XVIII IAG/USP Advanced School on Astrophysics (AWSA-II): Exoplanet Science in a Solar System Context

Andrew Szentgyorgyi Harvard-Smithsonian Center for Astrophysics

Universidad de Sao Paulo, 26 Feb 2018

IAG/USP XVIII * GMT Science and Instrumentation * ASz *26 Feb 2018

Talk Outline

- Exoplanet science in a historical context
- Exoplanet science today
- Solar System context
- Exoplanet science today, in a little more detail
- Orbital resonance
- Intro to planet formation

Exoplanet: A planet orbiting a star other than the Sun

Planet: Less massive than a star, more massive than a planetesimal.

- No internal nuclear burning, <u>ever</u> (but may be selfluminous from gravitational contraction).
- Shaped by gravity (spherical) rather than agglutination.
- Formed in protoplanetary disk.

Exoplanet Science- A Historical Context

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Paleohistory of Exoplanet Science:

- Giordano Bruno (1584) speculates on the inevitability that <u>Earth-like</u> exoplanets must exist.
- Newton (1713) asserts that exo-solar systems will not only harbor exo-Earths, but will be identical to the Solar System.
- Struve (1952) argues that there is no reason exoplanets should not be much closer to a host star than Mercury is to the Sun.
- Further proposes that super-Jupiters in close orbits should be detectable by Doppler spectroscopy of host star and forground extinction during transits.

"This space we declare to be infinite... In it are an infinity of worlds of the same kind as our own."

- De l'infinito universo et mondi (1584)

"And if the fixed stars are the centres of similar systems, they will all be constructed according to a similar design and subject to the dominion of *One*."."

- Principia, 2nd Edition (1713)

"But there seems to be no compelling reason why hypothetical stellar planets should not, in some instances, be closer to their parent stars than is the case in the solar system [sic]." *The Observatory*, **72**, 1952

PROPOSAL FOR A PROJECT OF HIGH-PRECISION STELLAR RADIAL VELOCITY WORK

By Otto Struce

The Observatory, 72, 1952

Lost in the Wilderness

- W.S. Jacob "discovers" a spurious planet orbiting 70 Oph by visually astrometry from the Madras Observatory. Rejected on stability grounds and later observationally.
- In the Observatory article, Struve asserts exoplanets have been discovered. 61 Cyg planet was 16 M₂₁ "discovered" by photographic astrometry.
- In the 1950's & 60's Peter van de Kamp make the claims Barnard's star hosts 1.1 M₂₄ &0.8 M₂₄ exoplanets. Subsequently disproved.
- Campbell *et al.* (1988 γ Ceph) & Latham *et al.* (1989 - HD114762) finally discover exoplanets, but data is not definitive and confirmation not made for 2 decades.

There is, then, some positive evidence in favour of the existence of a planetary body in connexion with this system, enough for us to pronounce it highly probable …

MNRAS, 1855

"K. A. Strand's discovery of a planet-like companion in the system 61 Cygni …" *-The Observatory*, **72**, 1952

Alternate Dynamical Analysis of Barnard's Star

PETER VAN DE KAMP

Sproul Observatory, Swarthmore College, Swarthmore, Pennsylvania

(Received 12 May 1969)

Astronomical Journal, 74, 1969

letters to nature

Nature 339, 38 - 40 (04 May 1989); doi:10.1038/339038a0

The unseen companion of HD114762: a probable brown dwarf

DAVID W. LATHAM*, TSEVI MAZEH[†], ROBERT P. STEFANIK*, MICHEL MAYOR[‡] & GILBERT BURKI

The Watershed

 1992 - Wolszczan & Frail discover several Earth-mass planets orbiting pulsar PSR B1257+12 by pulsar timing.

article

Nature 378, 355 - 359 (23 November 1995); doi:10.1038/378355a0

A Jupiter-mass companion to a solar-type star

MICHEL MAYOR & DIDIER QUELOZ

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

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 begin ~year later. 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.

- 1999 v And is found to be a multiple star system (Lissauer).
- 1999 Charbonneau *et al.* & Henry *et al.* detect transit of HD408458b. The radius of an exoplanet is measured. Mass (not *m Sin(i)*) is measured by PRV.

exoplanet candidates measured.

1999 – β Pic b, Fomalhaut b &

HR8977 b,c,d & e are imaged.

2002 - Evonlanets are discovered by

ams.

2003-BLG-235)

on launches and

- 2014 Kepler Discovers first Earthsized, habitable-zone (HZ) planet Kepler-186f.
- 2016 Trappist 1 system has multiple HZ planets (3).

Exoplanet Science Today

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Exoplanet Populations



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Many exoplanets are extremely small



Many exoplanets with radii smaller than the Earth have been discovered, however their masses cannot be measured with currently available telescopes.

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Kepler Habitable Zone Planets



Many exoplanets have been discovered within the exoplanetary Habitable Zones (HZ's) where the surface temperature is "right" for water to be liquid (not vapor or solid).

Not All Interesting Exoplanets are Discovered by Space Missions

Trappist-1 System



- Spectral Type: M8V
- M_V ~ 18.8
- 7 terrestrial, temperate planets
- 3 (e,f,g) in habitable zone
- Nearest neighbor resonances: 8/5, 5/, 3/2, 3/2, 4/3, and 3/2

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Trappist North, Oukaïmden Observatory, Morocco



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Planets vs. Stars: Stars Don't Burn Nuclear Fuel



Star	Mass
GL 229A	607 ${ m M}_{ m 24}$ (0.58 ${ m M}_{\odot}$)
Teide 1	57 M ₂
GL 229B	$21 - 52 M_{21}$
Wise 1828	5-20 M ₂₁

Planets vs. Stars: Stars Have Disks, Planets Form in Them



Planets vs. Planetesimals: Planets are Spherical, Planetesimal May Not Be



Ida

Pluto

Earth

Gravity dominates the morphology of planets. If Pluto is Spherical, Why is it a Planetesmial?

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A Solar System Context for Exoplanet Science

The "old" Solar system, i.e. the 9 planets we knew on October 5, 1995



Bode's "Mysterious" Law

- With such a small sample, planetary science was (mostly) reduced to numerology for 2 ¹/₂ centuries ...
- Bode's (really Titius') "law":
 - a = 4 + x (a = orbital semimajor axis)
 - Scaled to a_{Earth}= 10
 - x = 0, 3, 6, 12, 24, 48 for other planets
- "Mysterious" doubling of values.

See Murray & Dermont **Solar System Dynamics** for extended discussion of likelihood of Bode's law





Johann Daniel Titius 1729 - 1796



Johann Elert Bode 1749 – 1826)

Solar system fact-sheet

	Sun	Mercury	Venus	Earth	Moon	Mars	Ceres	Jupiter	Saturn	Uranus	Neptune	Pluto I	Makemake	Haumea	Eris
	star (G2V)	planet	planet	planet	satellite	planet	dwarf planet	planet	planet	planet	planet	dwarf planet	dwarf planet	dwarf planet	dwarf planet
Diameter (km)	1,392,000	4,879.4	12,103.6	12,742	3,476.3	6,792.4	974.6	14,2984	120,536	51,118	49,528	2,390	1,500	1,500	2,600
Mass (10 ²⁴ kg)	1,989,100	0.33	4.87	5.97	0.073	0.64	0.000943	1898.6	568.46	86.81	102.43	0.013	0.0004	0.0042	0.0167
Temperature, min (°C)	5,505	-173	462	-89	-173	-87	-106	-161	-189	-224	-218	-240	-243	-241	-243
Temperature, max (°C)	17,000,000	427	462	58	117	-5	-106	-161	-189	-216	-218	-218	-238	-241	-218
Rotation period (days)	25.1	58.6	-243.0	1.0	27.3	1.0	0.4	0.4	0.4	-0.7	0.7	-6.4	?	0.163	0.3
Axial tilt (°)		0.04	177.3	23.4	6.7	25.2	3	3.1	26.7	97.8	28.3	119.6	?	?	?
Surface gravity (m.s ²)	274.0	3.7	8.9	9.8	1.6	3.7	0.3	24.8	9.0	8.7	11.2	0.6	~0.5	0.4	~0.8
Escape velocity (km.s-1)	617.7	4.3	10.5	11.2	2.38	5.0	0.5	59.5	35.5	21.3	23.5	1.2	~0.8	0.84	?
Surface area (10 ⁶ km ²)	6,087,700	75	460	510	37.9	145	3	62,180	42,700	8,116	7,641	18	~7		21
Volume (1012 km3)	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density (kg.m ³)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo		0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	-26.7	-1.9	-4.6		-12.9	-2.9	6.9	-2.9	-0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (")	1,962.0	13.0	66.0		2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings		no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10 ⁶ km)	—	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10 ⁶ km)		69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity		0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)						1801				1781	1846	1930	2005	2004	2003



