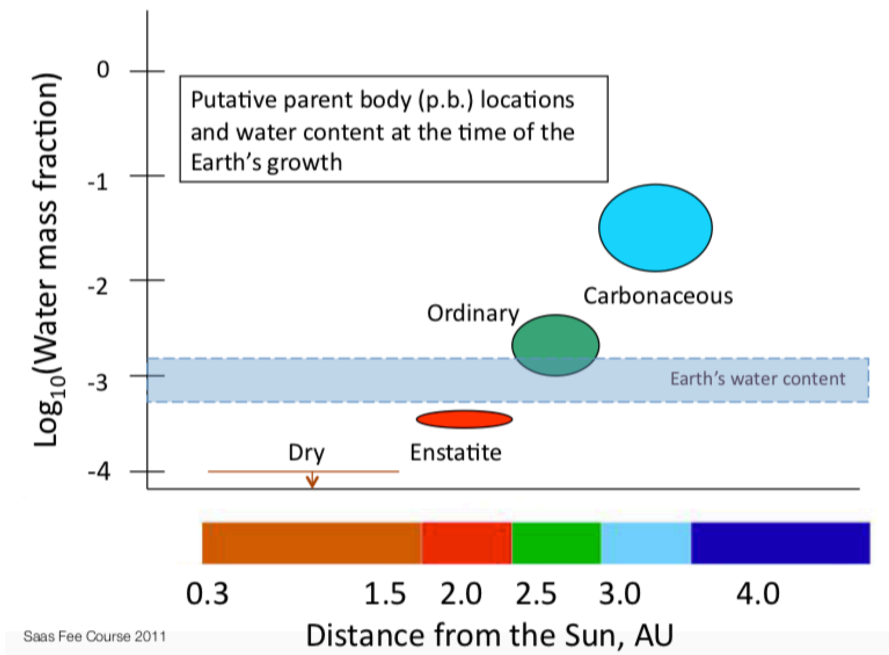
C-type asteroids are the largest population: at least 40% of all asteroids. They lie toward the outer part of the main belt.

- Dark, with albedo ~0.05; flat spectrum at red visible wavelengths
- Reflectance spectra generally similar to carbonaceous chondrite meteorites
- A few show additional absorption at UV wavelengths and are given by some the classification **G-type**.



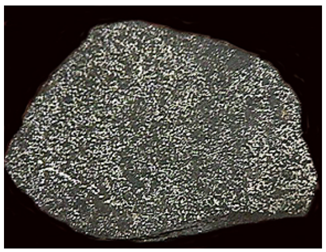
1 Ceres, a C- (or G-) type asteroid (HST/STScI/NASA), the largest and third brightest of the asteroids

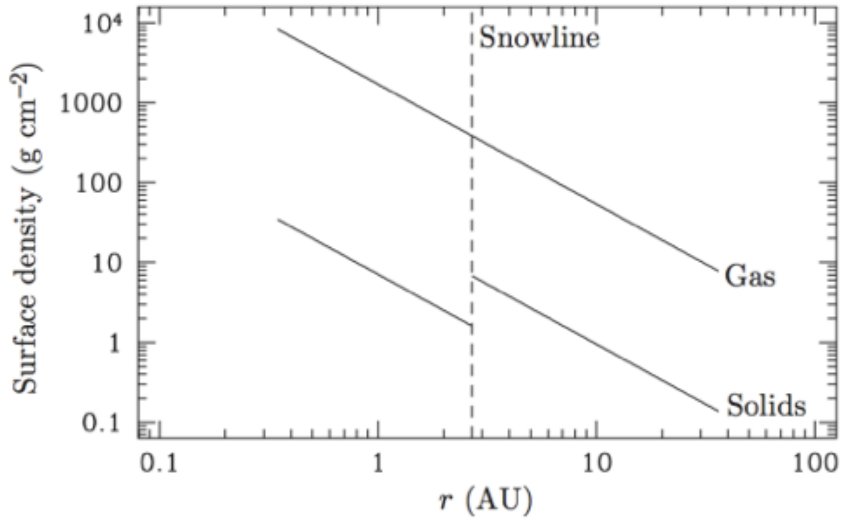
The Carbonaceous / Non-Carbonaceous Divide



Icelines

Enstatite chondrites
(E-Chondrites)





Carbonaceous chondrites
(C-Chondrites)

Water iceline
somewhere
in the asteroid belt

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EARTH

How Did Water Get on Earth?

