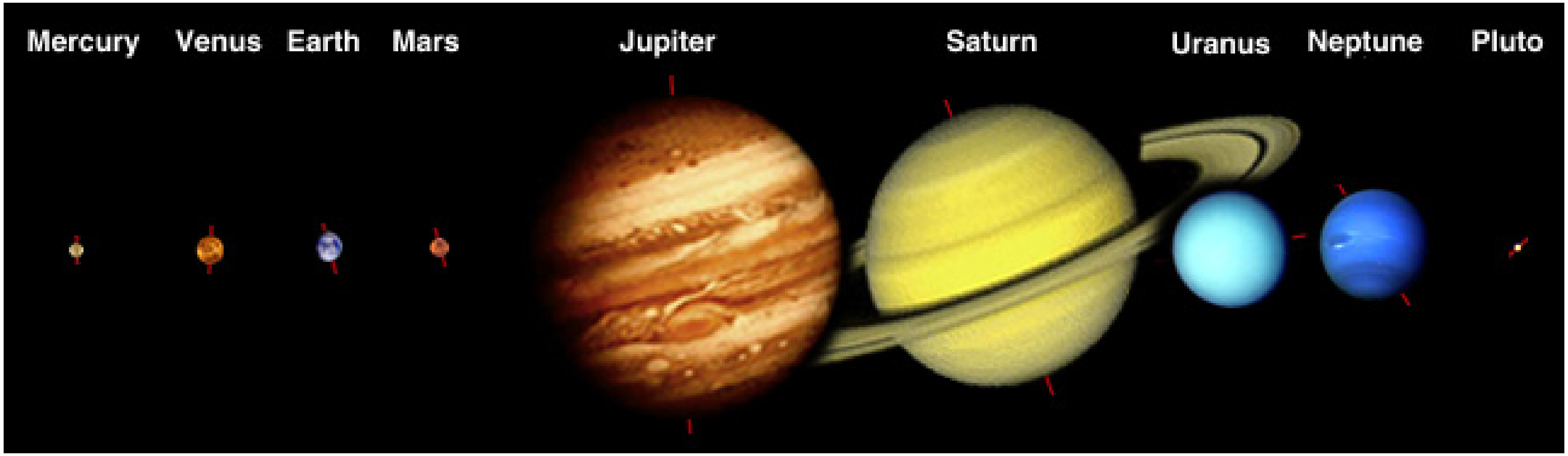
IL CIELO COME LABORATORIO

Lezione 4

Sistemi Planetari

Proprietà del Sistema Solare



Le orbite dei pianeti giacciono tutte sullo stesso piano con piccole deviazioni, in particolare del pianeta più vicino al Sole, Mercurio.

$$1\,\text{U.A.} = 1.5\times10^{8}\ \text{km}$$

$$1\,\text{A.L.} = \left(3\times10^{5}\ \text{km/s}\right)\times\left(3.15\times10^{7}\,\text{s}\right) = 9.45\times10^{12}\,\text{km}$$

$$1\,\text{pc} = 3.26\,\text{A.L.} = 3.09\times10^{13}\ \text{km}$$

- Il Sole ruota su se stesso con un periodo medio di circa 25 giorni, corrispondente ad una velocità tangenziale equatoriale di circa 2 km/s.

- I pianeti ruotano attorno al Sole nello stesso verso e le orbite sono quasi rigorosamente circolari, con l'eccezione di Mercurio. Anche Marte ha un'orbita con un'eccentricità apprezzabile.

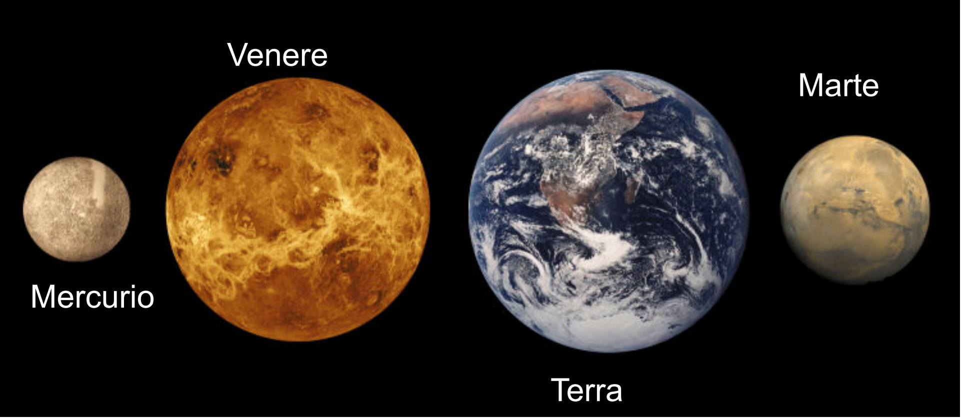
- I pianeti a loro volta ruotano attorno al proprio asse che per la maggioranza dei pianeti è quasi perpendicolare al piano dell'orbita. Eccezioni importanti sono quella di Venere, che ha un moto retrogrado, e di Urano, che ha l'asse di rotazione quasi parallelo al piano dell'orbita.

planets not shown to scale >>	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mean Distance from the Sun (AU)	0.3871	0.7233	1	1.524	5.203	9.539	19.19	30.06	39.48
Sidereal period of orbit (years)	0.24	0.62	1	1.88	11.86	29.46	84.01	164.79	248.54
Mean Orbital Velocity (km/sec)	47.89	35.04	29.79	24.14	13.06	9.64	6.81	5.43	4.74
Orbital Eccentricity	$\boxed{0.206}$	0.007	0.017	$\boxed{0.093}$	0.048	0.056	0.046	0.010	0.248
Inclination to ecliptic (degrees)	7.00	3.40	0	1.85	1.30	2.49	0.77	1.77	17.15
Equatorial Radius (km)	2439	6052	6378	3397	71490	60268	25559	25269	1160
Polar Radius (km)	same	same	6357	3380	66854	54360	24973	24340	same
Mass of planet (Earth=1)	0.06	0.82	1	0.11	317.89	95.18	14.53	17.14	0.002
Mean density (grams/centimeter^3)	5.43	5.25	5.52	3.95	1.33	0.69	1.29	1.64	2.03
Body rotation period (hours)	1408	5832	23.93	24.62	9.92	10.66	17.24	16.11	153.3
Tilt of equator to orbit (degrees)	2	$\boxed{177.3}$	23.45	25.19	3.12	26.73	$\boxed{97.86}$	29.6	122.46
Number of observed satellites	0	0	1	2	>28	30	24	8	1

$$D_{TS} = 1.5 \times 10^{8}\,\mathrm{km} = 1\,\mathrm{U.A.}$$

$$T_{Terra} = 365\ \mathrm{giorni} = 8760\ \mathrm{ore} = 3.15 \times 10^{7}\,\mathrm{sec}$$

$$M_{Terra} = 6 \times 10^{24}\,\mathrm{kg}$$



Pianeti interni o terrestri
$D_{sole} < 250$ milioni di km

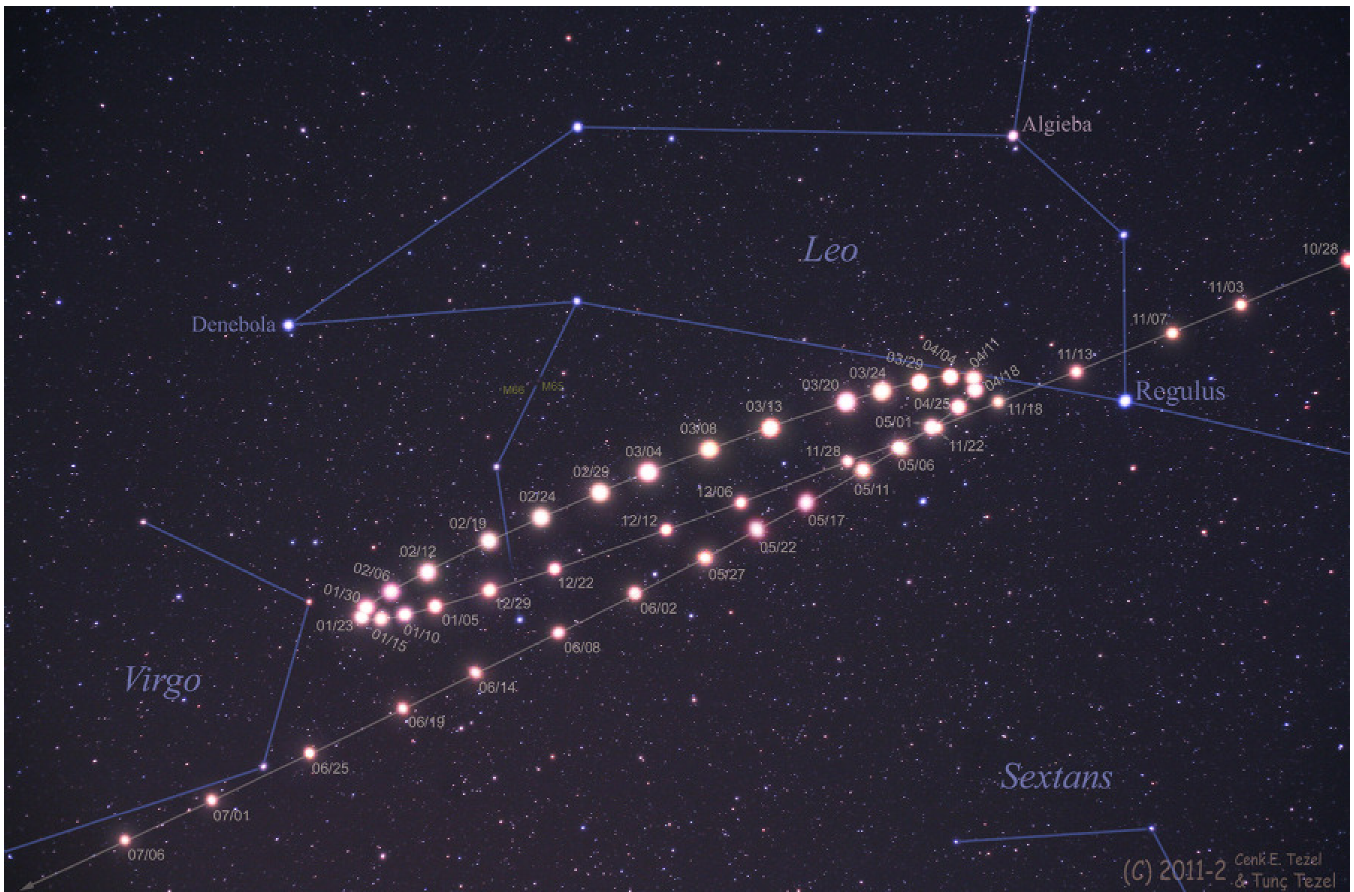
Pianeti esterni o gioviani
$D_{sole} > 700$ milioni di km

$T_{PI} > T_{PE}$

$r_{PI} < r_{PE}$

$M_{PI} < M_{PE}$

Le Leggi di Keplero



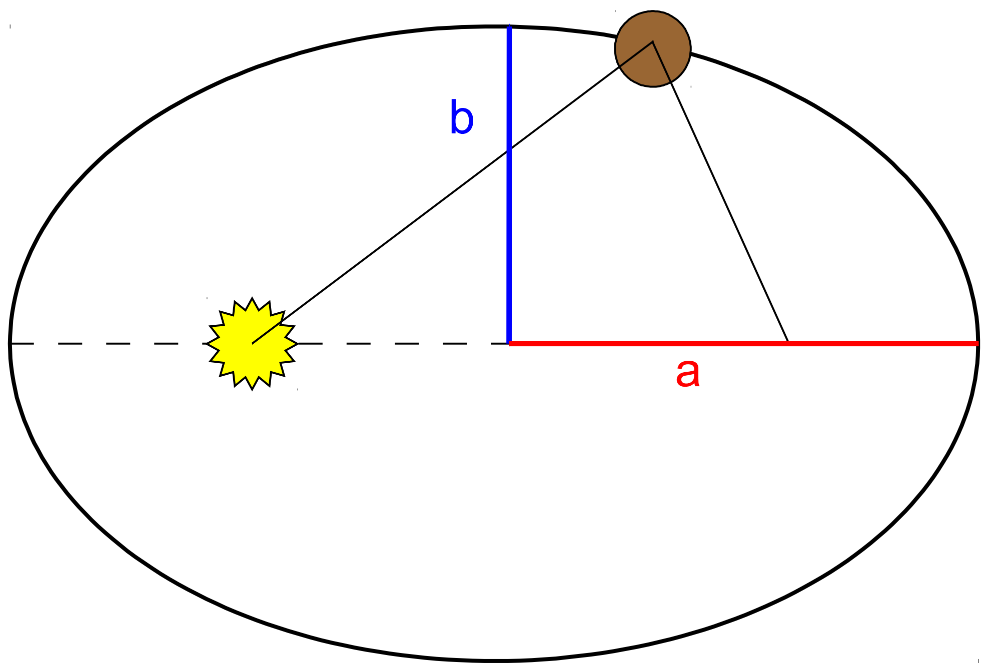
Keplero (1571-1630)