	Solar system fact-sheet																
		Merc	cury	Venus	; E	arth	Моо	n I	Mars	Jup	iter	Satur	n U	ranus	Nept	une	Pluto
Diame	eter (km)	4,87	79.4	12,103	3.6 1	2,742	3,476	6.3	6,792.4	14,2	2984	120,53	36 51	1,118	49,52	28	2,390
Mass	(10²⁴ kg)	0.33	3	4.87	5	.97	0.073	3 (0.64	189	8.6	568.46	6 86	5.81	102.4	3	0.013
	Axial tilt (°)	_	0.04	177.3	23.4	6.7	25.2	3	3.1	26.7	97.8	28.3	119.6	?	?	?	
	Surface gravity (m.s ²)	274.0	3.7	8.9	9.8	1.6	3.7	0.3	24.8	9.0	8.7	11.2	0.6	~0.5	0.4	~0.8	
	Escape velocity (km.s ⁻¹)	617.7	4.3	10.5	11.2	2.38	5.0	0.5	59.5	35.5	21.3	23.5	1.2	~0.8	0.84	?	
Surface area (10 ^s km²) 6,087,700 75 460 510 37.9 145 3 62,180 42,700 8,116 7,641 18 Volume (10 ¹² 1,412,200 0.06 0.9 1.1 0.02 0.16 0.0005 1431 827 68 63 0.007													~7		21		
	Volume (10^{12}) 1,412,200 0.06 0.9 1.1 0.02 0.16 0.0005 1431 827 68 63 0.007 ~0.002 0.009 Density (kg m ³) 1.41 5.41 5.19 5.51 3.35 3.93 1.89 1.33 0.69 1.27 1.64 1.86 ~2 ~3 ~2																
	Albedo	1.41	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.03	0.51	0.41	0.58	2	0.6	0.86	
	Annarent magnitude (V)	-26.7	_19	-4.6	0.07	_12.9	-29	6.9	-29	_0.2	5.3	7.8	13.7	16.7	17.5	18 7	
	Angular diameter, max. (")	1.962.0	13.0	66.0		2.046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04	
	Rings		no	no	no	no	no	no	ves	ves	ves	ves	no	no	no	no	
	Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1	
	Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
	Perihelion (10 ⁶ km)		46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650	
	Aphelion (10 ⁶ km)		69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600	
1000	Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
	Eccentricity		0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44	
100 C	Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2	
	Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,60	0
	Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4	
12.0	Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	
	Discovery (year)						1801		—		1781	1846	1930	2005	2004	2003	
	33			·	0						4		2		-		

If $M_{\oplus} = 1$, $M_{\phi} = 0.05 < M_{SSPlanets} < M_{21} = 300$

					Solar s	syster	n fact	t-shee	et							
	Mere	cury	Venus	E	arth	Моо	n I	Mars	Jup	iter	Satur	n U	ranus	Nept	une	Pluto
Diameter (km)	4,87	79.4	12,103	.6 12	2,742	3,476	5.3 6	6,792.4	14,2	2984	120,53	36 51	,118	49,52	8	2,390
Mass (10 ²⁴ kg)	0.33	3	4.87	5.	.97	0.073	3 ().64	189	8.6	568.46	6 86	.81	102.4	3	0.013
Density (kg.m ³)	5.4	1	5.19	5	.51	3.35	3	3.93	1.33	3	0.69	1.	27	1.64		1.86
Axial tilt (°) Surface gravity (m.s²) Escape velocity (km.s⁻¹)	 274.0 617.7	0.04 3.7 4.3	177.3 8.9 10.5	23.4 9.8 11.2	6.7 1.6 2.38	25.2 3.7 5.0	3 0.3 0.5	3.1 24.8 59.5	26.7 9.0 35.5	97.8 8.7 21.3	28.3 11.2 23.5	119.6 0.6 1.2	? ~0.5 ~0.8	? 0.4 0.84	? ~0.8 ?	
Surface area (10 ⁶ km²) Volume (10 ¹²	6,087,700 1,412,200	75 0.06	460 0.9	510 1.1	37.9 0.02	145 0.16	3 0.0005	62,180 1431	42,700 827	8,116 68	7,641 63	18 0.007	~7 ~0.002		21 0.009	
Density (kg.m ³) Albedo	1.41	5.41 0.11	5.19 0.65	5.51 0.37	3.35 0.12	3.93 0.15	1.89 0.09	1.33 0.52	0.69 0.47	1.27 0.51	1.64 0.41	1.86 0.58	~2 ?	~3 0.6	~2 0.86	
Apparent magnitude (V) Angular diameter, max. (")	–26.7 1,962.0	-1.9 13.0	-4.6 66.0	_	-12.9 2,046	-2.9 25.1	6.9 0.8	-2.9 50.1	-0.2 20.1	5.3 4.1	7.8 2.4	13.7 0.1	16.7 0.02	17.5 0.02	18.7 0.04	
Rings Satellites	billions!	no 0	no 0	no 1	no no	no 2	no 0	yes 63	yes 60	yes 27	yes 13	no 3	no O	no 2	no 1	
Orbits the: Perihelion (10 ⁶ km)	Milky Way	Sun 46	Sun 107.5	Sun 147.1	Earth 0.363	Sun 206.7	Sun 381.4	Sun 740.5	Sun 1,352.6	Sun 2,741.3	Sun 4,452.9	Sun 4,436.8	Sun 5,760.8	Sun 5,260	Sun 5,650	(
Semimajor axis (AU)		0.4	0.7	1.0	0.408	1.5 0.09	2.8 0.08	5.2	9.6	3,003.0 19.2 0.05	4,554 30.1 0.01	39.5 0.25	45.8	43.3	67.7 0.44	
Inclination (°)		7.0	3.4 224.7	0	5.1 27.3	1.9 687.0	10.6 1.679.8	1.3 4.331.6	2.5 10.832.3	0.8	1.8	17.1 90.613	29.0 113.183	28.2 104.234	44.2	0
Orbital period (years) Orbital velocity (km,s ⁻¹)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7 9.7	84.3 6.8	164.8 5.4	248.1 4.7	309.9 4.4	285.4 4.5	557.4 3.4	
Discovery (year)		_		_		1801		_		1781	1846	1930	2005	2004	2003	



					Solar	syster	n fact	-shee	et							
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Surface gravity (m.s ²)	274.0	3.7	8.9	9.8	1.6	3.7	0.3	24.8	9.0	8.7	11.2	0.6	~0.5	0.4	~0.8	
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Volume (10 ¹²	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009	
Density (kg.m ³)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2	
Albedo		0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86	
Apparent magnitude (V)	-26.7	-1.9	-4.6		-12.9	-2.9	6.9	-2.9	-0.2	5.3	7.8	13.7	16.7	17.5	18.7	
Angular diameter, max. (")	1,962.0	13.0	66.0		2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04	
Rings		no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no	
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1	
Orbits the:	Milky Wa	y Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Perihelion (10 ⁶ km)		46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650	
Aphelion (10 ⁶ km)		69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600)
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
Eccentricity		0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44	
Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2	
Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,60	00
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4	
Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	
Discovery (year)						1801				1781	1846	1930	2005	2004	2003	