About 70 percent of our planet's surface is covered with water, and it plays an important role in our daily lives. But how did water get on Earth in the first place?

Water delivery to dry protoplanets by hit-and-run collisions

Show affiliations

Burger, Christoph; Maindl, Thomas I.; Schäfer, Christoph

Final water inventories of newly formed terrestrial planets are shaped by their collision history. A setting where volatiles are transported from beyond the snowline to habitable-zone planets

On water delivery in the inner solar nebula

Monte Carlo simulations of forsterite hydration

M. D'Angelo[1,2], S. Cazaux

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September 6, 2018

Icarus

Volume 239, 1 September 2014, Pages 74-84

Water delivery and giant impacts in the 'Grand Tack' scenario

David P. O'Brien, Kevin J. Walsh, Alessandro Morbidelli, Sean N. Raymond, Avi M. Mandell

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Physical properties of terrestrial planets and water delivery in the habitable zone using N-body simulations with fragmentation

A. Dugaro[1,2] *, G. C. de Elía[1,2], and L. A. Darriba[1,2]

[1] Instituto de Astrofísica de La Plata, CCT La Plata-CONICET-UNLP Paseo del Bosque S/N (1900), La Plata, Argentina
[2] Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata Paseo del Bosque S/N (1900), La Plata, Argentina

Received / Accepted

[...EP] 7 Oct 2019

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Water delivery and giant impacts in the 'Grand Tack' scenario

David P. O'Brien, Kevin J. Walsh, Alessandro Morbidelli, Sean N. Raymond, Avi M. Mandell

ARTICLE INFO

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Planetary dynamics
Planets, migration

ABSTRACT

A new model for terrestrial planet formation (Hansen [2009]. Astrophys. J., 703, 1131–1140; Walsh, K.J., et al. [2011]. Nature, 211, 206–209) has explored accretion in a truncated protoplanetary disk, and found that such a configuration is able to reproduce the distribution of mass among the planets in the Solar System, especially the Earth/Mars mass ratio, which earlier simulations have generally not been able to match. Walsh et al. (Walsh, K.J., et al. [2011]. Nature, 211, 206–209) tested a possible mechanism to truncate the disk—a two-stage, inward-then-outward migration of Jupiter and Saturn, as found in numerous hydrodynamical simulations of giant planet formation. In addition to truncating the disk and producing a more realistic Earth/Mars mass ratio, the migration of the giant planets also populates the asteroid belt with two distinct populations of bodies—the inner belt is filled by bodies originating inside of 3 AU, and the outer belt is filled with bodies originating from between and beyond the giant planets (which are hereafter referred to as 'primitive' bodies).

arXiv.org > astro-ph > arXiv:1801.05456

Astrophysics > Earth and Planetary Astrophysics

The Delivery of Water During Terrestrial Planet Formation

David P. O'Brien, Andre Izidoro, Seth A. Jacobson, Sean N. Raymond, David C. Rubie

(Submitted on 16 Jan 2018 (v1), last revised 10 Feb 2018 (this version, v2))

The planetary building blocks that formed in the terrestrial planet region were likely very dry, yet water is comparatively abundant on Earth. We review the various mechanisms proposed ... incorporation of water into th... mechanisms have difficulties. ... efficiency is very low, such tha... accretion of material from bey... growing. Two main scenarios... disk of planetesimals and em... scenario, where early inward... planet region, where it can be... Tack scenario provides a bett... discrepancy may be reduced... implications for water deliver...

Comments: Accepted Jan 17, 2... Space Science Seri...

Water delivery by pebble accretion to rocky planets in habitable zones in evolving disks

Shigeru Ida, Takeru Yamamura and Satoshi Okuzumi

A&A, 624 (2019) A28

Published online: 03 April 2019

DOI: 10.1051/0004-6361/201834556

The Carbonaceous / Non-Carbonaceous Divide

The great isotopic dichotomy of the early Solar System

Thomas S. Kruijer[1]*, Thorsten Kleine[2] and Lars E. Borg[1]