1. Tutti i pianeti si muovono su orbite ellittiche, di cui il Sole occupa uno dei due fuochi.

$$\boxed{\frac{x^2}{a^2}+\frac{y^2}{b^2}=1}$$

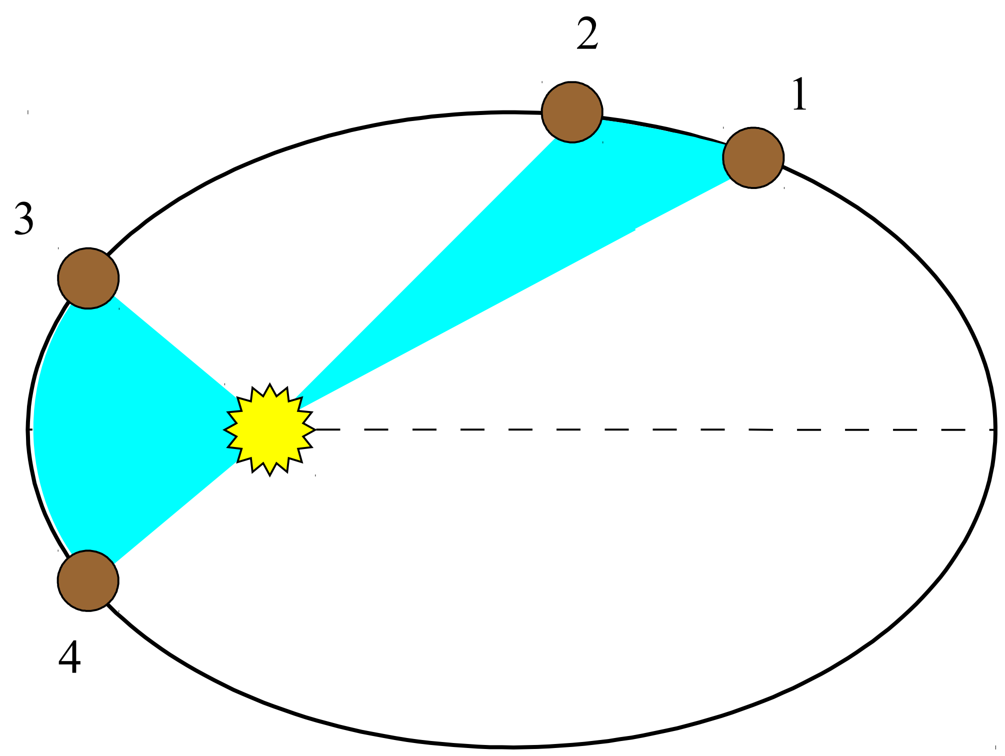
$$a^2-c^2=b^2$$

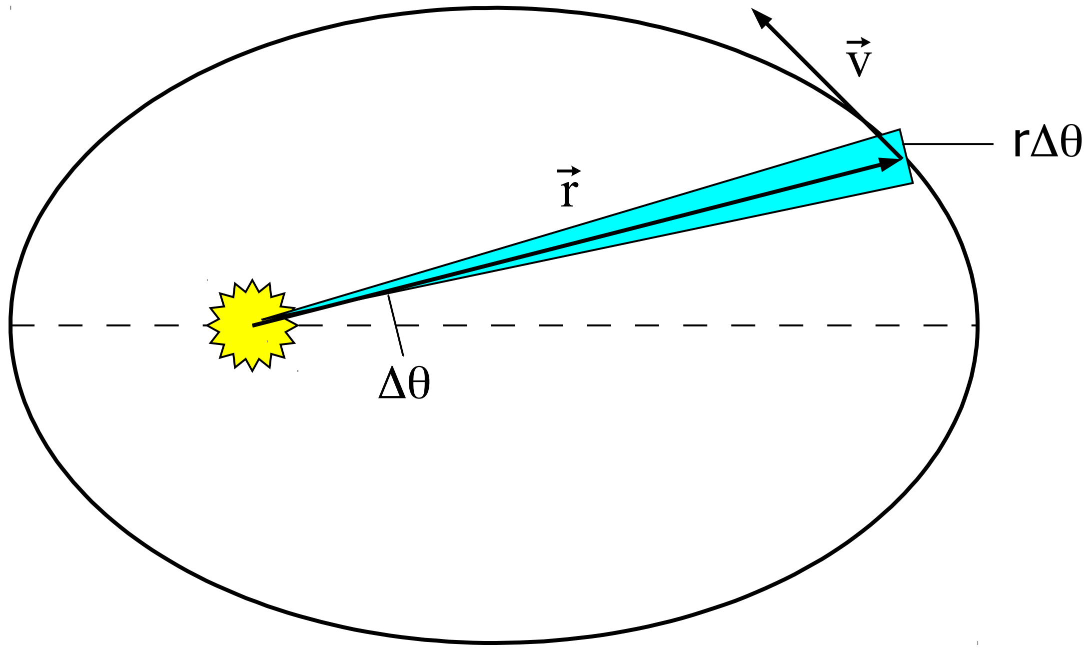
$$e=\sqrt{1-\frac{b^2}{a^2}}$$



2. Il segmento che collega un pianeta al Sole descrive aree uguali in tempi uguali.

$$\frac{\Delta A}{\Delta t} = \text{cost}$$





$$\frac{\Delta A}{\Delta t} = \frac{1}{2}\frac{r\,\Delta\theta\cdot r}{\Delta t} = \frac{1}{2}r^2\frac{\Delta\theta}{\Delta t} = \frac{1}{2}r^2\omega$$

$$\vec{L} = \vec{r} \wedge m\,\vec{v}$$

$$L = rm\cdot v\sin\theta = rmv_c = rm\,\omega\,r = mr^2\omega$$

$$\frac{\Delta A}{\Delta t} = \frac{L}{2m}$$

In un sistema isolato il momento angolare si conserva e il secondo membro è una costante

3. Il quadrato del periodo di qualunque pianeta è proporzionale al cubo della sua distanza media dal Sole.

$$\boxed{\frac{R^3}{T^2} = \text{cost}}$$

$$F_g = F_c \quad \Rightarrow \quad G\frac{Mm}{r^2} = m\,\omega^2 r \quad \Rightarrow \quad \omega^2 r^3 = GM$$

$$\omega = \frac{2\pi}{T} \quad \Rightarrow \quad \left(\frac{2\pi}{T}\right)^2 r^3 = GM$$

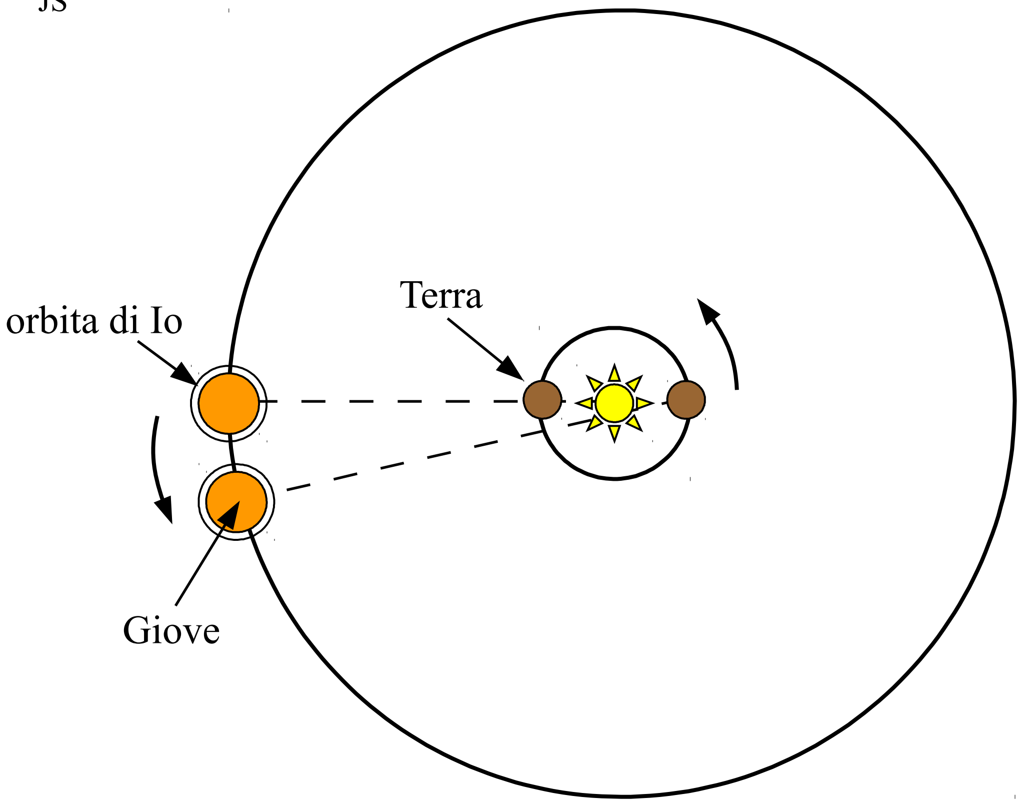
$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2} = k$$

I satelliti di Giove e la misura della velocità della luce

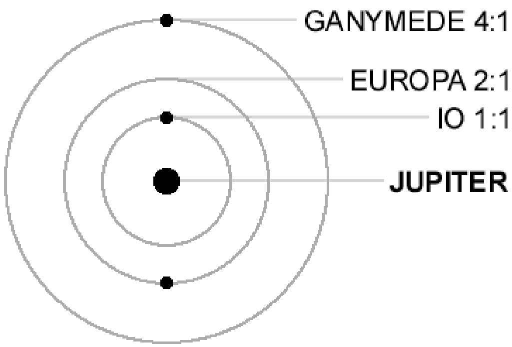
$D_{Io} = 421700\,km$

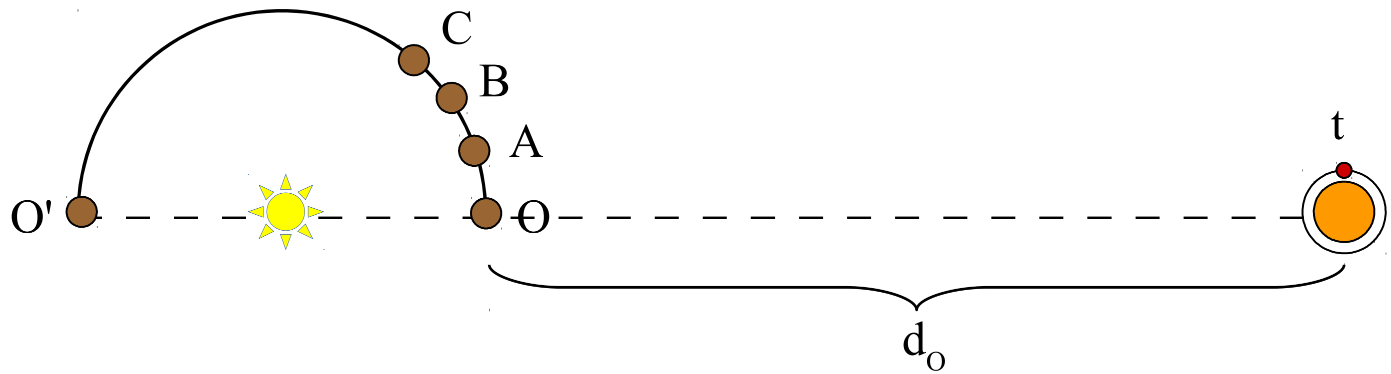
$T_{Io} = 42^h 27^m 34^s$

$D_{JS} = 5.2\,U.A.$



Olaf Rømer (1676)





$$t_A = t + \frac{d_A}{c}$$

$$t_B = t + T_{Io} + \frac{d_B}{c}$$

$$t_C = t + 2T_{Io} + \frac{d_C}{c}$$

$$t_B - t_A = T_{Io} + \frac{d_B - d_A}{c}$$

$$t_C - t_B = T_{Io} + \frac{d_C - d_B}{c}$$

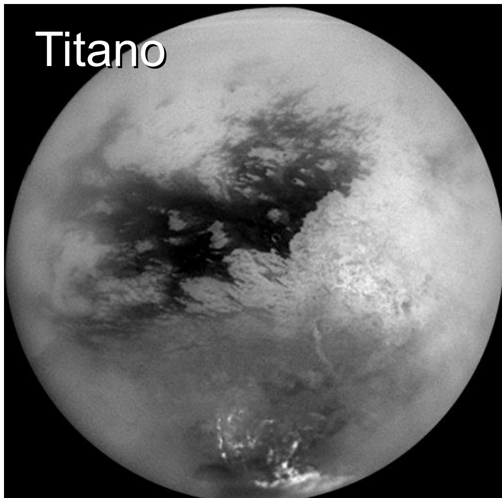
$$t_C - t_A = 2T_{Io} + \frac{d_C - d_A}{c}$$

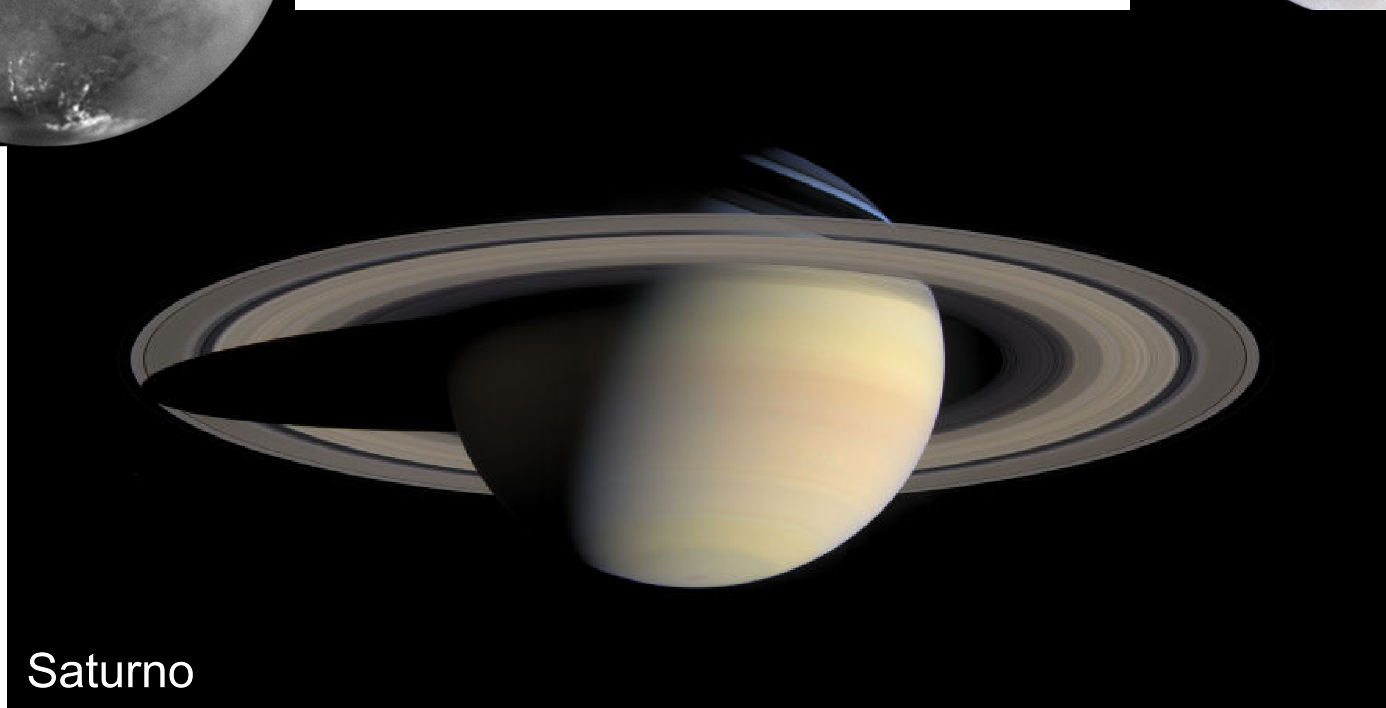
$$t_{O'} - t_O = (n-1)T_{Io} + \frac{d_{O'} - d_O}{c} = (n-1)T_{Io} + \frac{2D_{TS}}{c}$$