						Solar s	syster	nac	t-snee	:L							
		Me	rcury	Venus	; E	arth	Моо	n I	Mars	Jup	iter	Satur	n U	ranus	Nept	une	Pluto
Diameter (km	1)	4,	879.4	12,103	3.6 1	2,742	3,476	6.3 6	6,792.4	14,2	2984	120,53	36 51	,118	49,52	28	2,390
Mass (10 ²⁴ kg	g)	0.	33	4.87	5	.97	0.073	3 ().64	189	8.6	568.46	6 86	5.81	102.4	3	0.013
Density (kg.n	n³)	5.	41	5.19	5	5.51	3.35	3	3.93	1.33	3	0.69	1.	27	1.64		1.86
Axial tilt (' Surface g Escape ve	') ravity (m.s²) elocity (km.s⁻¹)	 274.0 617.7		R	loc lar	ky nets				26.7 9.0 35.5	97.8 8.7 21.3	28.3 11.2 23.5	119.6 0.6 1.2	? ~0.5 ~0.8	? 0.4 0.84	? ~0.8 ?	
Surface a	rea (10 ⁶ km²)	6,087	0 0.06	0.0	11	0.02	0.16	0 0005)	42,700	8,116	7,641	18	~7		21	
Density (k	a.m ³)	1,412,20	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2	
Albedo			0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86	
Apparent	magnitude (V)	-26.7	-1.9	-4.6	—	-12.9	-2.9	6.9	-2.9	-0.2	5.3	7.8	13.7	16.7	17.5	18.7	
Angular d	iameter, max. (")	1,962.0	13.0	66.0	_	2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04	
Rings			no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no	
Satellites		billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1	
Orbits the	:	Milky Wa	y Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Perihelion	i (10 ⁶ km)	—	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650	
Aphelion	(10 ⁶ km)		69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600	
Semimajo	r axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
Eccentrici	ty		0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44	
Inclination	1 (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2	
Orbital pe	riod (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,60	0
Orbital pe	riod (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4	
Orbital ve	locity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	
Discovery	(year)	_					1801				1781	1846	1930	2005	2004	2003	

0



Rocky Planets



	Solar system lact-sneet															
	Me	rcury	Venus	5 E	arth	Моо	n I	Nars	Jup	iter	Satur	n U	ranus	Nept	une	Pluto
Diameter (km)	4,8	879.4	12,103	3.6 1	2,742	3,476	5.3 E	6,792.4	14,2	984	120,53	36 51	,118	49,52	8	2,390
Mass (10 ²⁴ kg)	0.3	33	4.87	5	.97	0.073	3 ().64	189	8.6	568.46	6 86	5.81	102.4	3	0.013
Density (kg.m ³)	5.	41	5.19	5	.51	3.35	3	3.93	1.33	}	0.69	1.	27	1.64		1.86
Axial tilt (°) Surface gravity (m.s²) Escape velocity (km.s ⁻¹) Surface area (10 ⁶ km²)	274.0 617.7 6,087		R P	loc Iar	ky iets				Ga	is C	Gian	ts	? ~0.5 ~0.8 ~7	? 0.4 0.84	? ~0.8 ? 21	
Volume (10 ¹²	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009	
Density (kg.m ³)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2	
Albedo		0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86	
Apparent magnitude (V)	-26.7	-1.9	-4.6	—	-12.9	-2.9	6.9	-2.9	-0.2	5.3	7.8	13.7	16.7	17.5	18.7	
Angular diameter, max. (")	1,962.0	13.0	66.0		2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04	
Rings		no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no	
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1	
Orbits the:	Milky Way	y Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Perihelion (10 ⁶ km)		46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650	
Aphelion (10 ⁶ km)		69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600	
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
Eccentricity		0.21	0.01	0.02	0.06	0.09	80.0	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44	
Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2	
Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,60	0
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4	
Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	
Discovery (year)						1801				1781	1846	1930	2005	2004	2003	







					Solar s	syster	n fact	-shee	et						
	Me	rcury	Venus	s E	arth	Моо	n M	lars	Jup	iter	Satur	n U	ranus	Nept	une Pluto
Diameter (km)	4,8	379.4	12,103	3.6 1	2,742	3,476	6.3 6	,792.4	14,2	2984	120,53	36 5 [.]	1,118	49,52	2,390
Mass (10 ²⁴ kg)	0.3	33	4.87	5	.97	0.073	3 0	.64	189	8.6	568.46	5 86	5.81	102.4	3 0.013
Density (kg.m ³)	5.4	41	5.19	5	.51	3.35	3	3.93	1.33	3	0.69	1.	.27	1.64	1.86
Axial tilt (°) Surface gravity (m.s²) Escape velocity (km.s ⁻¹) Surface area (10 ⁶ km²) Volume (10 ¹²	274.0 617.7 6,087 1,412,200	0 0.05	R P	loc Ian	ky iets	0.16	0.0005)	Ga		Gian	ts	Ce	e Gi	ants
Density (kg.m ³)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo		0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	-26.7	-1.9	-4.6		-12.9	-2.9	6.9	-2.9	-0.2	5.3	7.8	13.7	16.7	17.5	18.7
Angular diameter, max. (*)	1,962.0	13.0	66.0		2,046	25.1	0.8	50.1	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Rings		no	no	no	no	no	no	yes	yes	yes	yes	no	no	no	no
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	/ Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perinelion (10° km)		46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10° km)		0.4	108.9	152.1	0.406	249.2	447.8	810.0	1,514.5	3,003.6	4,554	7,370	7,939.7	1,708	14,600
Semimajor axis (AO)		0.4	0.01	1.0	0.003	0.00	2.0	0.05	9.0	19.2	0.01	0.25	40.0	43.3	011
Inclination (°)		7.0	3.4	0.02	5.1	1 9	10.6	13	2.5	0.05	1.8	17 1	29.0	28.2	44 2
Orbital pariod (days)		88.0	224 7	365.3	27.3	697.0	1 679.8	1.331 6	10 832 3	20 700	60 100	90 613	112 192	104 224	203 600
Orbital period (days)		0.0	0.6	1 0	0.1	1 9	4.6	11 9	29.7	84 3	164.8	248 1	309 9	285 4	557 A
Orbital velocity (km s ⁻¹)		47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)						1801				1781	1846	1930	2005	2004	2003



Solar system fact-sneet																
	Merc	ury	Venus	E	arth	Моо	n l	Mars	Jup	iter	Satur	n Uı	ranus	Nept	une	Pluto
Diameter (km)	4,87	9.4	12,103	.6 1	2,742	3,476	.3 (6,792.4	14,2	2984	120,53	36 51	,118	49,52	28	2,390
Mass (10 ²⁴ kg)	0.33	ł	4.87	5	.97	0.073	. (0.64	189	8.6	568.46	6 86	.81	102.4	3	0.013
Density (kg.m ³)	5.41		5.19	5	.51	3.35	;	3.93	1.33	3	0.69	1.:	27	1.64		1.86
Satellites	0		0	1		no		2	63		60	27	,	13		×
Axial tilt (°) Surface gravity (m.s²) Escape velocity (km.s⁻1)	 274.0 617.7	0.04 3.7 4.3	177.3 8.9 10.5	23.4 9.8 11.2	6.7 1.6 2.38	25.2 3.7 5.0	3 0.3 0.5	3.1 24.8 59.5	26.7 9.0 35.5	97.8 8.7 21.3	28.3 11.2 23.5	119.6 0.6 1.2	? ~0.5 ~0.8	? 0.4 0.84	? ~0.8 ?	5
Surface area (10 ⁶ km²) Volume (10 ¹²	6,087,700 1,412,200	75 0.06	460 0.9	510 1.1	37.9 0.02	145 0.16	3 0.0005	62,180 1431	42,700 827	8,116 68	7,641 63	18 0.007	~7 ~0.002		21 0.009	
Density (kg.m ³) Albedo	1.41	5.41 0.11	5.19 0.65	5.51 0.37	3.35 0.12	3.93 0.15	1.89 0.09	1.33 0.52	0.69 0.47	1.27 0.51	1.64 0.41	1.86 0.58	~2 ?	~3 0.6	~2 0.86	
Apparent magnitude (V) Angular diameter, max. (")	–26.7 1,962.0	-1.9 13.0	-4.6 66.0		-12.9 2,046	-2.9 25.1	6.9 0.8	-2.9 50.1	-0.2 20.1	5.3 4.1	7.8 2.4	13.7 0.1	16.7 0.02	17.5 0.02	18.7 0.04	
Rings Satellites	billions!	no 0 Sun	no 0 Suo	no 1	no no Forth	no 2 Suo	no 0 Sun	yes 63	yes 60	yes 27 Sup	yes 13	no 3 Sun	no 0 Sun	no 2	no 1 Sun	
Perihelion (10 ⁶ km) Aphelion (10 ⁶ km)		46 69.8	107.5 108.9	147.1 152.1	0.363 0.406	206.7 249.2	381.4 447.8	740.5 816.6	1,352.6 1,514.5	2,741.3 3,003.6	4,452.9 4,554	4,436.8 7,376	5,760.8 7,939.7	5,260 7,708	5,650 14,600	
Semimajor axis (AU) Eccentricity		0.4 0.21	0.7 0.01	1.0 0.02	0.003 0.06	1.5 0.09	2.8 0.08	5.2 0.05	9.6 0.06	19.2 0.05	30.1 0.01	39.5 0.25	45.8 0.16	43.3 0.19	67.7 0.44	
Inclination (°) Orbital period (days)	_	7.0 88.0	3.4 224.7	0 365.3	5.1 27.3	1.9 687.0	10.6 1,679.8	1.3 4,331.6	2.5 10,832.3	0.8 30,799	1.8 60,190	17.1 90,613	29.0 113,183	28.2 104,234	44.2 203,60	0
Orbital period (years) Orbital velocity (km.s ⁻¹) Discovery (year)		47.9	35.0	29.8	0.1 1.0	1.9 24.1 1801	4.6 17.9	11.9 13.1	9.7 9.7	84.3 6.8 1781	164.8 5.4 1846	248.1 4.7 1930	309.9 4.4 2005	285.4 4.5 2004	3.4 2003	