The isotopic composition of meteorites and terrestrial planets holds important clues about the earliest history of the Solar System and the processes of planet formation. Recent work has shown that meteorites exhibit a fundamental isotopic dichotomy between non-carbonaceous (NC) and carbonaceous (CC) groups, which most likely represent material from the inner and outer Solar System, respectively. Here we review the isotopic evidence for this NC–CC dichotomy, discuss its origin and highlight the far-reaching implications for the dynamics of the solar protoplanetary disk. The NC–CC dichotomy combined with the chronology of meteorite parent-body accretion mandate an early and prolonged spatial separation of inner (NC) and outer (CC) disk reservoirs, lasting between ~1 and ~4 Myr after Solar System formation. This is most easily reconciled with the early and rapid growth of Jupiter's core, inhibiting substantial exchange of material from inside and outside its orbit. The growth and migration of Jupiter also led to the later implantation of CC bodies into the inner Solar System and, therefore, can explain the co-occurrence of NC and CC bodies in the asteroid belt, and the delivery of volatile and water-rich CC bodies to the terrestrial planets.

Meteorites exhibit notable isotope anomalies for elements such as O, Cr and Ti (note that the O isotope anomalies are not nucleosynthetic in origin, but nevertheless are indicative of spatial or temporal changes of solid material in the disk[12]). As such, it is no surprise that the NC–CC dichotomy was first recognized based on isotope anomalies for these three elements[8]. The dichotomy is most clearly observed when different isotope anomalies (for example, ^{54}Cr versus ^{50}Ti) are plotted against each other (Fig. 1). In spite of isotope variations among bulk meteorites within each reservoir, there is a clear 'gap' between the NC and CC reservoirs, indicating that there has not been substantial mixing of NC and CC materials during the formation of meteorites. Subsequent studies demonstrated that the NC–CC dichotomy extends to other elements, such as Ni (refs. [13,14]; Fig. 1d) and Mo (refs. [6,9,15,16]; Fig. 2a). Molybdenum is especially useful in identifying the NC–CC dichotomy because it allows anomalies of distinct origins to be distinguished and because, unlike Ti and Cr, the isotopic composition of Mo can be analysed in essentially all meteorites. Specifically, the heterogeneous distribution of carriers enriched in nuclides produced in the slow neutron capture process (s-process)