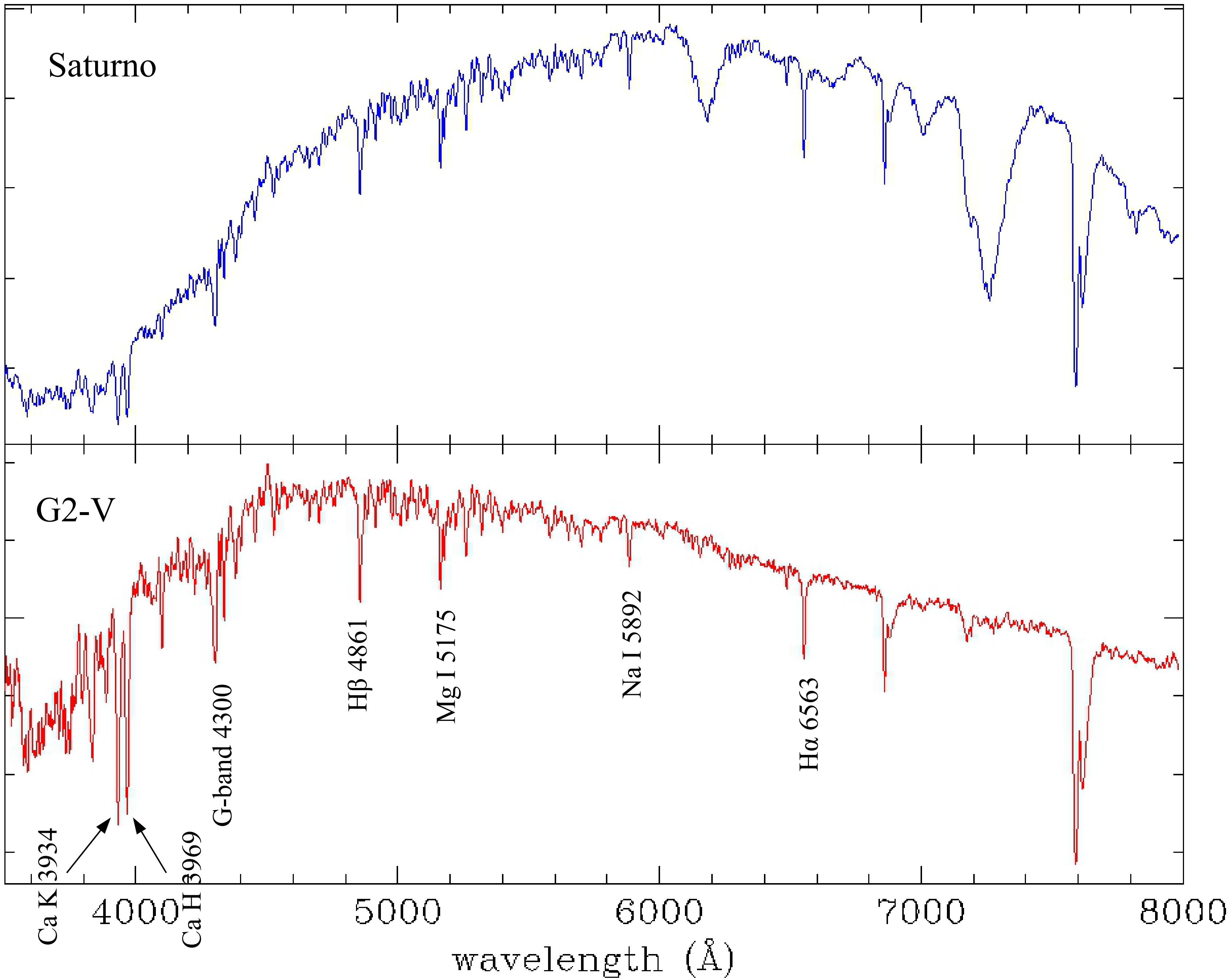
$$c = \frac{2D_{TS}}{t_{O'} - t_O - (n-1)T_{Io}}$$

Rømer → ~22 min ⇒ c ~ 220000 km/s

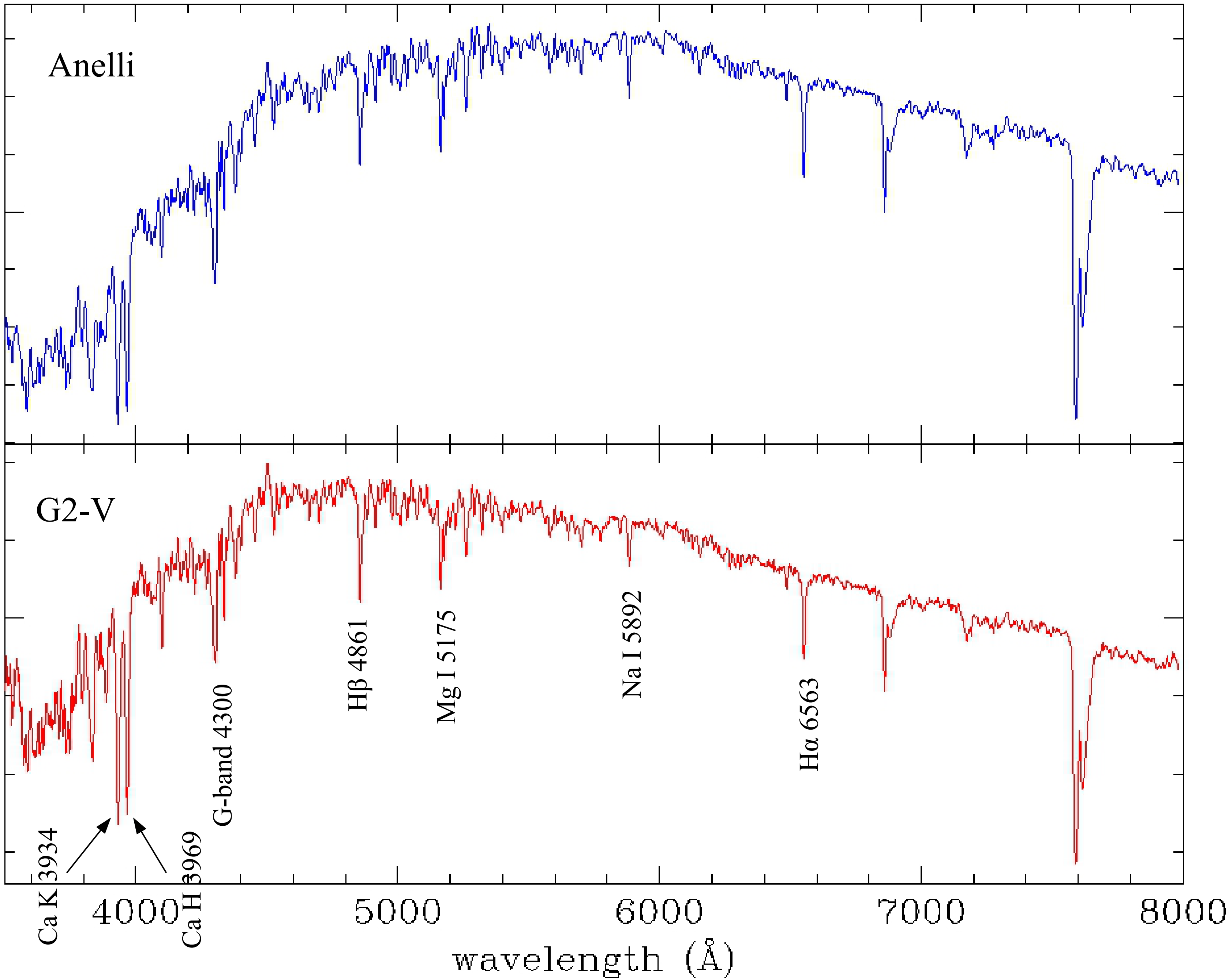
Spettroscopia dei pianeti



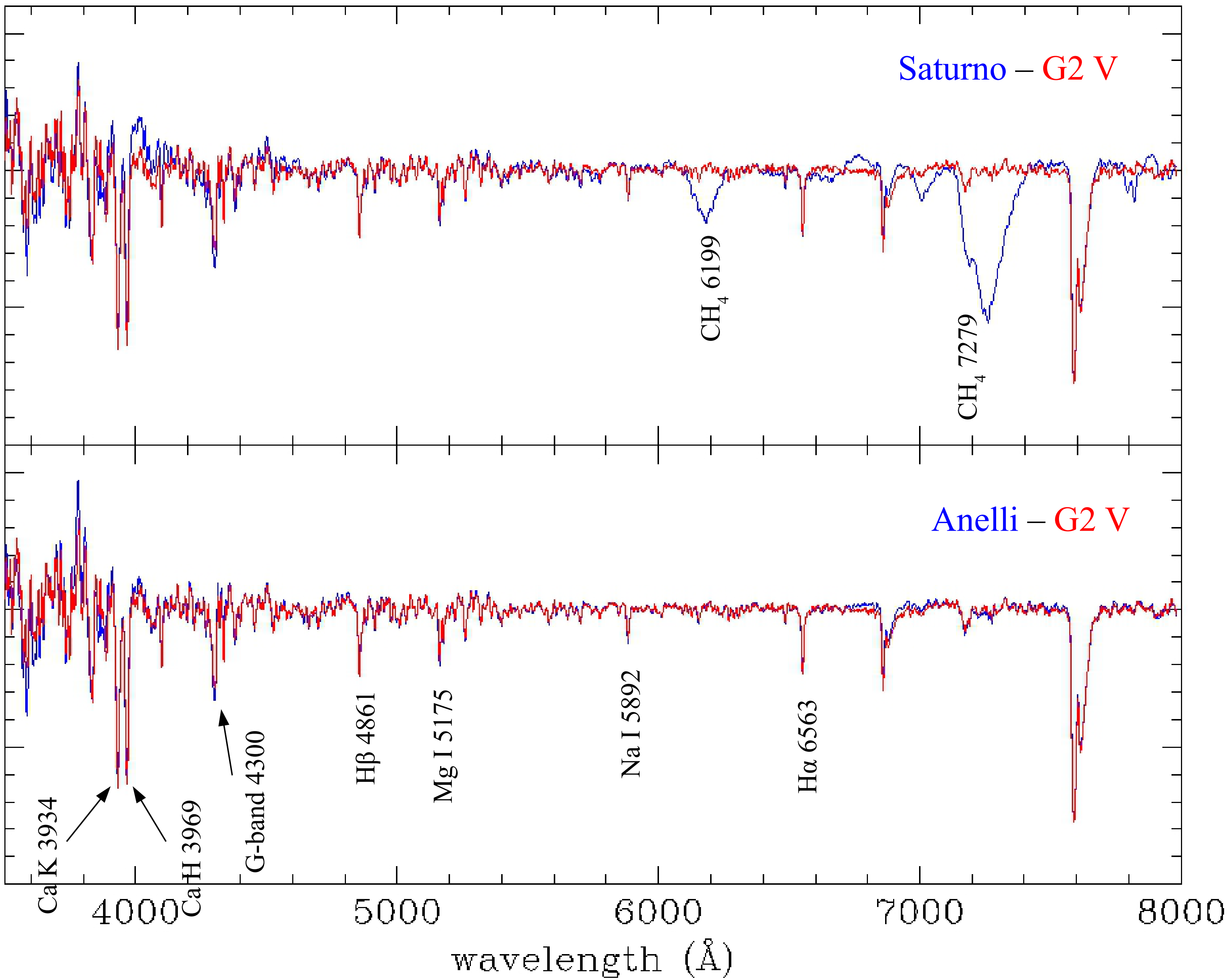




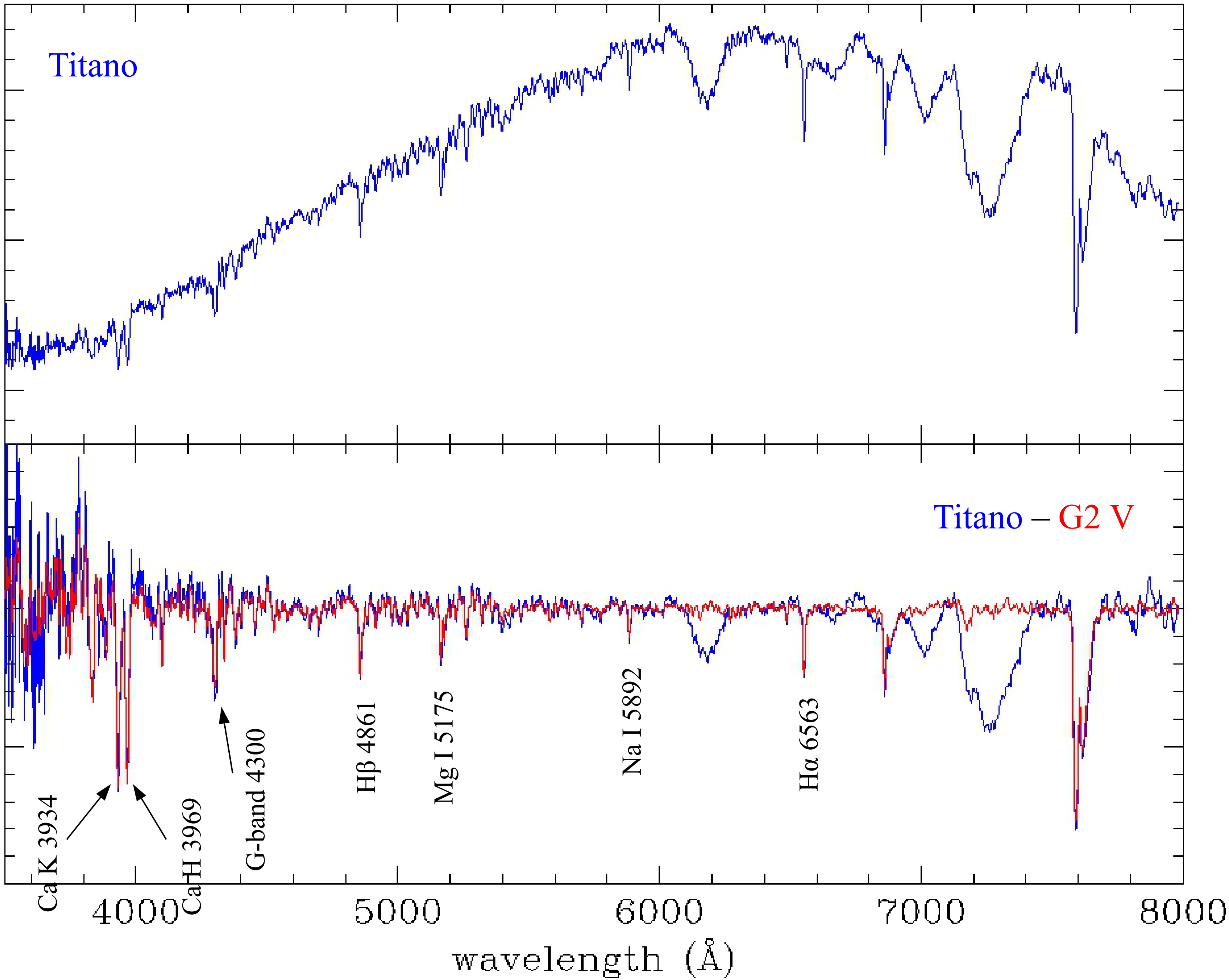
Saturno
G2-V
Ca K 3934
Ca H 3969
G-band 4300
Hβ 4861
Mg I 5175
Na I 5892
Hα 6563
4000
5000
6000
7000
8000
wavelength (Å)