Earth Mars Asteroid Jupiter Saturn Uranus Eris Neptune Pluto Ida 6 . Puck . Phobos Dactyl Mimas Proteus Dysnomia 0 Charon Miranda Moon Enceladus lo Deimos + Styx, Pix, Tethys Ariel Kerberos & 14.58 Triton Hydra Dione Europa Umbriel 8 Nereid Rhea 2 Titania Oberon Scale: 1 pixel = 25 km Ganymede Titan 6 Hyperion lapetus Callisto Phoebe Earth

Selected Moons of the Solar System, with Earth for Scale

Even Planeteismals Have Moons - 243 Ida and Moon Dactyl



IAG/USP XVIII * GMT Science and Instrumentation * ASz *26 Feb 2018

					Solar	syster	n iac	t-snee	÷t							
	Merc	cury	Venus	; E	arth	Моо	n I	Mars	Jup	iter	Satur	n Ui	ranus	Nept	une	Pluto
Diameter (km) Mass (10 ²⁴ kg)	4,87 0.33	79.4 3	12,103 4.87	3.6 12 5.	2,742 .97	3,476 0.073	6.36 30	6,792.4).64	14,2 189	2984 8.6	120,53 568.46	86 51 6 86	,118 .81	49,52 102.4	8 3	2,390 0.013
Density (kg.m ³)	5.4	1	5.19	5	.51	3.35		3.93	1.33	3	0.69	1.	27	1.64		1.86
Satellites	0		0	1		no	2	2	63		60	27	,	13		X
Axial tilt (°) Surface gravity (m.s ²) Escape velocity (km.s ⁻¹) Surface area (10 ⁶ km ²) Volume (10 ¹² Density (kg.m ³) Albedo Apparent magnitude (V) Angular diameter, max. (*) Rings	274.0 617.7 6,087,700 1,412,200 1.41 	0.04	$\begin{array}{c ccccccccccccccccccccccccccccccccccc$? ~0.8 ? 21 0.009 ~2 0.86 18.7 0.04 no	5		
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1	
Orbits the: Perihelion (10 ⁶ km) Aphelion (10 ⁶ km) Semimajor axis (AU) Eccentricity Inclination (°) Orbital period (days) Orbital period (years) Orbital velocity (km.s ⁻¹) Discovery (year)		Sun 46 69.8 0.4 0.21 7.0 88.0 0.2 47.9	Sun 107.5 108.9 0.7 0.01 3.4 224.7 0.6 35.0 	Sun 147.1 152.1 1.0 0.02 0 365.3 1.0 29.8	Earth 0.363 0.406 0.003 0.06 5.1 27.3 0.1 1.0	Sun 206.7 249.2 1.5 0.09 1.9 687.0 1.9 24.1 1801	Sun 381.4 447.8 2.8 0.08 10.6 1,679.8 4.6 17.9	Sun 740.5 816.6 5.2 0.05 1.3 4,331.6 11.9 13.1	1,352.6 1,514.5 9.6 0.06 2.5 10,832.3 29.7 9.7	Sun 2,741.3 3,003.6 19.2 0.05 0.8 30,799 84.3 6.8 1781	Sun 4,452.9 4,554 30.1 0.01 1.8 60,190 164.8 5.4 1846	Sun 4,436.8 7,376 39.5 0.25 17.1 90,613 248.1 4.7 1930	Sun 5,760.8 7,939.7 45.8 0.16 29.0 113,183 309.9 4.4 2005	Sun 5,260 7,708 43.3 0.19 28.2 104,234 285.4 4.5 2004	Sun 5,650 14,600 67.7 0.44 44.2 203,60 557.4 3.4 2003	0
Ares Sa				0						-		2		-		

					Solar s	syster	n fac	ct-shee	et							
	Merc	cury	Venus	E	Earth	Моо	n	Mars	Jup	iter	Satur	n U	ranus	Nept	une	Pluto
Diameter (km) Mass (10 ²⁴ kg)	4,87 0.33	79.4 3	12,103 4.87	.6 1 5	2,742 5.97	3,476 0.073	6.3 3	6,792.4 0.64	14,2 189	2984 8.6	120,53 568.46	36 5 ⁴ 3 86	l,118 5.81	49,52 102,4	8 3	2,390 0.013
Density (kg.m ³) Satellites	5.4 ⁻ 0	1	5.19 0	5	5.51 I	3.35 no		3.93 2	1.33 63	3	0.69 60	1. 2	27 7	1.64 13		1.86 3
Rotation period (days)	58.6	6	-243.0	1	.0	27.3		1.0	0.4		0.4	-().7	0.7		-6.4
Axial tilt (°)	xial tilt (°) 0.04		177.3	2	23.4	6.7		25.2	3.1		26.7	97	7.8	28.3		119.6
Density (kg.m ³) Albedo Apparent magnitude (V) Angular diameter, max. (*) Rings Satellites Orbits the: Perihelion (10 ⁶ km) Aphelion (10 ⁶ km) Semimajor axis (AU) Eccentricity Inclination (*)	1.41 -26.7 1,962.0 	5.41 0.11 -1.9 13.0 no 0 Sun 46 69.8 0.4 0.21 7.0	5.19 0.65 -4.6 66.0 no 0 Sun 107.5 108.9 0.7 0.01 3.4	5.51 0.37 	3.35 0.12 12.9 2,046 no Earth 0.363 0.406 0.003 0.06 5.1	3.93 0.15 -2.9 25.1 no 2 Sun 206.7 249.2 1.5 0.09 1.9	1.89 0.09 6.9 0.8 no 0 Sun 381.4 447.8 2.8 0.08 10.6	1.33 0.52 2.9 50.1 yes 63 Sun 740.5 816.6 5.2 0.05 1.3	0.69 0.47 -0.2 20.1 yes 60 Sun 1,352.6 1,514.5 9.6 0.06 2.5	1.27 0.51 5.3 4.1 yes 27 Sun 2,741.3 3,003.6 19.2 0.05 0.8	1.64 0.41 7.8 2.4 yes 13 Sun 4,452.9 4,554 30.1 0.01 1.8	1.86 0.58 13.7 0.1 no 3 Sun 4,436.8 7,376 39.5 0.25 17.1	~2 ? 16.7 0.02 no 0 Sun 5,760.8 7,939.7 45.8 0.16 29.0	~3 0.6 17.5 0.02 no 2 Sun 5,260 7,708 43.3 0.19 28.2	~2 0.86 18.7 0.04 no 1 Sun 5,650 14,600 67.7 0.44 44.2	1
Orbital period (days) Orbital period (years) Orbital velocity (km.s ⁻¹) Discovery (year)	-	88.0 0.2 47.9	224.7 0.6 35.0	365.3 1.0 29.8	27.3 0.1 1.0	687.0 1.9 24.1 1801	1,679.4 4.6 17.9	8 4,331.6 11.9 13.1	10,832.3 29.7 9.7	30,799 84.3 6.8 1781	60,190 164.8 5.4 1846	90,613 248.1 4.7 1930	113,183 309.9 4.4 2005	104,234 285.4 4.5 2004	203,60 557.4 3.4 2003	0



			Solar s	vstem fa	ct-sheet					
	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10 ²⁴ kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m ³)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	-243.0	1.0	27.3	1.0	0.4	0.4	-0.7	0.7	-6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6

Virtually every spin configuration is present – prograde, retorgrade, angular momentum parallel and perpendicular to orbital plane

Apricitor (10° Kitt)		03.0	100.9	102.1	0.400	243.2	447.0	010.0	1,014.0	3,003.0	4,004	1,510	1,000.1	1,100	14,000
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity		0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)						1801				1781	1846	1930	2005	2004	2003