NATURE ASTRONOMY REVIEW ARTICLE

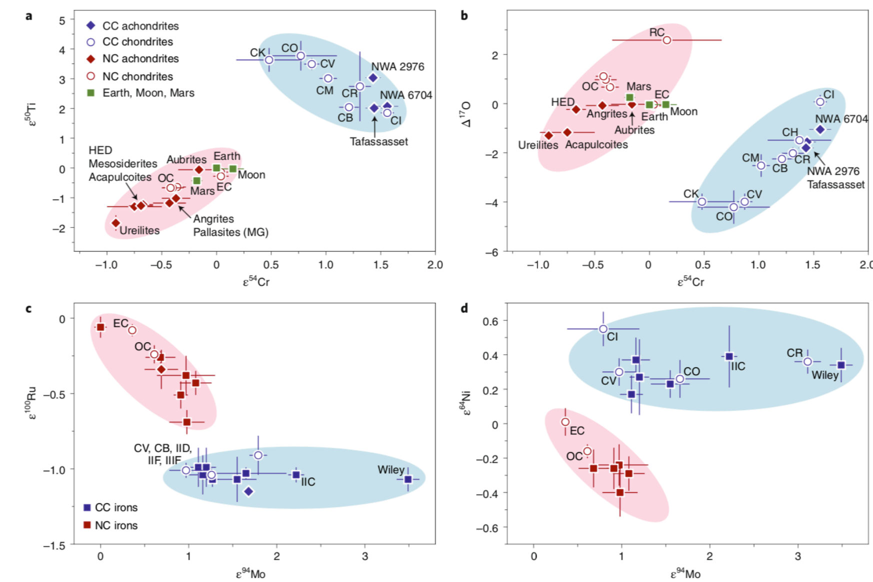


Fig. 1 | NC–CC meteorite dichotomy inferred from isotopic signatures of bulk meteorites. a–d, ε^{50}Ti versus ε^{54}Cr (**a**), Δ^{17}O versus ε^{54}Cr (**b**), ε^{100}Ru versus ε^{94}Mo (**c**), ε^{64}Ni versus ε^{94}Mo (**d**). Note that 1 ε-unit represents the 0.01% deviation (and 1 δ-unit the 0.1% deviation) in the isotopic ratio of a sample relative to terrestrial rock standards. Mass-independent O isotope variations are expressed in Δ^{17}O ($\Delta^{17}O \equiv \delta^{17}O - 0.52\delta^{18}O$, where 0.52 is the slope of mass-dependent mass fractionation). Note that Δ^{17}O variations are not nucleosynthetic in origin, but probably reflect photochemical processes in the molecular cloud or the solar nebula[12]. Errors bars denote external uncertainties (2σ) reported in respective studies. OC, ordinary chondrites; EC, enstatite chondrites; RC, rumuruti chondrites; HED, howardites, eucrites, diogenites; MG, Main Group. The isotopic data plotted here are summarized and tabulated in refs. [18,56].

The Carbonaceous / Non-Carbonaceous Divide

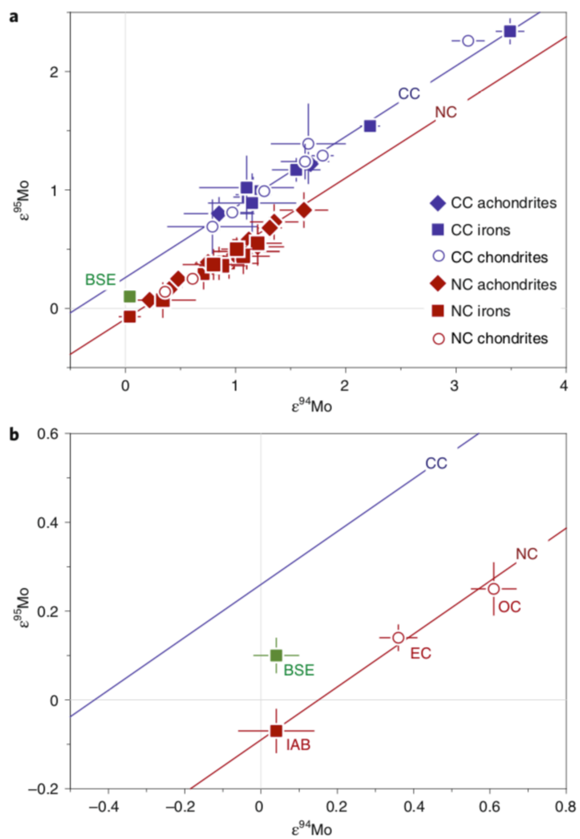
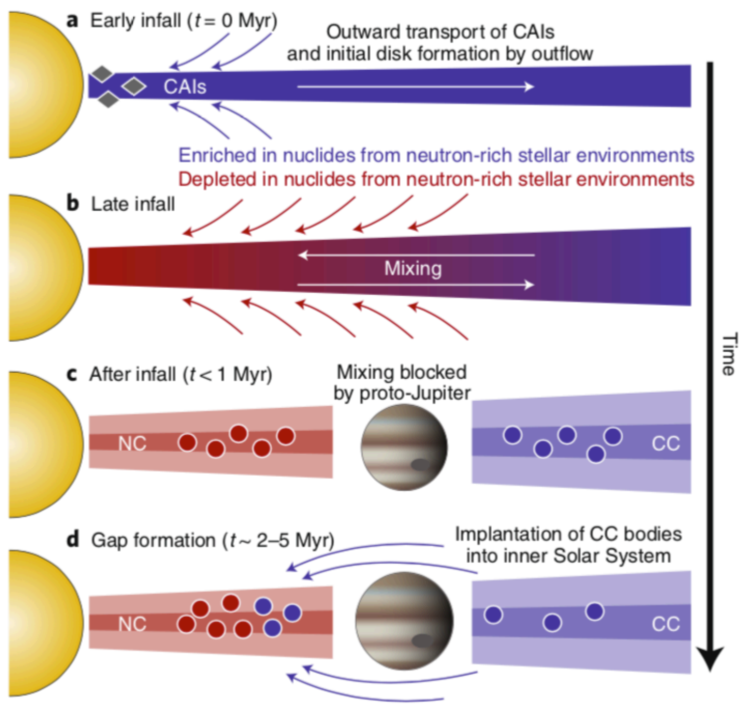