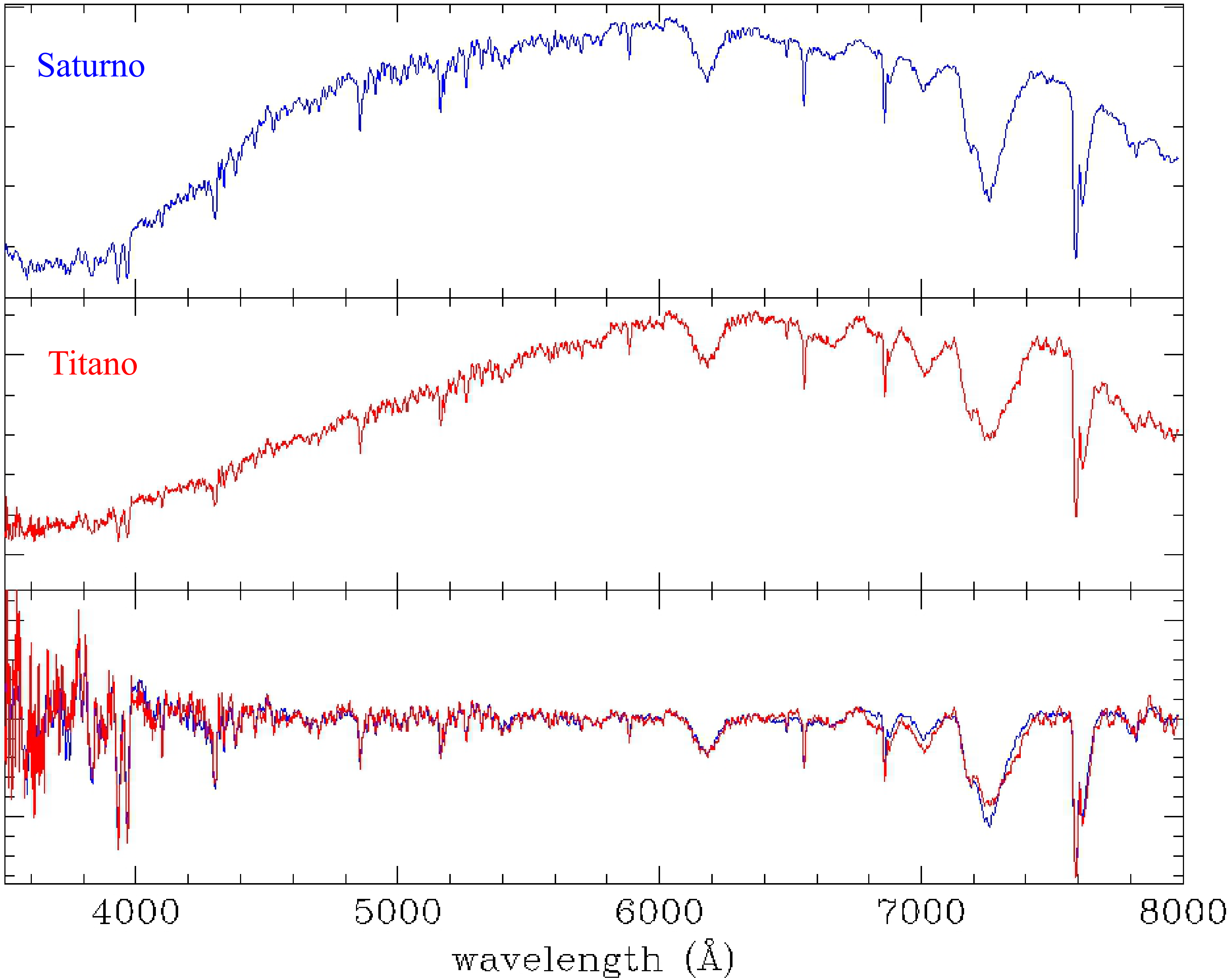


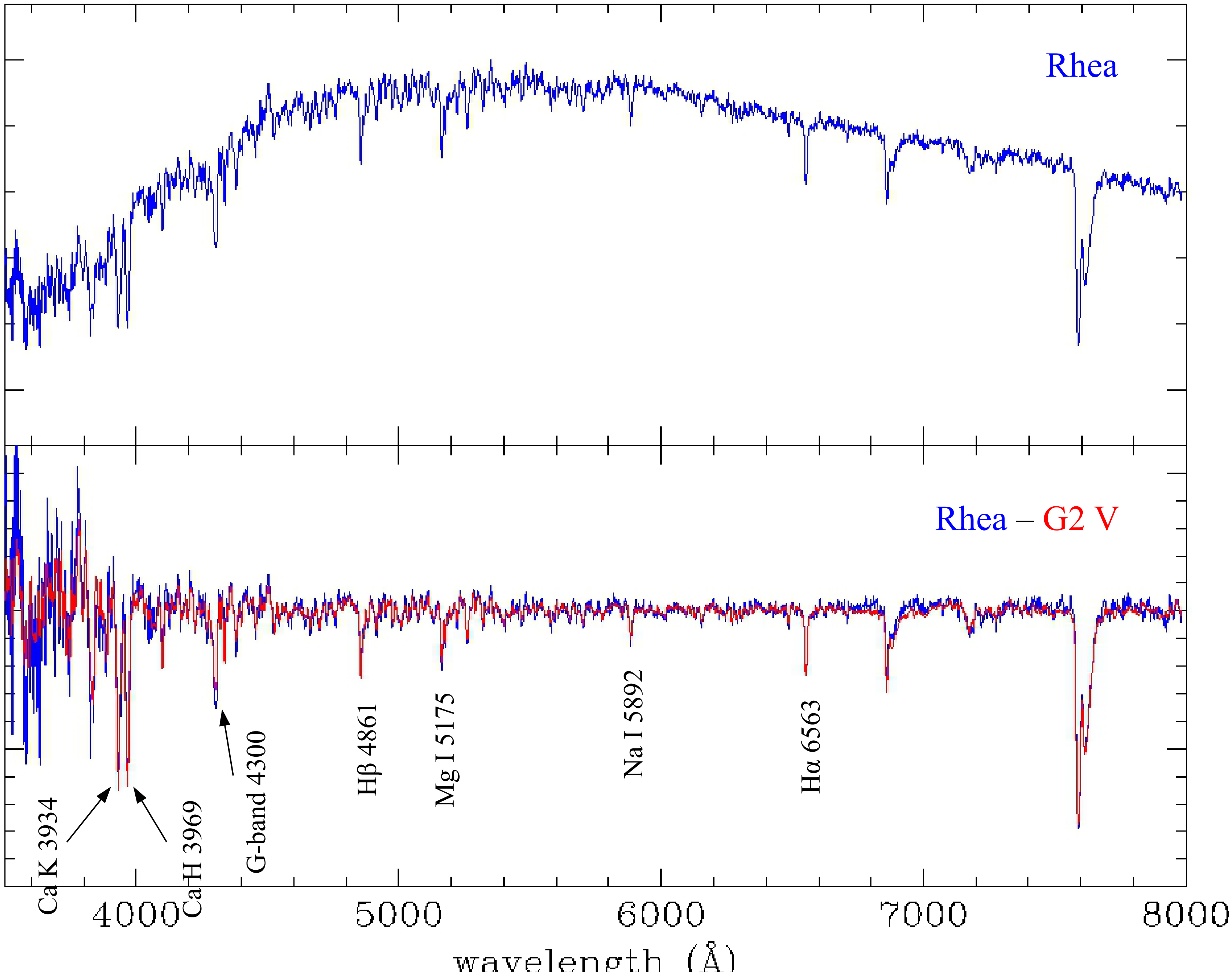
Anelli
G2-V
Ca K 3934
Ca H 3969
G-band 4300
Hβ 4861
Mg I 5175
Na I 5892
Hα 6563
4000
5000
6000
7000
8000
wavelength (Å)



Saturno – G2 V
CH$_4$ 6199
CH$_4$ 7279
Anelli – G2 V
Ca K 3934
Ca H 3969
G-band 4300
Hβ 4861
Mg I 5175
Na I 5892
Hα 6563
4000
5000
6000
7000
8000
wavelength (Å)

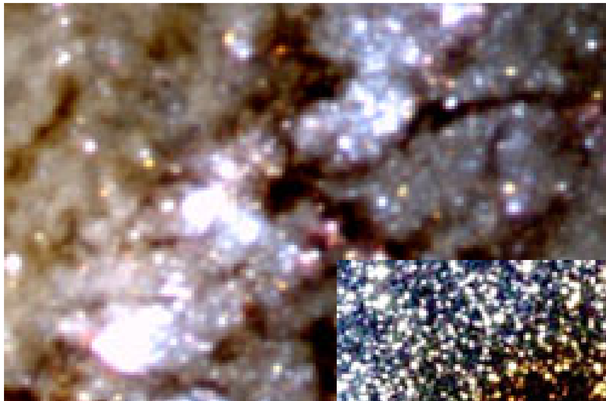

Titano
Titano – G2 V
Ca K 3934
CaH 3969
G-band 4300
Hβ 4861
Mg I 5175
Na I 5892
Hα 6563
4000
5000
6000
7000
8000
wavelength (Å)


Saturno
Titano
4000
5000
6000
7000
8000
wavelength (Å)

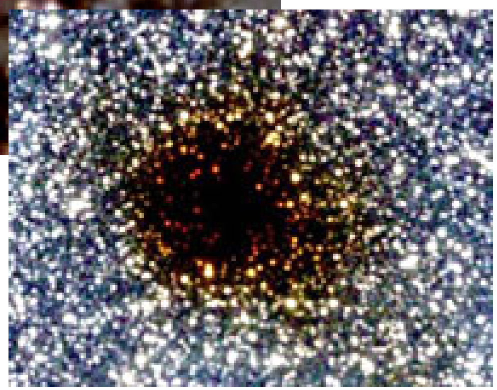


Rhea
Rhea – G2 V
Ca K 3934
Ca H 3969
G-band 4300
Hβ 4861
Mg I 5175
Na I 5892
Hα 6563
4000
5000
6000
7000
8000
wavelength (Å)

Formazione del Sistema Solare



Nube

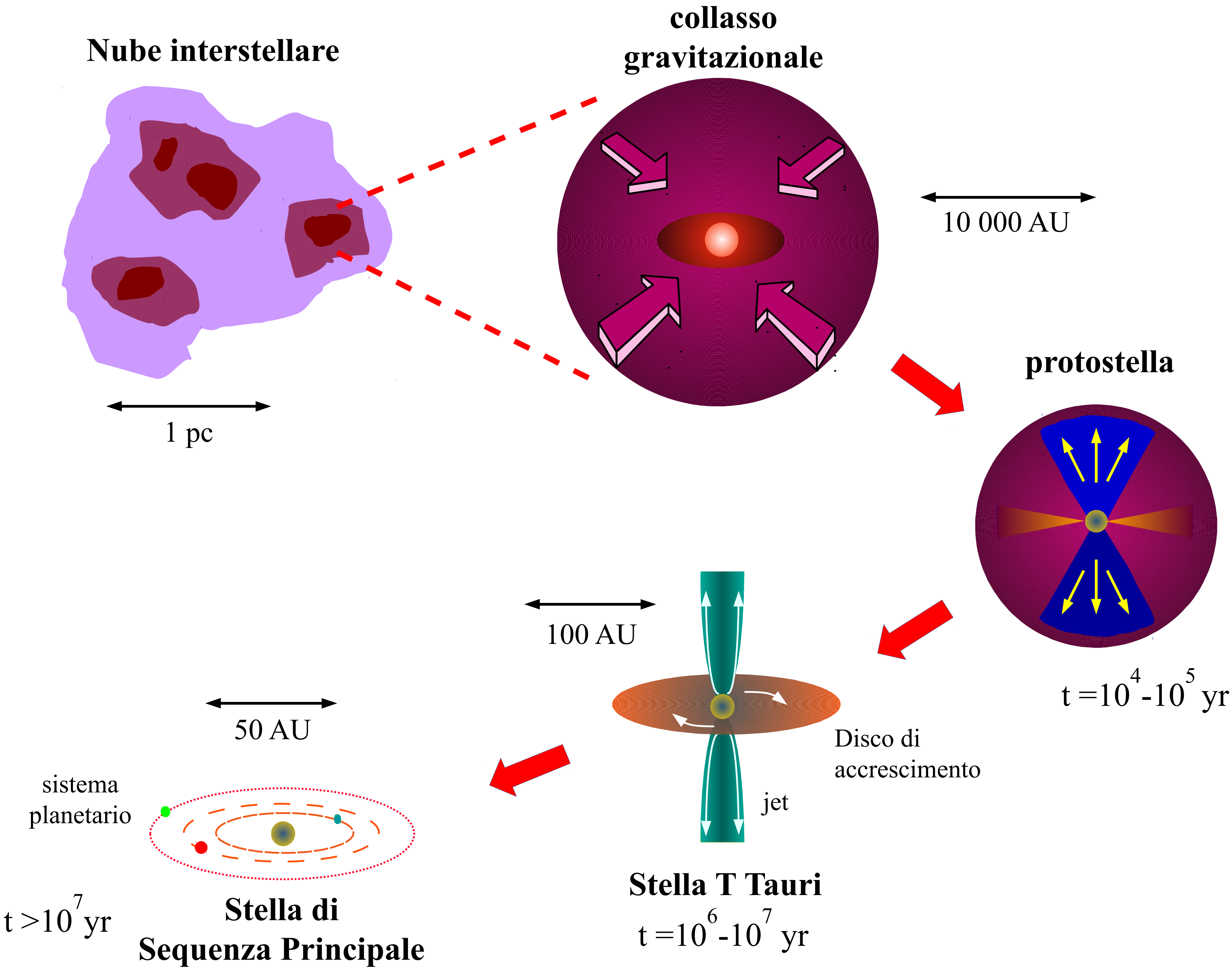


Nucleo

Disco

Stella

Pianeta



Nube interstellare
1 pc
collasso gravitazionale
10 000 AU
protostella
$t = 10^4 - 10^5$ yr
100 AU
Disco di accrescimento
jet
Stella T Tauri
$t = 10^6 - 10^7$ yr
50 AU
sistema planetario
$t > 10^7$ yr
Stella di Sequenza Principale