Solar system fact-sheet																
Mercury Venus E				Earth	Моо	n	Mars	Jup	iter	Satur	n Uı	ranus	Nept	une	Pluto	
Diameter (km)	4,87	79.4	12,103	.6	12,742	3,476.3		6,792.4	14,2	2984	120,53	36 51	51,118		28	2,390
Mass (10 ²⁴ kg)		3	4.87		5.97 0.073		3	0.64	1898.6		568.46	6 86	.81	102.4	3	0.013
Density (kg.m ³)	5.4	1	5.19		5.51	3.35		3.93 1.33		33 0.69		1.:	27	1.64		1.86
Satellites	0	0			1	no		2	2 63		60		,	13		3
Rotation period (days)	58.6	6	-243.0		1.0	27.3		1.0	0.4		0.4 -		.7	0.7	0.7	
Axial tilt (°)	0.04	Ļ	177.3		23.4	6.7		25.2	3.1		26.7 97		.8 28.3			119.6
Semimajor axis (AO)	0.4		0.7		1.0	0.003)	1.5	5.2		9.0	19	.2	30.1		39.5
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Perihelion (10 ⁶ km)		46	107.5	147.	.1 0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650	
Aphelion (10 ⁶ km)		69.8	108.9	152.	.1 0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600	0
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
Eccentricity		0.21	0.01	0.02	2 0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44	
Inclination (°)	-	7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2	
Orbital period (days)		88.0	224.7	365.	.3 27.3	687.0	1,679	.8 4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,60	00
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4	
Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	3 1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	
Discovery (year)						1801				1781	1846	1930	2005	2004	2003	
A COLOR MARKED							CALCULATION OF									



Solar system fact-sheet														
	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto				
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792 <mark>4</mark>	14,2984	120,536	51,118	49,528	2,390				
Mass (10 ²⁴ kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013				
Density (kg.m ³)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86				
Satellites	0	0	1	no	2	63	60	27	13	3				
Rotation period (days)	58.6	-243.0	1.0	27.3	1.0	0.4	0.4	-0.7	0.7	-6.4				
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6				
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5				
 Rocky planets are all inside ~1.5 AU. 														

Orbits the: Perihelion (106 km Aphelion (10⁶ km) Semimajor axis (A Eccentricity Inclination (°) Orbital period (day Orbital period (yea

Orbital velocity (I

Discovery (year)

•	Gas giants @ ~5 AU or greater?
•	Gas giants must form beyond the "Ice/
	Snow Line" where water, ammonia,
	methane, CO2, &c. freeze out

1801





1781

1846

1930

2005

Solar system fact-sheet														
	Mercury	Venus	Earth	Moon Mars		Jupiter	Saturn	Uranus	Neptune	Pluto				
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390				
Mass (10 ²⁴ kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013				
Density (kg.m ³)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86				
Satellites	0	0	1	no	2	63	60	27	13	3				
Rotation period (days)	58.6	-243.0	1.0	27.3	1.0	0.4	0.4	-0.7	0.7	-6.4				
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6				
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5				
Orbital period (days)	88.0	224.7	365.3	27.3	687.0	4,331.6	10,832.3	30,799	60,190	90,613				

Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10 ⁶ km)		46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10 ⁶ km)		69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity		0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s ⁻¹)	_	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)						1801		_		1781	1846	1930	2005	2004	2003



Solar system fact-sheet																
	Mercury Venus		: I	Earth	Моо	n I	Mars Jupi		iter	r Saturn		ranus	Nept	tune	Pluto	
Diameter (km)	4,87	4,879.4		.6 1	2,742	3,476	i.3 (6,792.4	2.4 14,2984		120,53	86 51	1,118	49,52	49,528	
Mass (10 ²⁴ kg)	0.33	0.33		4.87 5.97		0.073		0.64	1898.6		568.46	6 86	5.81	102.4	102.43	
Density (kg.m ³)	5.41		5.19		5.51 3.			3.93	1.33		0.69	1.	27	1.64		1.86
Satellites	0	0		0		no	2		63	63		27	7	13	13	
Rotation period (days)	58.6	;	-243.0 1.0		.0	27.3		1.0	.0 0.4		0.4	-C).7	0.7		-6.4
Axial tilt (°) Semimaior axis (ALI)	0.04		177.3 23.4		6.7		25.2 1 5	3.1		26.7 9.6	97 10	7.8	28.3	28.3		
Orbital period (days)	88.0		224.7	365.3		27.3	27.3 687.0		4,33	4,331.6 10,832		.3 30,799		60,190		90,613
			P^{2} _	-	$4\pi^2$	2	~	$4\pi^2$		neto	nt					
			$a^{3} - c$		G(M+m)		$\overline{m)} \simeq \overline{GM}$ –		- 00	- constan						
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Aphelion (10 ⁶ km)		40 69.8	107.5	152.1	0.303	200.7	447.8	740.5 816.6	1,552.6	3,003.6	4,452.9	4,430.0 7,376	7,939.7	5,200 7,708	14,60	0
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
Eccentricity		0.21	0.01	0.02	0.06	0.09	80.0	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44	
Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2	~~
Orbital period (days)	_	88.0	224.7	365.3	27.3	19	4.6	4,331.6 11 9	10,832.3	30,799	164.8	90,613 248 1	309.9	104,234 285.4	203,0	00
Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	
Discovery (year)			—	—		1801				1781	1846	1930	2005	2004	2003	
A. S. A.				0								2		1		
a for a			and a	6		No.	Tay			1	/					
					Solar	syster	n fac	t-shee	et							
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	Merc	ury	Venus	s E	arth	Моо	Moon I		Mars Jupiter		Saturn U		ranus	Neptune		Pluto
Diameter (km)	er (km) 4,879.4 12,10		12,103	8.6 1	2,742	3,476	6.3	6,792.4	792.4 14,2984		120,536		1,118	49,52	49,528	
Mass (10 ²⁴ kg)	0.33	3	4.87	5	.97	0.073	3	0.64	189	8.6	568.46	6 86	5.81	102.43		0.013
Density (kg.m ³)	541 519		5.19	5	5.51	3.35		3.93	1.33	3	0.69	1.	27	1.64	1.64	
Satellites	0		0	,		no		2	63		60	2	7	13		3
Rotation period (days)	58 6		_243 () 1	0	27.3		10	04		04	_) 7	07		-64
	00.0	,	-240.0	, ,		27.0		1.0	0.4		0.4			0.7		-0.4
Axial tilt (°)	0.04		177.3		3.4	6.7		25.2	3.1		26.7	9	7.8	28.3		119.6
Semimajor axis (AU)	0.4		0.7	1	.0	0.003	3	1.5	5.2		9.6	19	9.2	30.1		39.5
Orbital period (days)	88.0		224.7	3	65.3	27.3	(687.0	4,33	1.6	10,832	2.3 30	,799	60,19	0	90,613
Eccentricity	0.21		0.01	0	.02	0.06	(0.09	0.05		0.06	0.	05	0.01		0.25
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Aphelion (10 ⁶ km)		46 69.8	107.5	147.1	0.363	206.7	447.8	740.5 816.6	1,352.6	3,003.6	4,452.9	4,430.8	5,760.8	5,260 7,708	5,650 14,60	0
Semimajor axis (AU) Eccentricity Inclination (°) Orbital period (days)	_	0.4 0.21 7.0 88.0	0.7 0.01 3.4 224.7	1.0 0.02 0 365.3	0.003 0.06 5.1 27.3	1.5 0.09 1.9 687.0	2.8 0.08 10.6 1,679.8	5.2 0.05 1.3 3 4,331.6	9.6 0.06 2.5 10,832.3	19.2 0.05 0.8 30,799	30.1 0.01 1.8 60,190	39.5 0.25 17.1 90,613	45.8 0.16 29.0 113,183	43.3 0.19 28.2 104,234	67.7 0.44 44.2 203,6	00
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4	
Orbital velocity (km.s ⁻⁺) Discovery (vear)	_	47.9	35.0	29.8	1.0	24.1 1801	17.9	13.1	9.7	6.8 1781	5.4 1846	4.7 1930	4.4 2005	4.5 2004	3.4 2003	
				*								2				