Fig. 2 | Molybdenum isotope dichotomy of meteorites. a, ε^{95}Mo versus ε^{94}Mo data for bulk meteorites. NC (red) and CC (blue) meteorites define two parallel s-process mixing lines with identical slopes, but distinct intercept values[6,9,18]. The offset between the two lines reflects an approximately uniform r-process excess in the CC reservoir relative to the NC reservoir. **b**, Zoomed-in version of **a** illustrating that the BSE plots between the NC and CC lines. Plotted NC and CC lines are based on regression results reported in ref. [18]. Error bars denote external uncertainties reported in respective studies (2σ). A summary of the Mo isotopic data shown in the figure is also given in ref. [18]. Abbreviations as given in main text and Fig. 1; group IAB non-magmatic iron meteorites are denoted 'IAB'. Figure reproduced with permission from ref. [18], Springer Nature Ltd.

The Carbonaceous / Non-Carbonaceous Divide

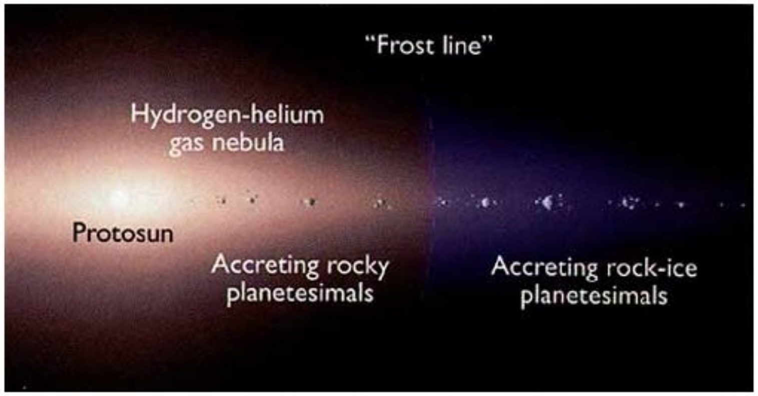
Linked to the formation of Jupiter?



The idea, *roughly*

Inward of snowline

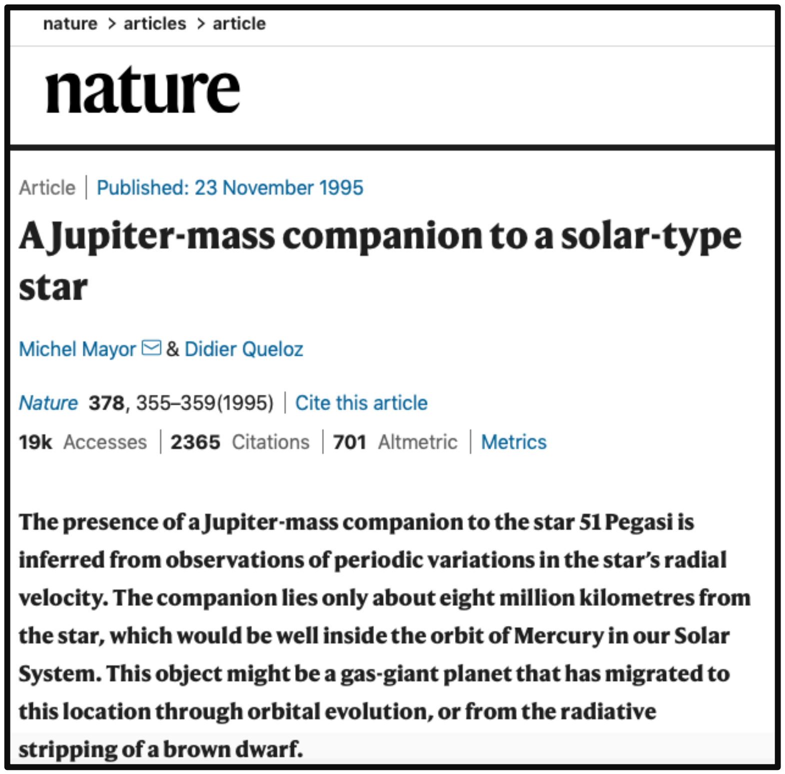
Rocks only
(small)



Outward of snowline

Ice comes to aid!
Growing big
icy/rocky cores.