Formazione dei protopianeti

condensazione del gas in particelle solide (grani)

↓

aggregazione di grani di particelle solide fino alla formazione di planetesimi di dimensioni attorno al chilometro

↓

agglomerazione dei planetesimi in protopianeti

↓

acquisizione di gas dal mezzo interplanetario e/o produzione di gas da impatti successivi

↓

formazione dell'atmosfera

Eliminazione della nube residua

Stella in fase T Tauri (10^6-10^7 anni)

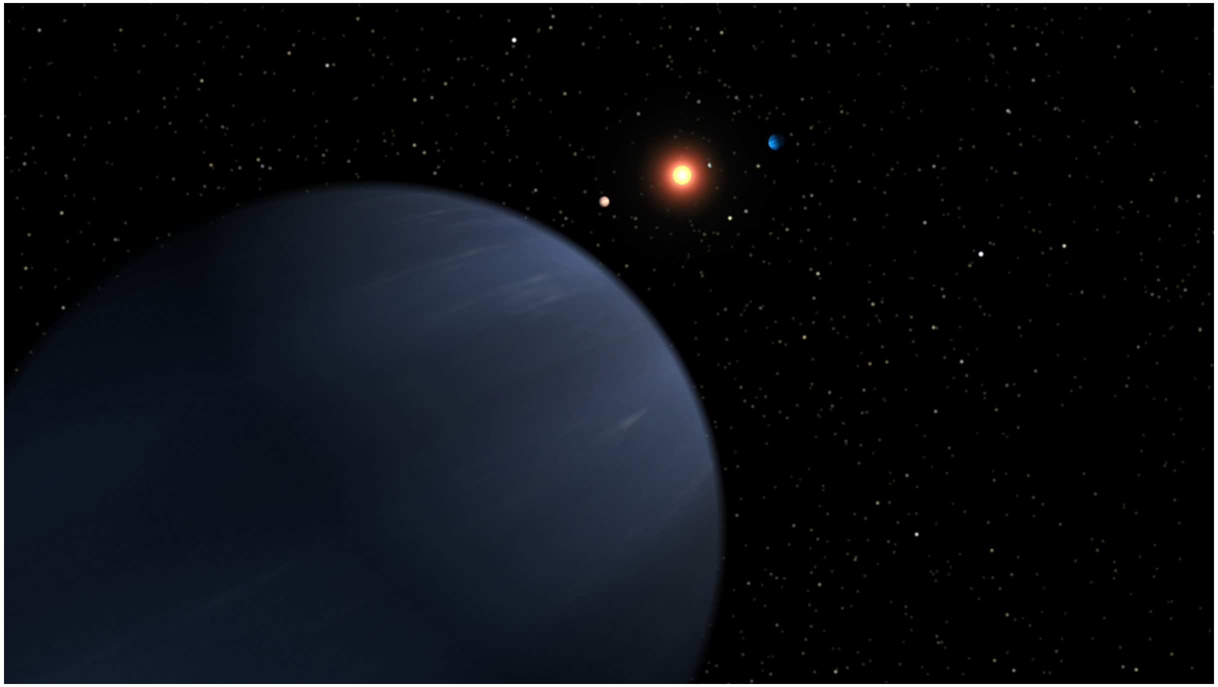
⬇

Vento stellare con v = 400 - 500 km/s

⬇

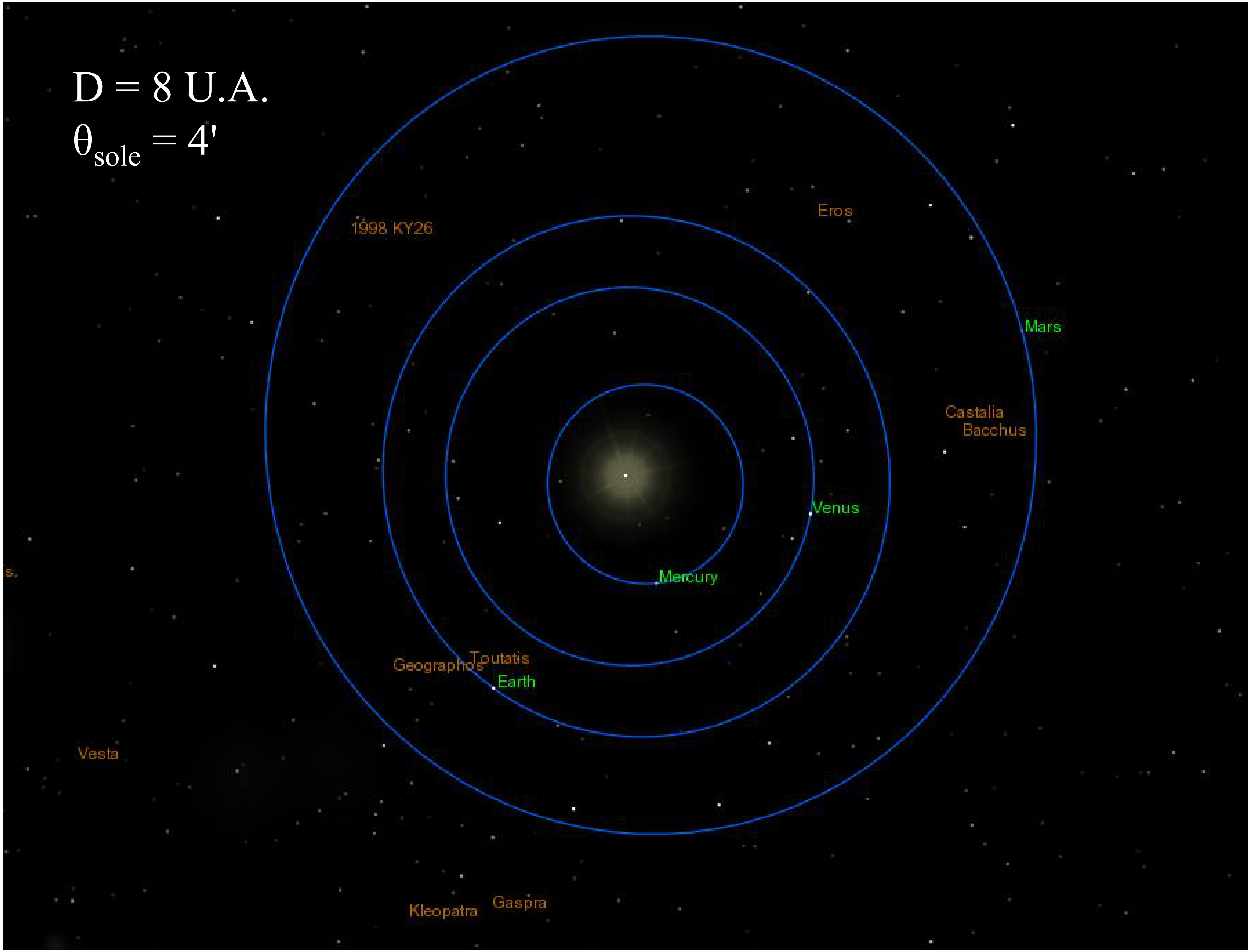
Il gas e le particelle con diametro inferiore a una decina di centimetri vengono eliminate dal sistema protoplanetario

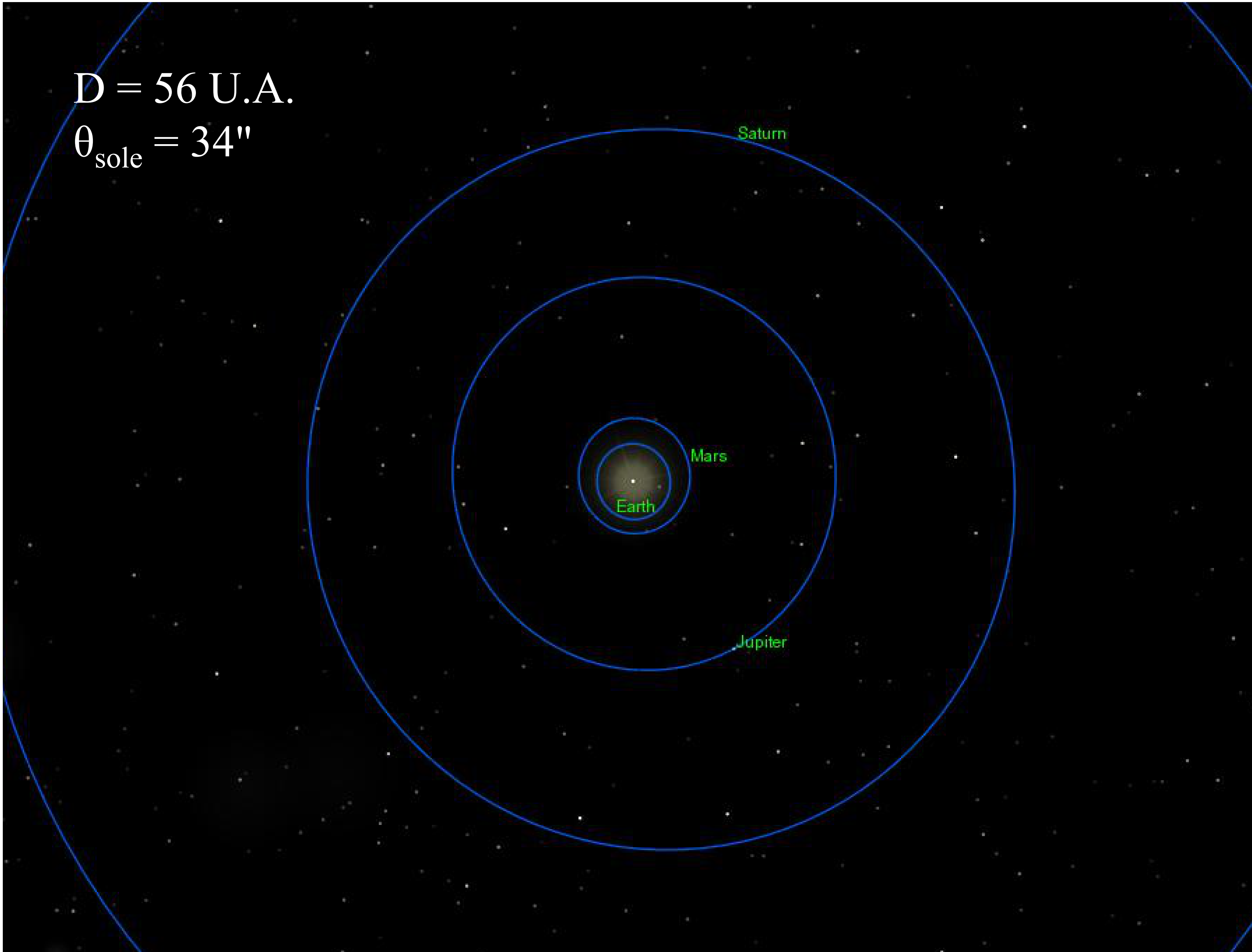
La ricerca di pianeti extrasolari

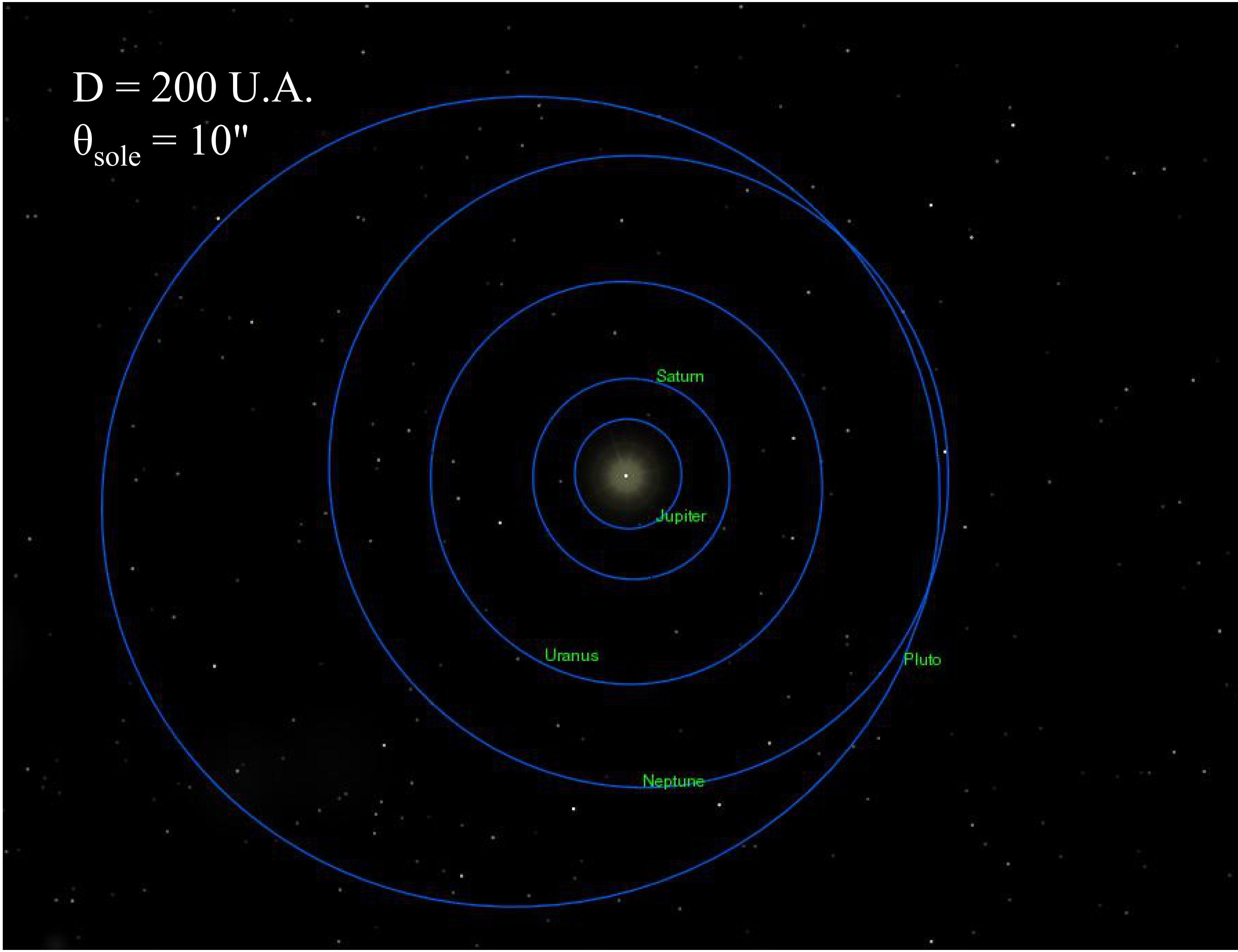


D = 8 U.A.