				S	Solar	syster	n fac	t-shee	t							
	Merc	cury	Venus	5 E	arth	Моо	n	Mars	Jup	iter	Satur	n l	Jranus	Nept	une	Pluto
Diameter (km)	4,87	79.4	12,103	3.6 12	2,742	3,476	6.3	6,792.4	14,2	984	120,53	36 5	51,118	49,52	28	2,390
Mass (10 ²⁴ kg)	0.33	3	4.87	5.	.97	0.073	3	0.64	189	8.6	568.46	5 8	86.81	102.4	3	0.013
Density (kg.m ³)	5.4	1	5.19	5.	.51	3.35		3.93	1.33	3	0.69	1	.27	1.64		1.86
Satellites	0		0	1		no		2	63		60	2	27	13		3
Rotation period (days)	58.6	6	-243.0) 1.	.0	27.3		1.0	0.4		0.4	_	-0.7	0.7		-6.4
Axial tilt (°) Semimaior axis (AU)	0.04	Ļ	177.3 0.7	23	3.4 0	6.7 0.003	3	25.2 1.5	3.1 5.2		26.7 9.6	9 1	97.8 9.2	28.3 30.1		119.6 39.5
Orbital period (days)	88.0)	224.7	36	65.3	27.3	(687.0	4,33	1.6	10,832	.3 3	0,799	60,19	0	90,613
Eccentricity	0.21		0.01	0.	02	0.06	.(0.09	0.05		0.06	0	.05	0.01		0.25
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Perihelion (10 ⁶ km)	<u></u>	46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.	8 5,760.8	5,260	5,650	
Aphelion (10 ⁶ km)		69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,60	0
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
Inclination (°)		7.0	3.4	0.02	5.1	19	10.6	1.3	2.5	0.05	1.8	17 1	29.0	28.2	44 2	
Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1.679.8	4.331.6	10.832.3	30,799	60,190	90.613	3 113,183	104.234	203.6	00
Orbital period (vears)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4	
Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	
Discovery (year)						1801				1781	1846	1930	2005	2004	2003	
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					Solar s	vsten	n fac	ct-shee	t							
	Merc	ury	Venus		Earth	Моо	n	Mars	Jup	iter	Satur	n U	ranus	Nept	une	Pluto
Diameter (km)	4,87	'9.4	12,103	.6	12,742	3,476	5.3	6,792.4	14,2	984	120,53	36 51	,118	49,52	28	2,390
Mass (10 ²⁴ kg)	0.33	;	4.87		5.97	0.073	3	0.64	189	8.6	568.46	6 86	5.81	102.4	3	0.013
Density (kg.m ³)	5.41		5.19		5.51	3.35		3.93	1.33	}	0.69	1.	27	1.64		1.86
Satellites	0		0		1	no		2	63		60	27	7	13		3
Rotation period (days)	58.6	;	-243.0		1.0	27.3		1.0	0.4		0.4	-0).7	0.7		-6.4
Axial tilt (°) Semimajor axis (AU)	0.04 0.4	Ļ	177.3 0.7		23.4 1.0	6.7 0.003		25.2 1.5	3.1 5.2		26.7 9.6	97 19	7.8 0.2	28.3 30.1		119.6 39.5
Orbital period (days)	88.0		224.7		365.3	27.3		687.0	4,33	1.6	10,832	.3 30	,799	60,19	0	90,613
Eccentricity	0.21		0.01	(0.02	0.06		0.09	0.05		0.06	0.0)5	0.01		0.25
Inclination (°)	7.0		3.4	(0	5.1		1.9	1.3		2.5	0.8	В	1.8		17.1
Orbits the	Milky Way	Sun	Sun	Sup	Farth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	
Perihelion (10 ⁶ km)	——	46	107.5	147.	1 0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650	
Aphelion (10 ⁶ km)		69.8	108.9	152.	1 0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,60	0
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7	
Eccentricity		0.21	0.01	0.02	0.06	0.09	80.0	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44	
		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2	00
Orbital period (days)		88.0	224.7	305.	0 1	1.0	1,6/9.	0 4,331.6	10,832.3	30,799	164 9	90,613	200.0	295 4	203,60	00
Orbital velocity (km.s ⁻¹)	1	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4	

1801 1781 _ . 0

Discovery (year)

2004

2003

2005

1930

1846

			Solar s	system fa	act-sheet					
	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km)	4,879.4	12,103.6	12,742	3,476.3	6,792.4	14,2984	120,536	51,118	49,528	2,390
Mass (10 ²⁴ kg)	0.33	4.87	5.97	0.073	0.64	1898.6	568.46	86.81	102.43	0.013
Density (kg.m ³)	5.41	5.19	5.51	3.35	3.93	1.33	0.69	1.27	1.64	1.86
Satellites	0	0	1	no	2	63	60	27	13	3
Rotation period (days)	58.6	-243.0	1.0	27.3	1.0	0.4	0.4	-0.7	0.7	-6.4
Axial tilt (°)	0.04	177.3	23.4	6.7	25.2	3.1	26.7	97.8	28.3	119.6
Semimajor axis (AU)	0.4	0.7	1.0	0.003	1.5	5.2	9.6	19.2	30.1	39.5
Orbital period (days)	88.0	224.7	365.3	27.3	687.0	4,331.6	10,832.3	30,799	60,190	90,613
Eccentricity	0.21	0.01	0.02	0.06	0.09	0.05	0.06	0.05	0.01	0.25
Inclination (°)	7.0	3.4	0	5.1	1.9	1.3	2.5	0.8	1.8	17.1
Orbits the:	Milky Way Sun	Sun Su	un Earth	Sun Sun	Sun	Sun Sun	Sun Su	n Sun	Sun Sun	
Perihelion (10 ^e km) Aphelion (10 ^e km)	46 69.8	107.5 14 108.9 15	7.1 0.363 52.1 0.406	206.7 381. 249.2 447.	.4 740.5 .8 816.6	1,352.6 2,741.3 1,514.5 3,003.6	4,452.9 4,4 4,554 7,3	36.8 5,760.8 376 7,939.7	5,260 5,650 7,708 14,600	0