The Surprise



nature > articles > article

nature

Article | Published: 23 November 1995

A Jupiter-mass companion to a solar-type star

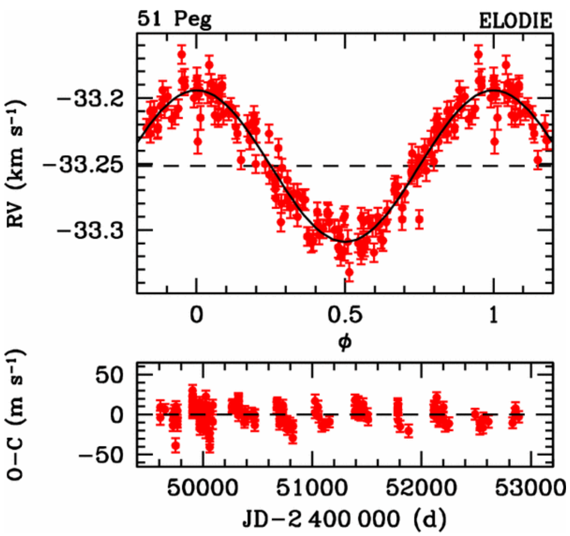
Michel Mayor & Didier Queloz

Nature **378**, 355–359(1995) | Cite this article

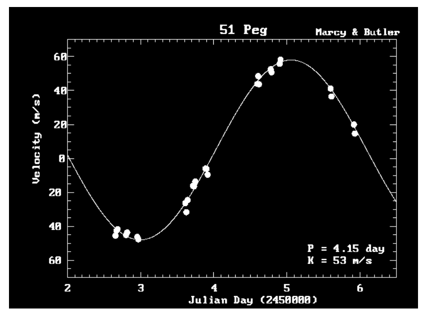
19k Accesses | **2365** Citations | **701** Altmetric | Metrics

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

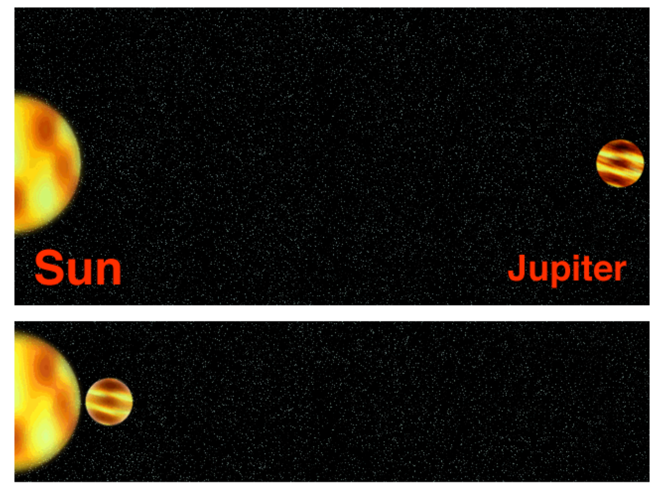
The Surprise



Original detection
(Mayor & Queloz 1995)



Confirmation
(Marcy & Butler 1995)



A **HOT** Jupiter!

a = 0.052 AU
P = 4.23 days
M sin I = 0.468 M_J

Planet Migration
was not new…

ApJ, 241, 425 (October 1, 1980)

DISK-SATELLITE INTERACTIONS

Peter Goldreich
California Institute of Technology
AND
Scott Tremaine
Institute for Advanced Study, Princeton, New Jersey