$\theta_{sole} = 4'$



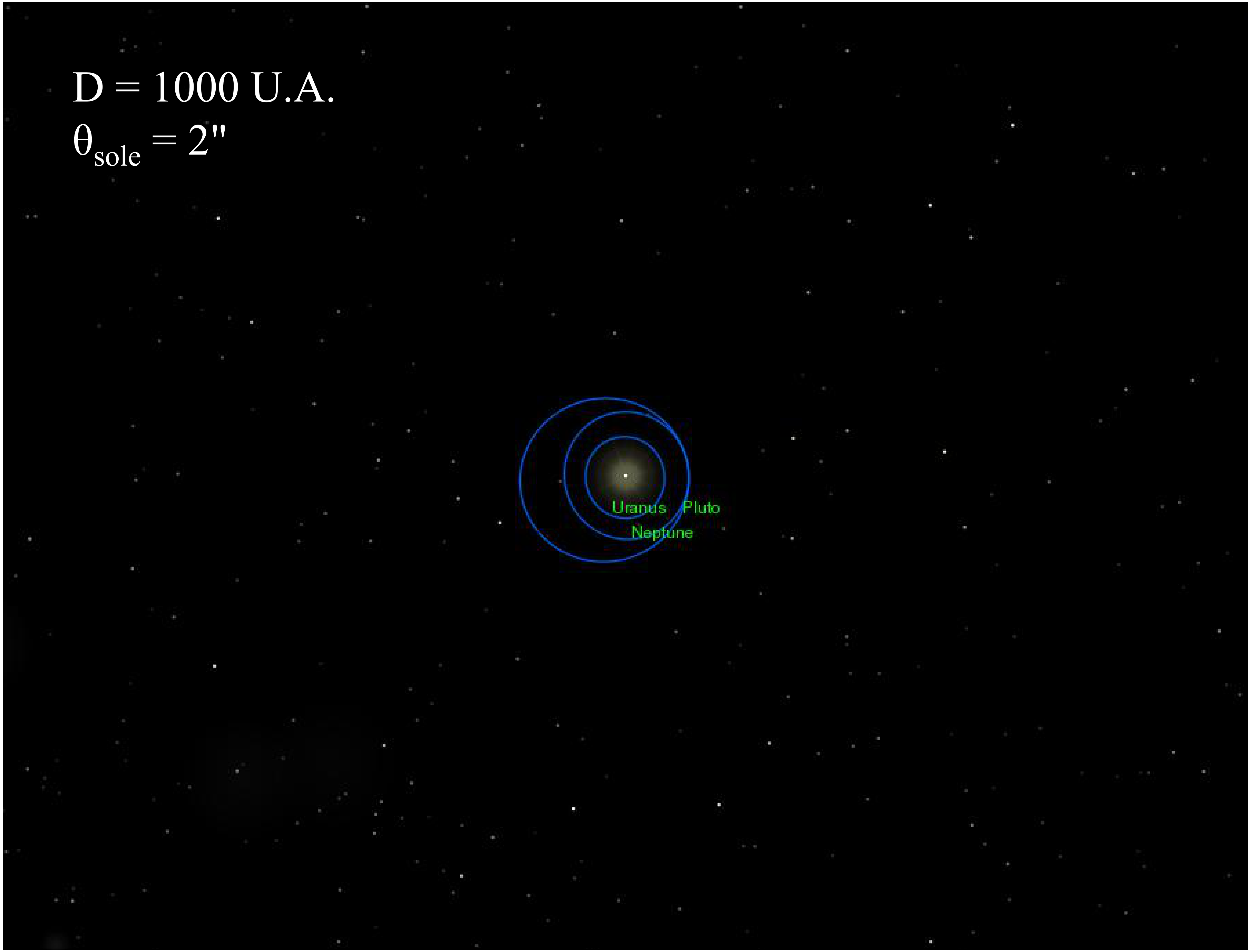

$D = 56$ U.A.
$\theta_{sole} = 34''$
Saturn
Mars
Earth
Jupiter



D = 200 U.A.
θsole = 10"
Saturn
Jupiter
Uranus
Neptune
Pluto

$D = 1000$ U.A.

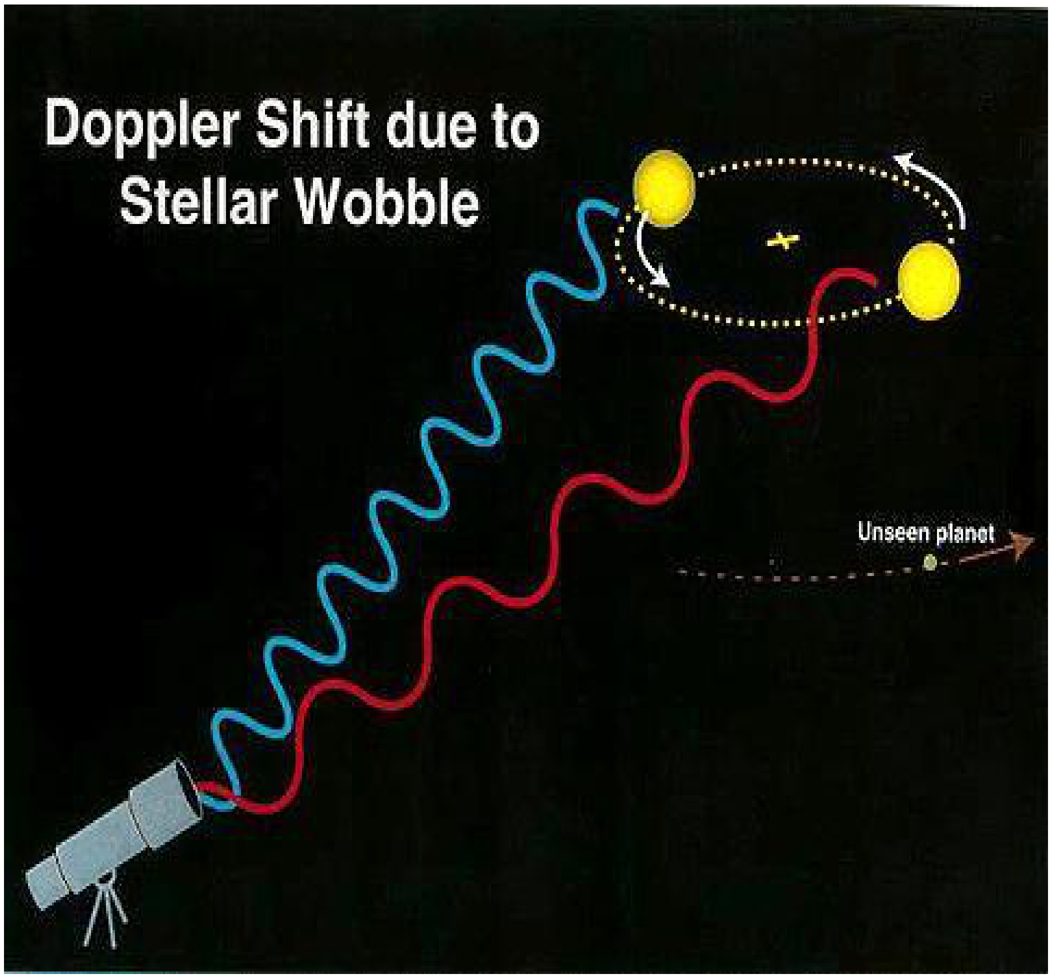
$\theta_{sole} = 2''$

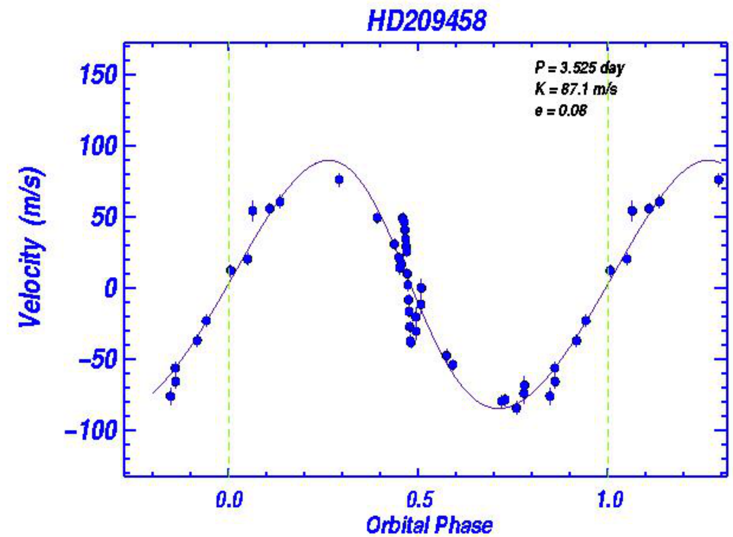


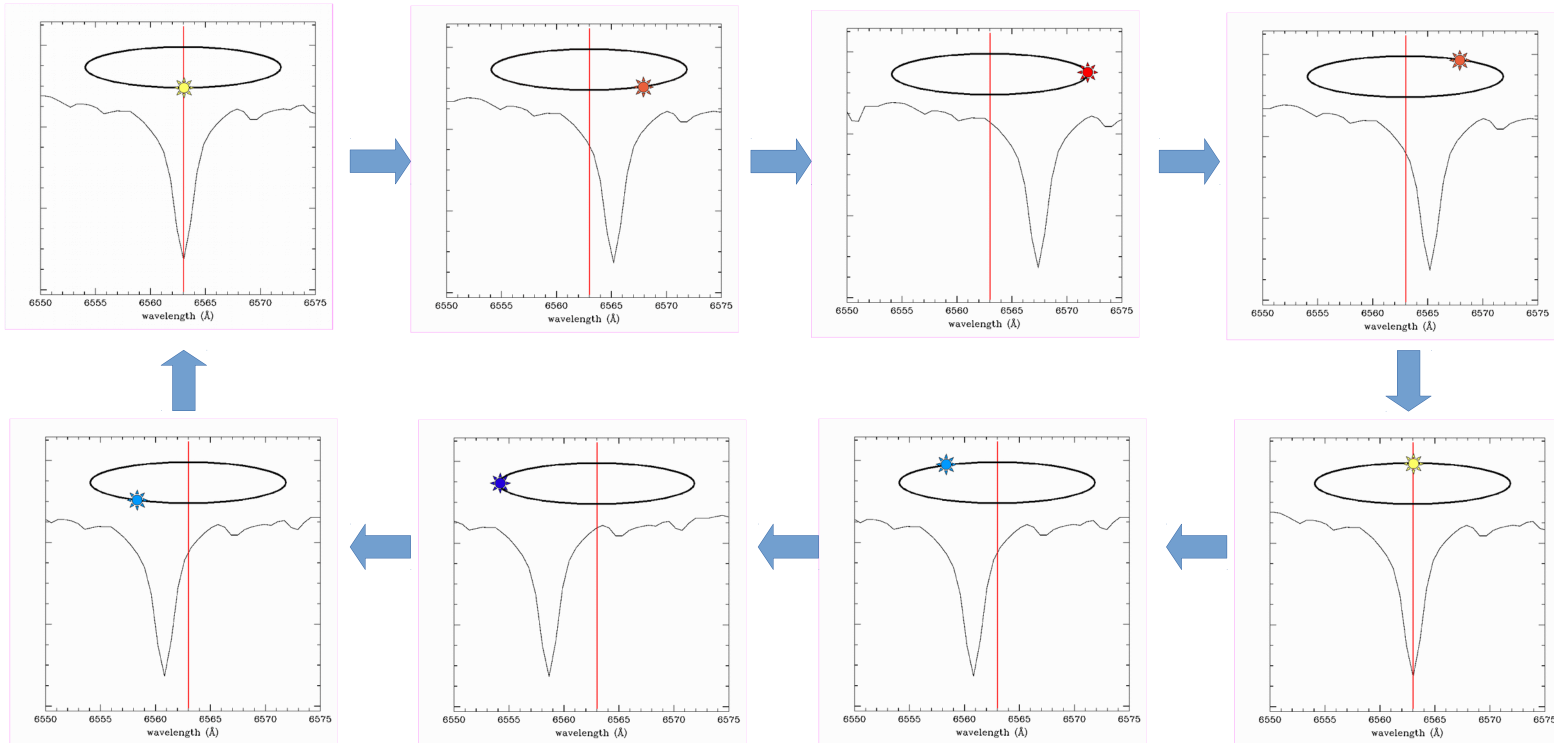

D = 0.027 A.L.
$\theta_{sole} = 1''$
Pluto
Neptune


D = 0.1 A.L.