erene une.	initial initia	ean	Carr	ean	Earth	oan	0011	Carr	oan	oun	ean	oan	oan	Call	oun
Perihelion (10 ⁶ km)		46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10 ⁶ km)		69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity		0.21	0.01	0.02	0.06	0.09	80.0	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s ⁻¹)	_	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)						1801				1781	1846	1930	2005	2004	2003
	Perihelion (10 ⁶ km) Aphelion (10 ⁶ km) Semimajor axis (AU) Eccentricity Inclination (°) Orbital period (days) Orbital period (years) Orbital velocity (km.s ⁻¹) Discovery (year)	Derihelion (10° km) — Aphelion (10° km) — Semimajor axis (AU) — Eccentricity — Inclination (°) — Orbital period (days) — Orbital period (years) — Discovery (year) —	Derine and Mark Mark Mark Mark Mark Derine Derine	Perihelion (10 ⁶ km) — 46 107.5 Aphelion (10 ⁶ km) — 69.8 108.9 Semimajor axis (AU) — 0.4 0.7 Eccentricity — 0.21 0.01 Inclination (°) — 7.0 3.4 Orbital period (days) — 88.0 224.7 Orbital period (years) — 0.2 0.6 Orbital velocity (km.s ⁻¹) — 47.9 35.0 Discovery (year) — — —	Perihelion (10 ⁶ km) — 46 107.5 147.1 Aphelion (10 ⁶ km) — 69.8 108.9 152.1 Semimajor axis (AU) — 0.4 0.7 1.0 Eccentricity — 0.21 0.01 0.02 Inclination (°) — 7.0 3.4 0 Orbital period (days) — 88.0 224.7 365.3 Orbital velocity (km.s ⁻¹) — 47.9 35.0 29.8 Discovery (year) — — — — —	Perihelion (10 ⁶ km) — 46 107.5 147.1 0.363 Aphelion (10 ⁶ km) — 69.8 108.9 152.1 0.406 Semimajor axis (AU) — 0.4 0.7 1.0 0.003 Eccentricity — 0.21 0.01 0.02 0.06 Inclination (°) — 7.0 3.4 0 5.1 Orbital period (days) — 88.0 224.7 365.3 27.3 Orbital period (years) — 0.2 0.6 1.0 0.1 Orbital velocity (km.s ⁻¹) — 47.9 35.0 29.8 1.0 Discovery (year) — — — — — —	Perihelion (10 ⁶ km) — 46 107.5 147.1 0.363 206.7 Aphelion (10 ⁶ km) — 69.8 108.9 152.1 0.406 249.2 Semimajor axis (AU) — 0.4 0.7 1.0 0.003 1.5 Eccentricity — 0.21 0.01 0.02 0.06 0.09 Inclination (°) — 7.0 3.4 0 5.1 1.9 Orbital period (days) — 88.0 224.7 365.3 27.3 687.0 Orbital period (years) — 0.2 0.6 1.0 0.1 1.9 Orbital velocity (km.s ⁻¹) — 47.9 35.0 29.8 1.0 24.1 Discovery (year) — — — — — 1801	Perihelion (10 ⁶ km) — 46 107.5 147.1 0.363 206.7 381.4 Aphelion (10 ⁶ km) — 69.8 108.9 152.1 0.406 249.2 447.8 Semimajor axis (AU) — 0.4 0.7 1.0 0.003 1.5 2.8 Eccentricity — 0.21 0.01 0.02 0.06 0.09 0.08 Inclination (°) — 7.0 3.4 0 5.1 1.9 10.6 Orbital period (days) — 88.0 224.7 365.3 27.3 687.0 1,679.8 Orbital period (years) — 0.2 0.6 1.0 0.1 1.9 4.6 Orbital velocity (km.s ⁻¹) — 47.9 35.0 29.8 1.0 24.1 17.9 Discovery (year) — — — — — — 1801 —	Derive using resp. 100% 1	Derine lion (10 ⁶ km) — 46 107.5 147.1 0.363 206.7 381.4 740.5 1,352.6 Aphelion (10 ⁶ km) — 69.8 108.9 152.1 0.406 249.2 447.8 816.6 1,514.5 Semimajor axis (AU) — 0.4 0.7 1.0 0.003 1.5 2.8 5.2 9.6 Eccentricity — 0.21 0.01 0.02 0.06 0.09 0.08 0.05 0.06 Inclination (°) — 7.0 3.4 0 5.1 1.9 10.6 1.3 2.5 Orbital period (days) — 88.0 224.7 365.3 27.3 687.0 1,679.8 4,331.6 10,832.3 Orbital period (years) — 0.2 0.6 1.0 0.1 1.9 4.6 11.9 29.7 Orbital velocity (km.s ⁻¹) — 47.9 35.0 29.8 1.0 24.1 17.9 13.1 9.7 Discovery (year) — — — — — — — — <th>Derive using the j Construction Construction</th> <th>Perihelion (10⁶ km) — 46 107.5 147.1 0.363 206.7 381.4 740.5 1,352.6 2,741.3 4,452.9 Aphelion (10⁶ km) — 69.8 108.9 152.1 0.406 249.2 447.8 816.6 1,514.5 3,00.6 4,554 Semimajor axis (AU) — 0.4 0.7 1.0 0.003 1.5 2.8 5.2 9.6 19.2 30.1 Eccentricity — 0.21 0.01 0.02 0.06 0.09 0.08 0.05 0.06 0.05 0.01 Inclination (°) — 7.0 3.4 0 5.1 1.9 10.6 1.3 2.5 0.8 1.8 Orbital period (days) — 88.0 224.7 365.3 27.3 687.0 1,679.8 4,331.6 10,832.3 30,799 60,190 Orbital period (years) — 0.2 0.6 1.0 0.1 1.9 4.6 11.9 29.7 84.3 164.8 Orbital velocity (km.s⁻¹) — 47.9 35.0 29</th> <th>Derived using height of the series of the</th> <th>Derived using height of the series of the</th> <th>Derivation Main Main</th>	Derive using the j Construction	Perihelion (10 ⁶ km) — 46 107.5 147.1 0.363 206.7 381.4 740.5 1,352.6 2,741.3 4,452.9 Aphelion (10 ⁶ km) — 69.8 108.9 152.1 0.406 249.2 447.8 816.6 1,514.5 3,00.6 4,554 Semimajor axis (AU) — 0.4 0.7 1.0 0.003 1.5 2.8 5.2 9.6 19.2 30.1 Eccentricity — 0.21 0.01 0.02 0.06 0.09 0.08 0.05 0.06 0.05 0.01 Inclination (°) — 7.0 3.4 0 5.1 1.9 10.6 1.3 2.5 0.8 1.8 Orbital period (days) — 88.0 224.7 365.3 27.3 687.0 1,679.8 4,331.6 10,832.3 30,799 60,190 Orbital period (years) — 0.2 0.6 1.0 0.1 1.9 4.6 11.9 29.7 84.3 164.8 Orbital velocity (km.s ⁻¹) — 47.9 35.0 29	Derived using height of the series of the	Derived using height of the series of the	Derivation Main



Pluto is "different"



Pluto is Demoted



- Eris discovery in 2005 27% more massive than Pluto
- 2006 IAU definition of a planet excludes Pluto, now a minor planet
- New Horizons (2016) probe imagery shows rich, complex topography

New Horizons Shows Pluto Also Has An Atmosphere





Largest known trans-Neptunian objects (TNOs)







TNOs Have A Wide Range of Eccentricities& Incliantions



Asteroid "Live" Between Jupiter and Mars



IAG/USP XVIII * GMT Science and Instrumentation * ASz *26 Feb 2018

Asteroid Belt Taxonomy



A Migration History of the Solar System



The Oort Cloud is an Unseen Swarm of Comets



Comets supplies water to Earth during "Grand Tack" in the "Grand Tack" model

The Space Between the Stars



The Habitable Zone



Exoplanet Science Today, in a Little More Detail

Pluto Kicked Our of Planet Club



• 2006 – IAU definition of a planet excludes Pluto, now a minor planet

But is there another Planet 9?





A Least One Solar System Object is a "Visitor"



The Kepler Mission has Discovered Most of the Known Exoplanets



Kepler "Stared" at a ~100² deg field of view for ~3 years

Where Kepler Searched



Exoplanet Discoveries



Kepler only measure the radius of an exoplanet

Kepler only measure the radius of an exoplanet



Most Exoplanets are Earth size, many in habitable zone.



Dressing & Charbonneau, 2013, ApJ, 767, 95

Extreme Exoplanets

Planet	Characteristic
HD10180 System	System with most exoplanets (\geq 7 planets, = 9?)
Kepler 64 b	In circumbinary orbit with 4 star system
NY Virginis b	Jupiter mass planet orbiting binay with B dwarf
HD 208527 b	Host star is a M1III red giant
HD 106906 b	650 AU from host star (Pluto 49.3 at aphelion)
V830 Tau b	Orbits 2 million year old T Tauri star (Youngest Host Star)
GJ 1214 b	"Waterworld"



Ternary ("Toblerone") Representation of Density and Composition



Composition seems to determine radius and mass, or vice versa.

The Earth is a Rocky Exoplanet



MARS is a Rocky Exoplanet TOO



The Earth is not "Wet"

Oceans in the Solar System



The Search for Earth 2.0

Nama	Earth	Earth	Nete	Planet +	ESI +	Notes +
Name	masses (M _⊕)	(<i>R</i> _⊕)	Note	Earth	1.00	
Kepler-69c	0.98	1.7	Originally thought to be in the circumstellar habitable zone (CHZ), now thought to be too hot.	Gliese 581 g	0.89	unconfirmed
Kepler-9d	>1.5 ^[27]	1.64	Extremely hot.	Kepler-438b	0.88	
COROT-	<9	1.58	Extremely hot	Ross 128 b	0.86	
7b	~	1.00		Gliese-3323b	0.86	
Kepler-20f	< 14.3 ^[25]	1.03 ^[25]	Slightly larger and likely more massive, far too hot to be Earth-like.	Kepler-62e	0.83	[10]
Tau Ceti b	2		Extremely hot. Not known to transit.	Gliese 832 c	0.81	
Alpha Centauri	1.1 ^[28]		Closest known mass to Earth but much hotter.	Gliese 581 d	0.74	
Bb	999595		NOTE: May not exist (NYT, June 10, 2013).[20]	Gliese 581 c	0.70	
Kepler- 186f		1.1 ^[30]	Orbits in CHZ.	Mercury	0.60	
Earth	1	1	Orbits in habitable zone.	HD 69830 d	0.60	
Venus	0.815	0.949	Much hotter.	55 Cnc c	0.56	
Kepler- 20e	< 3.08 ^[24]	0.87 ^[24]	Too hot to be Earth-like.	Moon	0.56	
Proxima b	>1.27	>1.1	Closest exoplanet to Earth.	Gliese 581 e	0.53	

No "true" analogue has been found to date.