Received 1980 January 7; accepted 1980 April 9

ABSTRACT

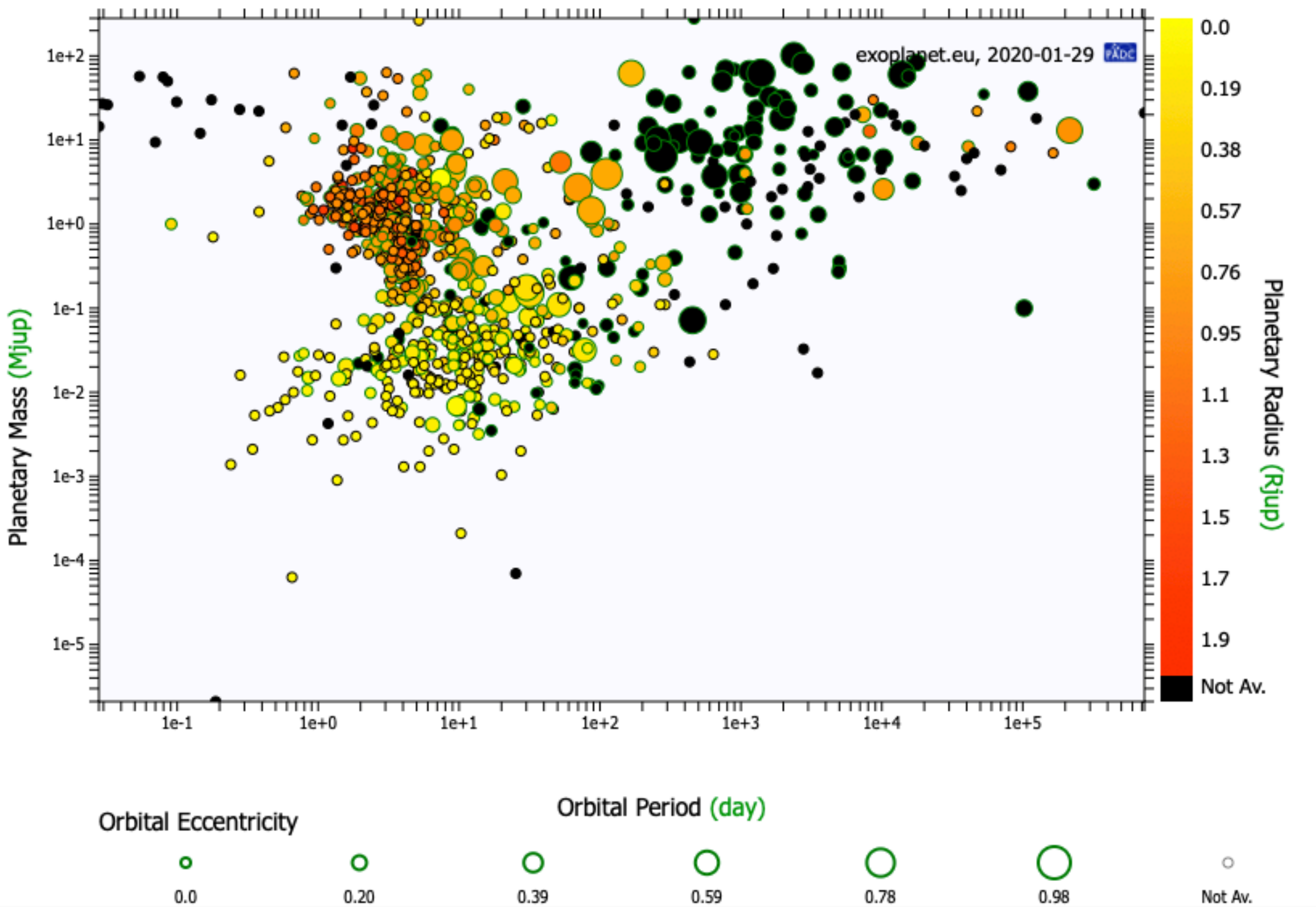
We calculate the rate at which angular momentum and energy are transferred between a disk and a satellite which orbit the same central mass. A satellite which moves on a circular orbit exerts a torque on the disk only in the immediate vicinity of its Lindblad resonances. The direction of angular momentum transport is outward, from disk material inside the satellite's orbit to the satellite and from the satellite to disk material outside its orbit. A satellite with an eccentric orbit exerts a torque on the disk at corotation resonances as well as at Lindblad resonances. The angular momentum and energy transfer at Lindblad resonances tends to increase the satellite's orbit eccentricity whereas the transfer at corotation resonances tends to decrease it. In a Keplerian disk, to lowest order in eccentricity and in the absence of nonlinear effects, the corotation resonances dominate by a slight margin and the eccentricity damps. However, if the strongest corotation resonances saturate due to particle trapping, then the eccentricity grows.

We present an illustrative application of our results to the interaction between Jupiter and the protoplanetary disk. The angular momentum transfer is shown to be so rapid that substantial changes in both the structure of the disk and the orbit of Jupiter must have taken place on a time scale of a few thousand years.