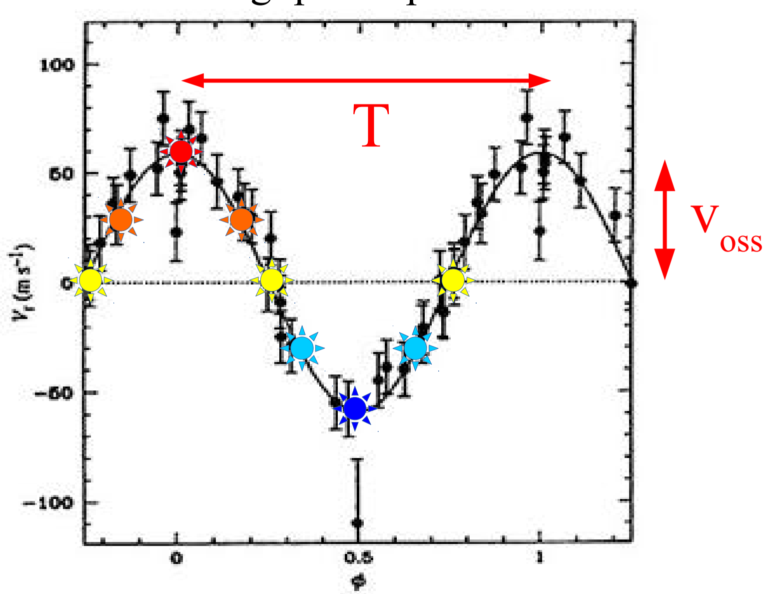
Tecnica spettroscopica: le velocità radiali



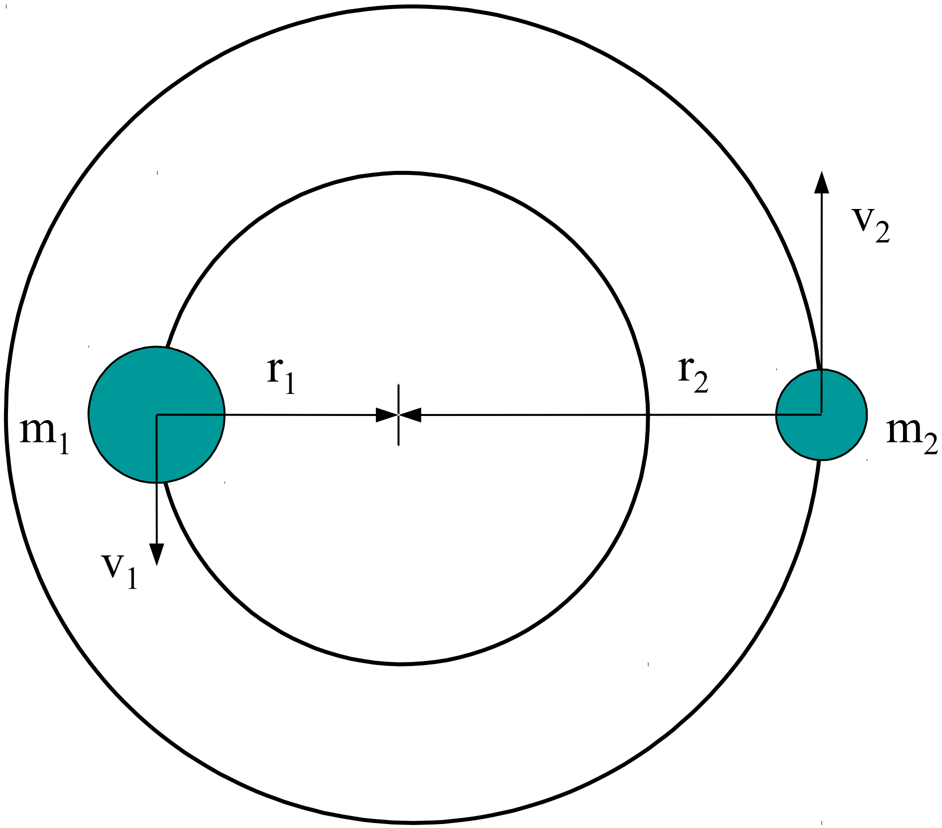




51 Peg: primo pianeta



Mayor & Queloz (1995)



centro di massa

$$\boxed{m_1 r_1 = m_2 r_2}$$

$$r = r_1 + r_2 = \left(\frac{m_1 + m_2}{m_1}\right) r_2$$

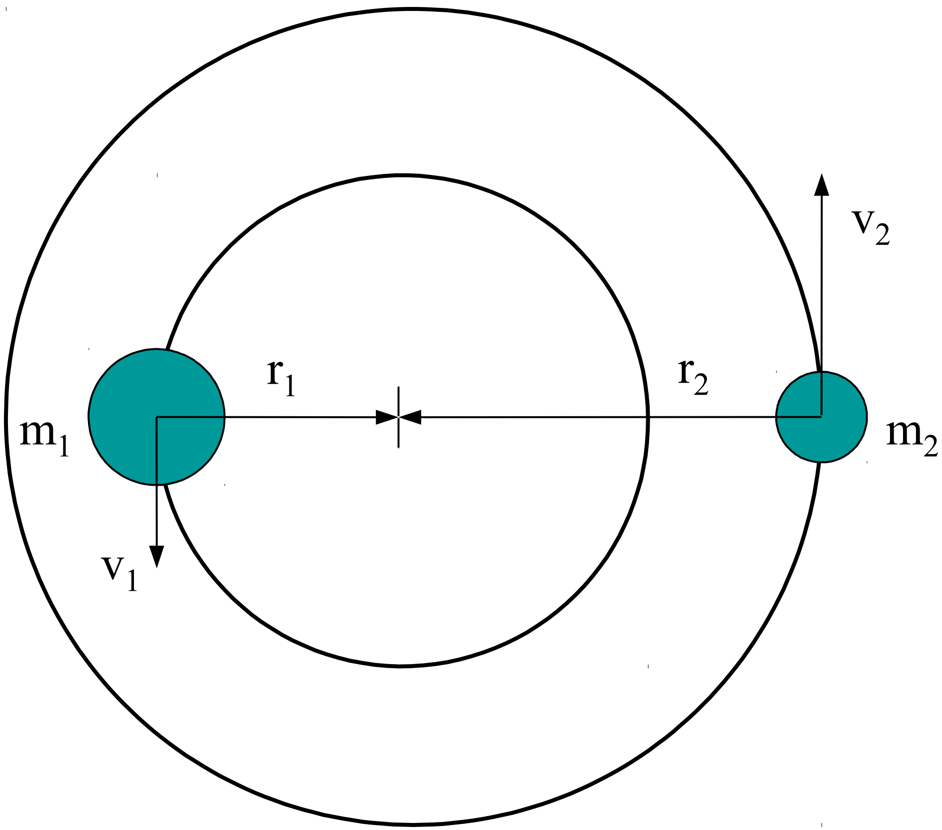
$F_g = F_c$

$$G\frac{m_1 m_2}{r^2} = m_2 \omega^2 r_2 = \frac{m_1 m_2}{m_1 + m_2}\omega^2 r$$

$$\omega^2 = G\frac{m_1 + m_2}{r^3}$$

3ª legge di Keplero →

$$\boxed{\frac{r^3}{T^2} = \frac{G}{4\pi^2}(m_1 + m_2)}$$



velocità circolare

$$\boxed{v_1 = \frac{2\pi r_1}{T} \qquad v_2 = \frac{2\pi r_2}{T}}$$

$$r = r_1 + r_2 = \frac{T}{2\pi}(v_1 + v_2)$$

$$m_1 v_1 = m_2 v_2$$

$$\frac{T^3}{8\pi^3}(v_1 + v_2)^3 \frac{1}{T^2} = \frac{G}{4\pi^2}(m_1 + m_2)$$

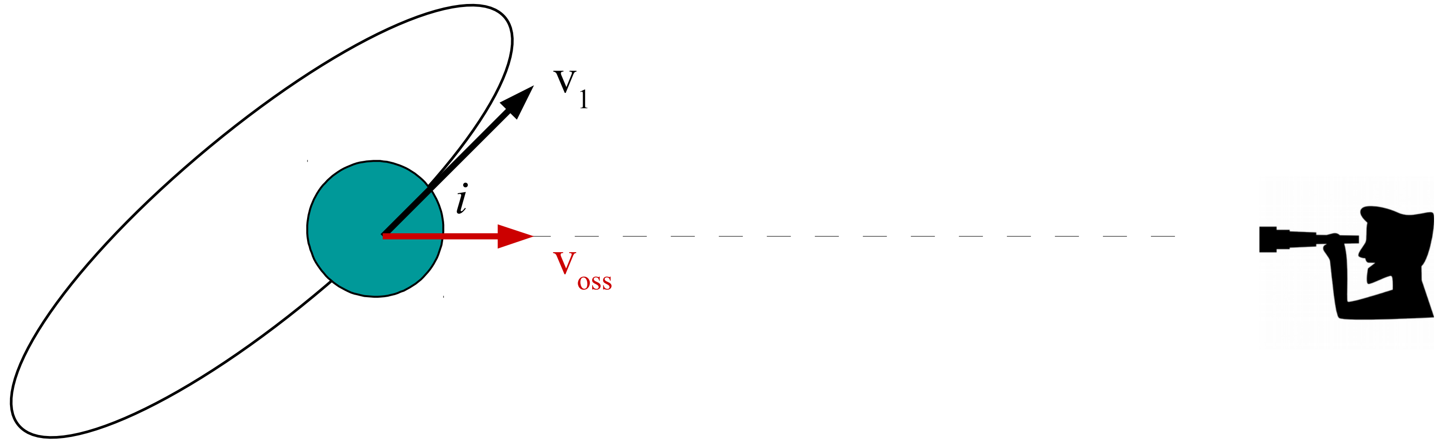
$$m_1 + m_2 = \frac{T}{2\pi G}(v_1 + v_2)^3 = \frac{T}{2\pi G}\left(v_1 + \frac{m_1}{m_2} v_1\right)^3$$

$$\boxed{\frac{m_2^3}{(m_1 + m_2)^2} = \frac{T v_1^3}{2\pi G}}$$

$$m_1 = M_S$$
$$m_2 = m_P$$
$$M_S \gg m_P$$

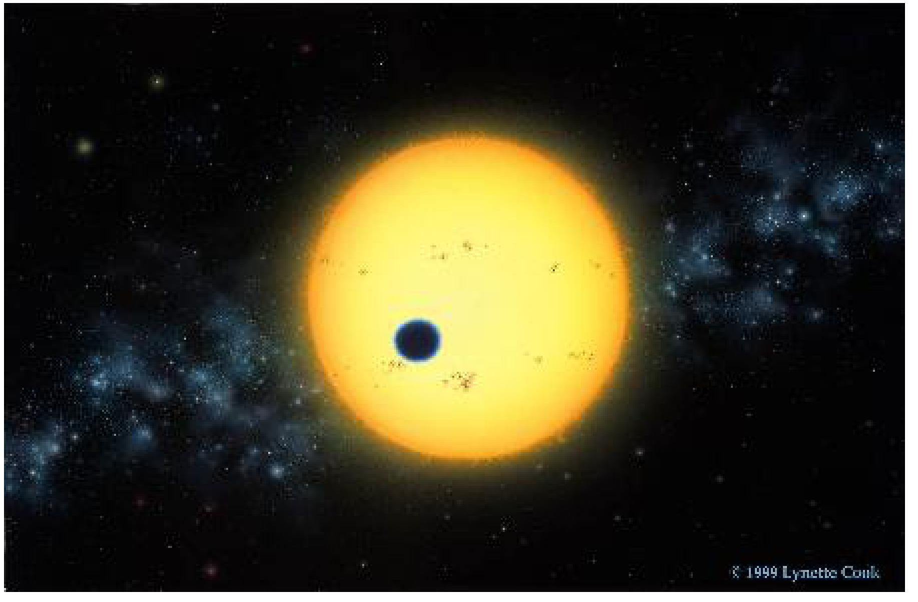
$$\boxed{r^3 \simeq \frac{G\,T^2\,M_S}{4\pi^2}}$$

$$m_P^3 \simeq \frac{T\,M_S^2\,v_1^3}{2\pi G}$$



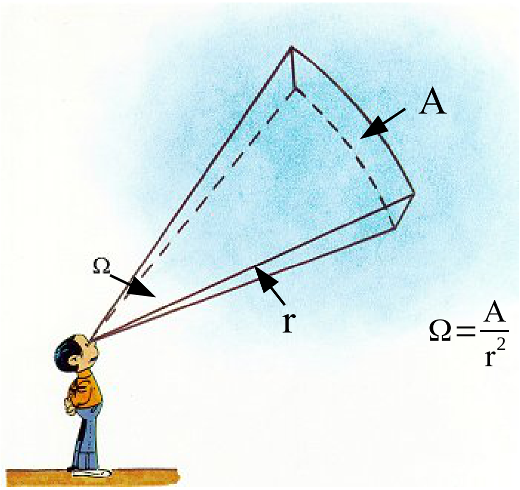
$$v_1 = \frac{v_{oss}}{\sin i} \Rightarrow \boxed{(m_P \sin i)^3 \simeq \frac{T\,M_S^2\,v_{oss}^3}{2\pi G}}$$

Tecnica fotometrica: i transiti



Esempio Sole-Giove

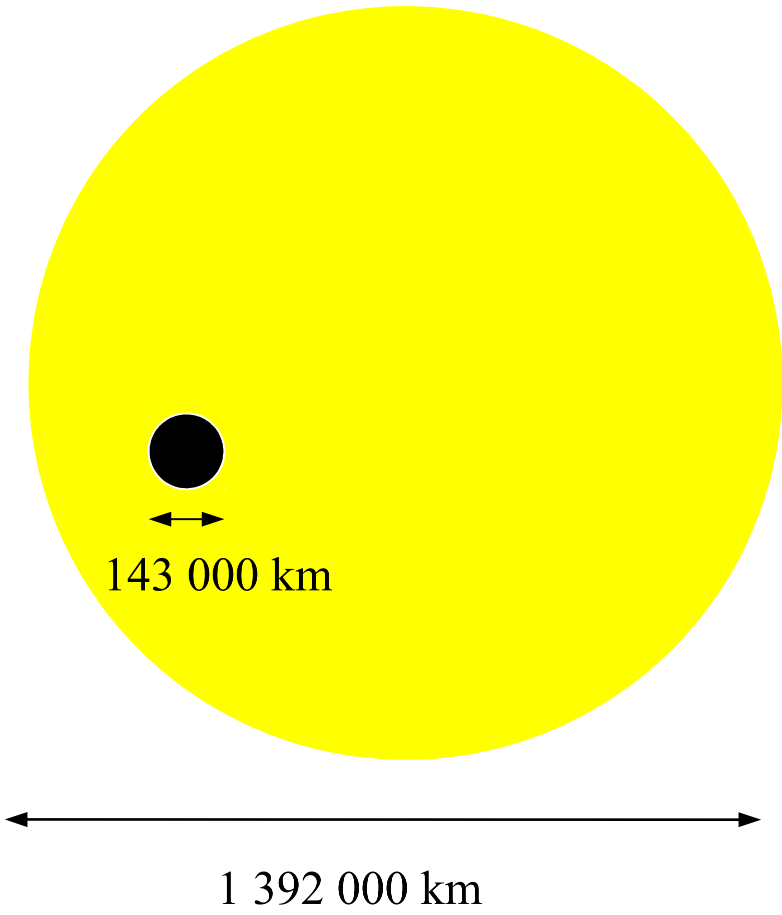
$$D_{oss} \gg D_{SG}$$



$$\Omega_{sole} = \frac{\pi R^2_{sole}}{D^2_{oss}}$$

$$\Omega_{giove} = \frac{\pi R^2_{giove}}{D^2_{oss}}$$

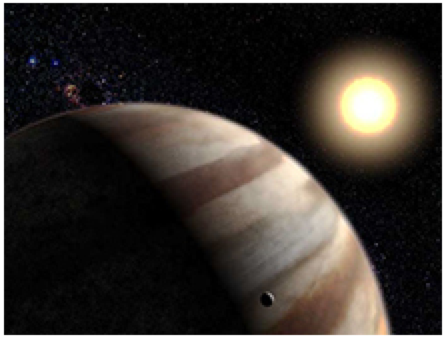
$$\frac{\Omega_{giove}}{\Omega_{sole}} = \frac{R^2_{giove}}{R^2_{sole}} \simeq 0.01$$