"Gas Bag" Planets (Jupiters) and Water Worlds


Neptune is a Frozen Waterworlds





Gliese 436b is a Liquid Waterworld



Stellar Type	M2.5V
Orbital Period	2.64d
Orbital Radius	0.0291 AU
Mass	22.2 M_\oplus
Radius	4.33 R_\oplus
Temperature	712K

Jupiter is Mostly Metallic Hydrogen



51 Peg b is a Jupiter Analogue

The first exoplanet was a Jupiter analogue!



Solar system fact-sheet															
	Me	rcury	Venus	E	arth	Моо	n N	lars	Jup	iter	Satur	n U	ranus	Nept	une Pluto
Diameter (km)	4,8	379.4	12,103	.6 12	2,742	3,476	6.3 6	,792.4	14,2	984	120,53	36 5	1,118	49,52	8 2,390
Mass (10 ²⁴ kg)	0.3	33	4.87	5.	97	0.073	3 0	.64	189	8.6	568.46	5 8	6.81	102.4	3 0.013
Density (kg.m ³)	5.4	11	5.19	5	.51	3.35	3	.93	1.33	3	0.69	1	.27	1.64	1.86
Axial tilt (°) Surface gravity (m.s²) Escape velocity (km.s ⁻¹) Surface area (10 ⁶ km²)	274.0 617.7 6,087		R P	ocl Ian	ky ets)	Ga	s G	lian	ts	lce	Gia	ants
Volume (10 ¹²	1,412,200	0.06	0.9	1.1	0.02	0.16	0.0005	1431	827	68	63	0.007	~0.002		0.009
Density (kg.m ³)	1.41	5.41	5.19	5.51	3.35	3.93	1.89	1.33	0.69	1.27	1.64	1.86	~2	~3	~2
Albedo	06.7	0.11	0.65	0.37	0.12	0.15	0.09	0.52	0.47	0.51	0.41	0.58	?	0.6	0.86
Apparent magnitude (V)	-20.7	-1.9	-4.b		-12.9	-2.9	0.9	-2.9	-0.2	5.3	7.8	13.7	10.7	17.5	18.7
Rings	1,502.0	13.0	00.0		2,040	20.1	0.0	V09	20.1	4.1	2.4	0.1	0.02	0.02	0.04
Satellites	billions!	0	0	1	no	2	0	63	60	27	13	3	0	2	1
Orbits the:	Milky Way	Sun	Sun	Sun	Earth	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
Perihelion (10 ⁶ km)		46	107.5	147.1	0.363	206.7	381.4	740.5	1,352.6	2,741.3	4,452.9	4,436.8	5,760.8	5,260	5,650
Aphelion (10 ⁶ km)	<u> </u>	69.8	108.9	152.1	0.406	249.2	447.8	816.6	1,514.5	3,003.6	4,554	7,376	7,939.7	7,708	14,600
Semimajor axis (AU)		0.4	0.7	1.0	0.003	1.5	2.8	5.2	9.6	19.2	30.1	39.5	45.8	43.3	67.7
Eccentricity		0.21	0.01	0.02	0.06	0.09	0.08	0.05	0.06	0.05	0.01	0.25	0.16	0.19	0.44
Inclination (°)		7.0	3.4	0	5.1	1.9	10.6	1.3	2.5	0.8	1.8	17.1	29.0	28.2	44.2
Orbital period (days)		88.0	224.7	365.3	27.3	687.0	1,679.8	4,331.6	10,832.3	30,799	60,190	90,613	113,183	104,234	203,600
Orbital period (years)		0.2	0.6	1.0	0.1	1.9	4.6	11.9	29.7	84.3	164.8	248.1	309.9	285.4	557.4
Orbital velocity (km.s ⁻¹)	-	47.9	35.0	29.8	1.0	24.1	17.9	13.1	9.7	6.8	5.4	4.7	4.4	4.5	3.4
Discovery (year)						1801				1781	1846	1930	2005	2004	2003



Solar system fact-sheet										
	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Diameter (km) Mass (10 ²⁴ kg)	4,879.4 0.33	12,103.6 4.87	12,742 5.97	3,476.3 0.073	6,792 4 0.64	14,2984 1898.6	120,536 568.46	51,118 86.81	49,528 102.43	2,390 0.013
Density (kg.m ³) Satellites	5.41 0	5.19 0	5.51 1	3.35 no	3.93 2	1.33 63	0.69 60	1.27 27	1.64 13	1.86 3
Rotation period (days) Axial tilt (°) Semimajor axis (AU)	58.6 0.04 0.4	–243.0 177.3 0.7	1.0 23.4 1.0	27.3 6.7 0.003	1.0 25.2 1.5	0.4 3.1 5.2	0.4 26.7 9.6	0.7 97.8 19.2	0.7 28.3 30.1	-6.4 119.6 39.5
 Crbits the: Perihelion (10° km) Aphelion (10° km) Semimajor axis (A Eccentricity Inclination (*) Orbital period (day Orbital period (gap Orbital velocity (km) 										0
Discovery (year) —	What	is a ga	as giar	nt doin	g in a	4 day	period	2005 ?	2004 2003	

Hot vs. Cold Jupiters





Hot Jupiters like HD18977 - b and WASP-12b are probably evaporating

Jupiter					
Period	1,680 d				
Orb. Rad.	2.8 AU				
Temp	Complicated				

HD18	HD189733-b						
Period	2.22 d						
Orb. Rad.	0.03 AU						
Temp	1117 K						

	•				
WASP-12b					
Period	1.09 d				
Orb. Rad.	0.023 AU				
Temp	2525 K				

Mercury							
Period	2.22 d						
Orb. Rad.	0.466 AU						
Temp	~350 K						

The Exoplanet "Ice Line"



Artist's impression of a protoplanetary disk with warm inner circle of dust and outer ring of "snow"

A Migration History of the Solar System





The Solar System Grand Tack in Manga



But Dynamical Interations Are Important Too

Let's simply play the game!

http://www.stefanom.org/spc/



A Paradigm-Shifting Exoplanet System – Trappist-1

The TRAPPIST-1 planetary system

Companion (in order from star)		Spectra	al Type			M8V		Radius ^{[6][33]}
b	C	Evoluti	onary Type		Ma	in Seque	nce	1.086 ±0.035 <i>B</i>
		Appare	nt V Magnitu	ıde		18.8		
C	1	Distance					1.056 ±0.035 <i>R</i> _⊕	
d	C	Mass				0.772 ±0.030 <i>R</i> ⊕		
е		Radius				0.114 R _c)	0.918 ±0.039 <i>R</i> _⊕
f	c	Temperature				2550K	1.045 ±0.038 <i>R</i> ⊕	
g	0.	Age				3-8 Gyr		1.127 ±0.041 <i>R</i> ⊕
h	0.		(8.92 million km)		FI	ares & Sj	oot	0.715 ^{+0.047} _{−0.043} _{<i>R</i>⊕}

Trappist-1 in the The HR Diagram



IAG/USP XVIII * GMT Science and Instrumentation * ASz *26 Feb 2018



Trappist-1 Has 3 Planets in Its Habitable Zone!



Mean Motion Resonance (MMR) "Herds" the Asteroid Belt



Mean Motion Resonance: The Asteroid Movie



MMR – Multiples of Small Integers





Resonances in Trappist-1 Are Very Complex!



The relative orbital periods (proceeding outward) approximate whole integer ratios of: 24/24, 24/15, 24/9, 24/6, 24/4, 24/3, and 24/2, respectively, or nearest-neighbor period ratios of about:

8/5, 5/3, 3/2, 3/2, 4/3, and 3/2 (1.603, 1.672, 1.506, 1.509, 1.342, and 1.519)

The Nearest Star Hosts Exoplanets

- The star nearest the Sun hosts an exoplanet
- It is conceivable to send probes to that planet



NATURE | LETTER

日本語要約

A terrestrial planet candidate in a temperate orbit around Proxima Centauri

A terrestrial planet candidate in a temperate orbit around Proxima Centauri Anglade-Escude et al (2016) Nature, 536, 437.

Nature, 2012,491, 207



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Proxima Cen in the The HR Diagram



Sunset at your beach house on Proxima Cen b



* T of Quartz-Halogen Lamp is 3100K

Breakthrough Starshot takes its first step toward interstellar travel

First ... low Earth orbit. But eventually, these chip-sized spacecraft could explore Proxima Centauri.