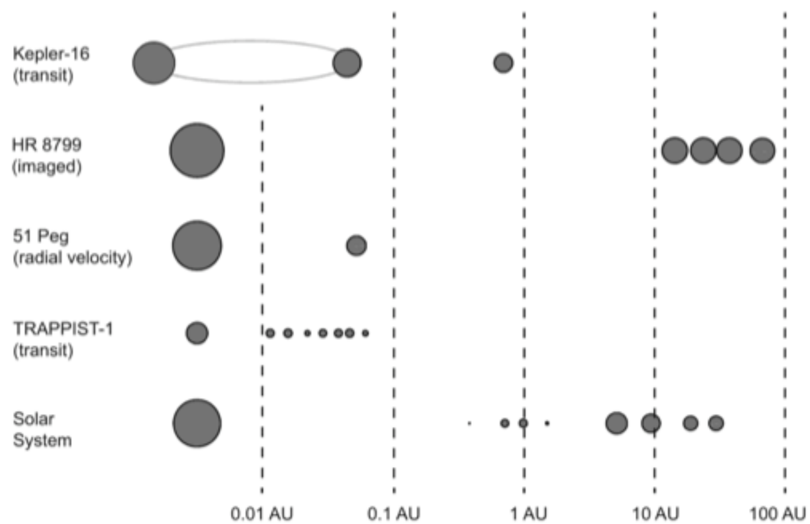
Subject headings: hydrodynamics — planets: Jupiter — planets: satellites — solar system: general

discovered 15 years earlier... by theorists!

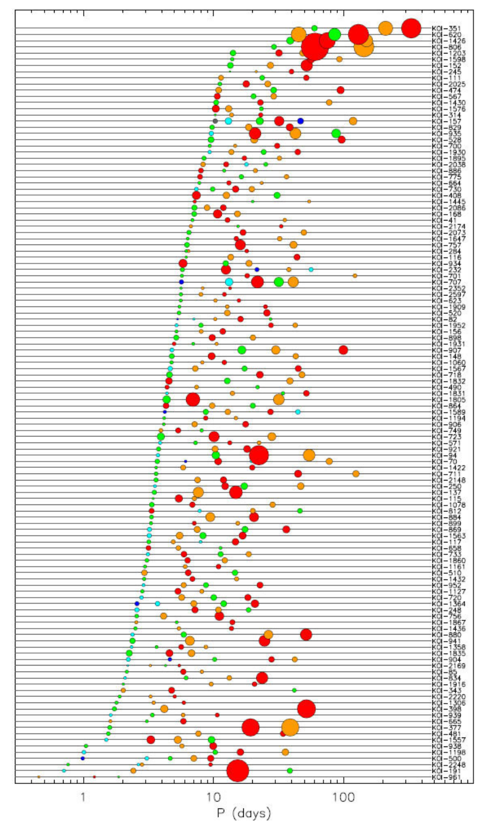
The Exoplanet Landscape

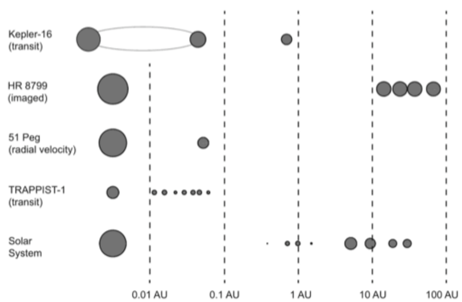


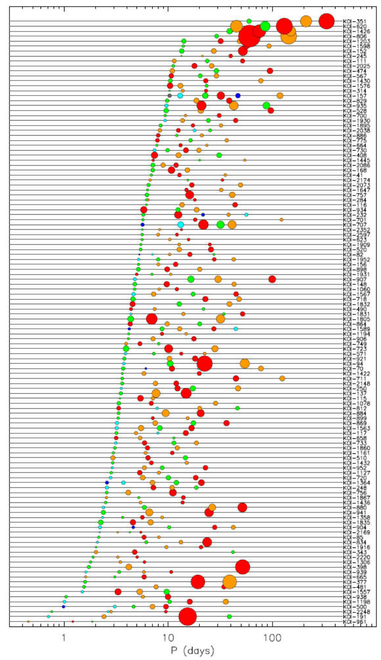
Different Architectures



Kepler multi-planet systems
(Fabricky+ 2014)




Kepler-16
(transit)
HR 8799
(imaged)
51 Peg
(radial velocity)
TRAPPIST-1
(transit)
Solar
System
0.01 AU
0.1 AU
1 AU
10 AU
100 AU


1
10
100
P (days)