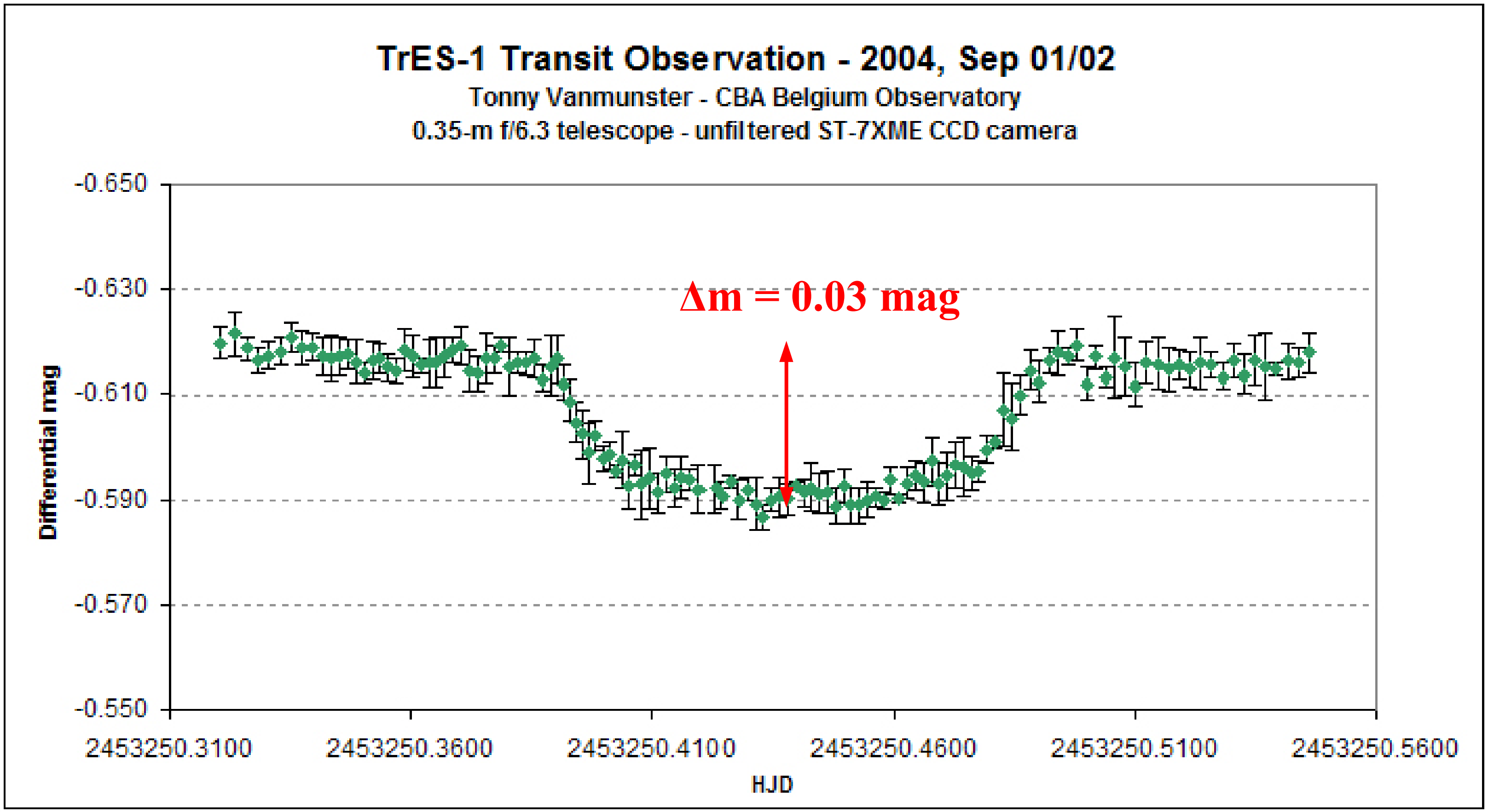


$$m'_{sole} - m_{sole} = -2.5 \log\left(\frac{f'_{sole}}{f_{sole}}\right)$$

$$f'_{sole} = f_{sole} - f_{sole}\frac{\Omega_{giove}}{\Omega_{sole}} = f_{sole}\left(1 - \frac{\Omega_{giove}}{\Omega_{sole}}\right)$$

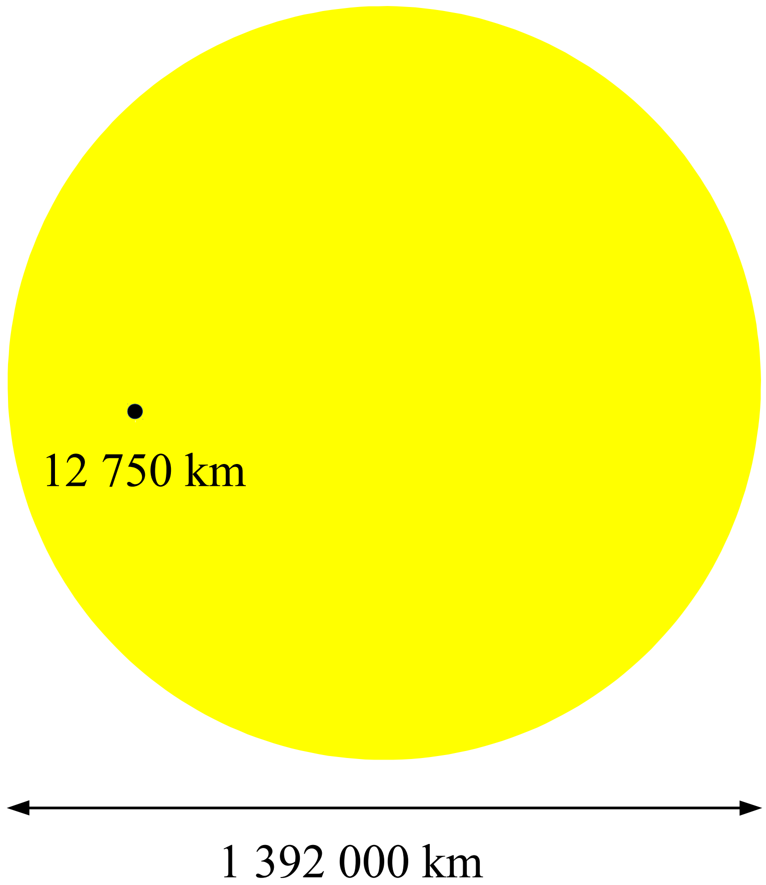
$$\Delta m_{sole} = -2.5 \log\left(1 - \frac{\Omega_{giove}}{\Omega_{sole}}\right) = 0.01$$





TrES-1 Transit Observation - 2004, Sep 01/02
Tonny Vanmunster - CBA Belgium Observatory
0.35-m f/6.3 telescope - unfiltered ST-7XME CCD camera
Δm = 0.03 mag
Differential mag
-0.650
-0.630
-0.610
-0.590
-0.570
-0.550
2453250.3100
2453250.3600
2453250.4100
2453250.4600
2453250.5100
2453250.5600
HJD

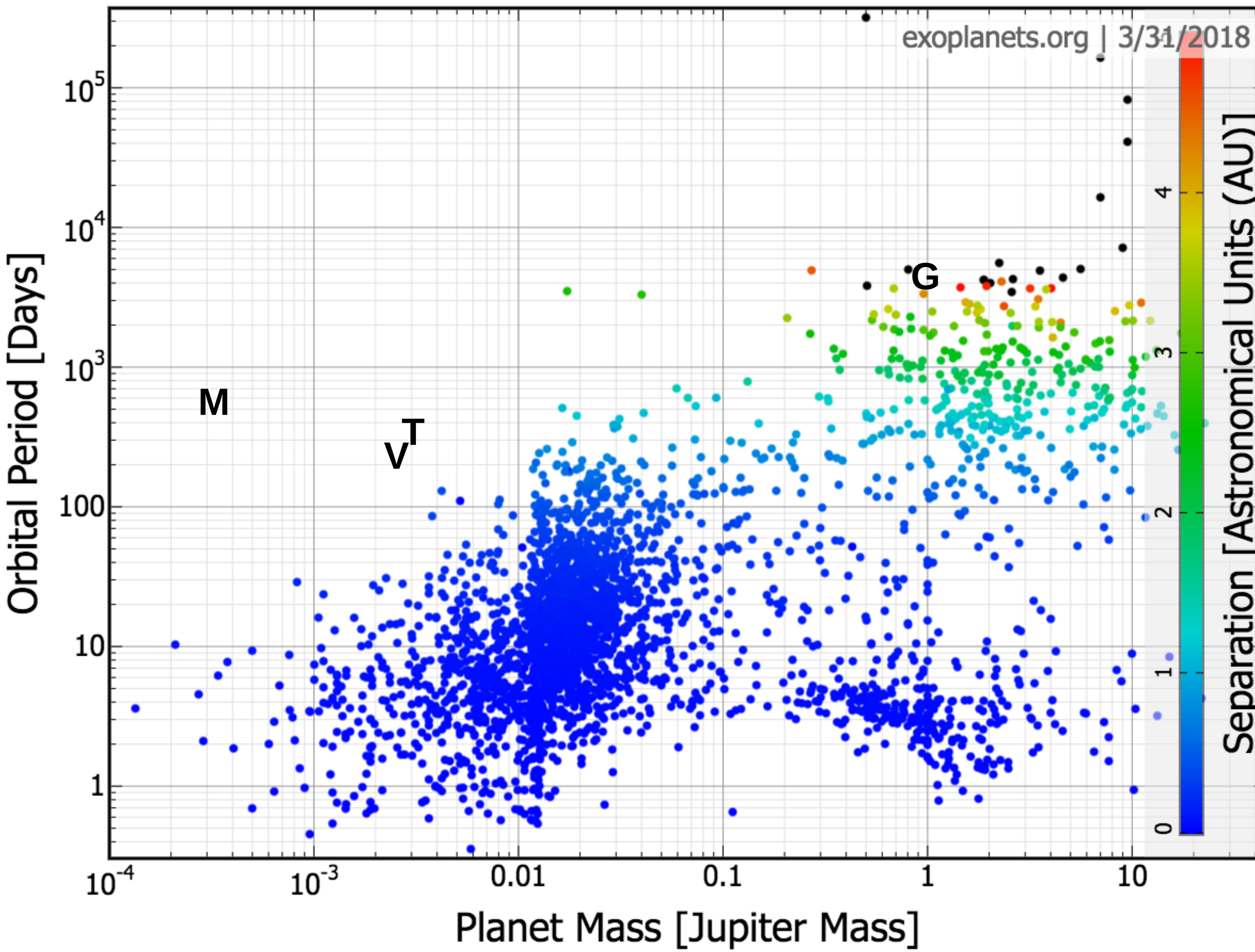
Esempio Sole-Terra

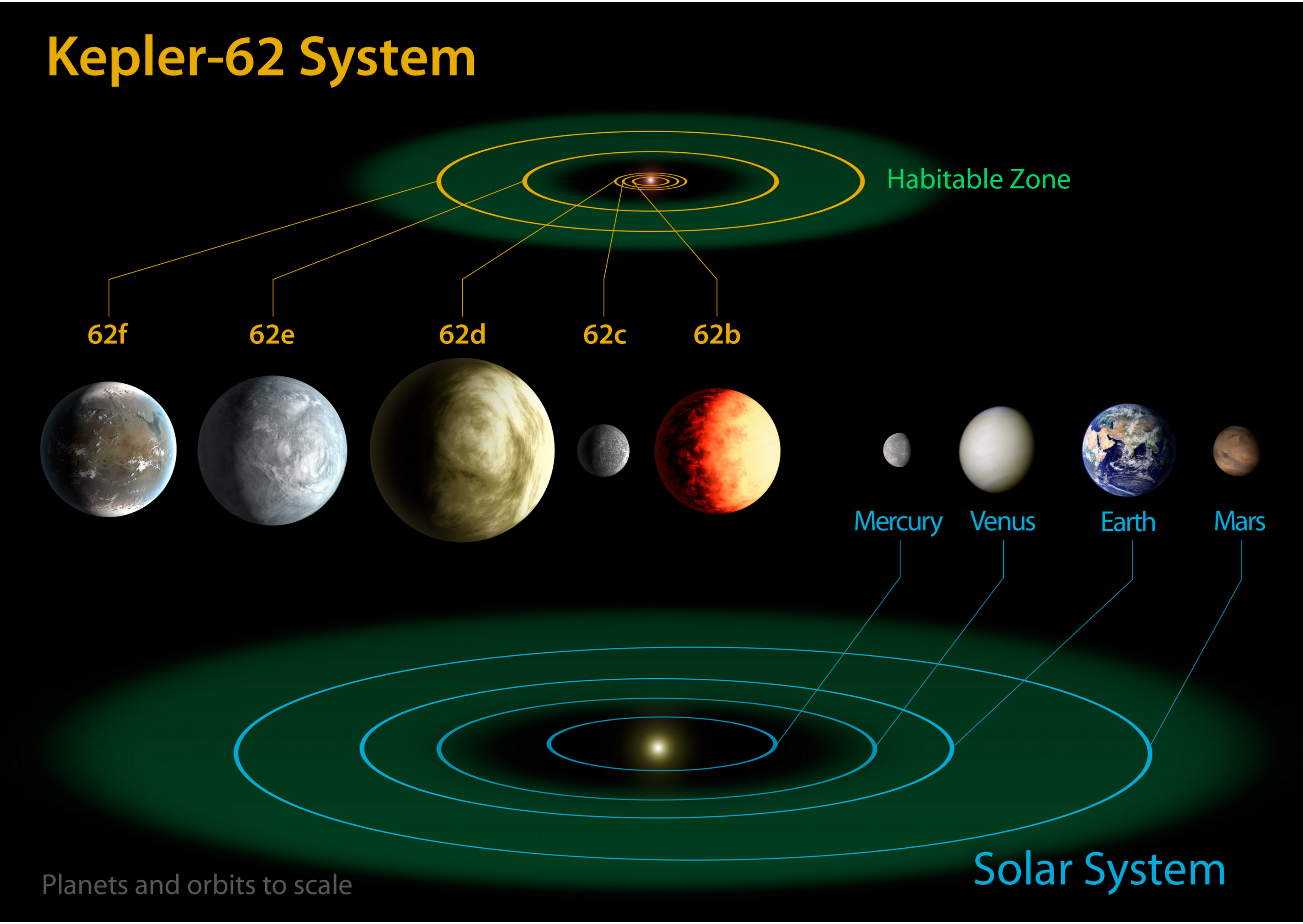


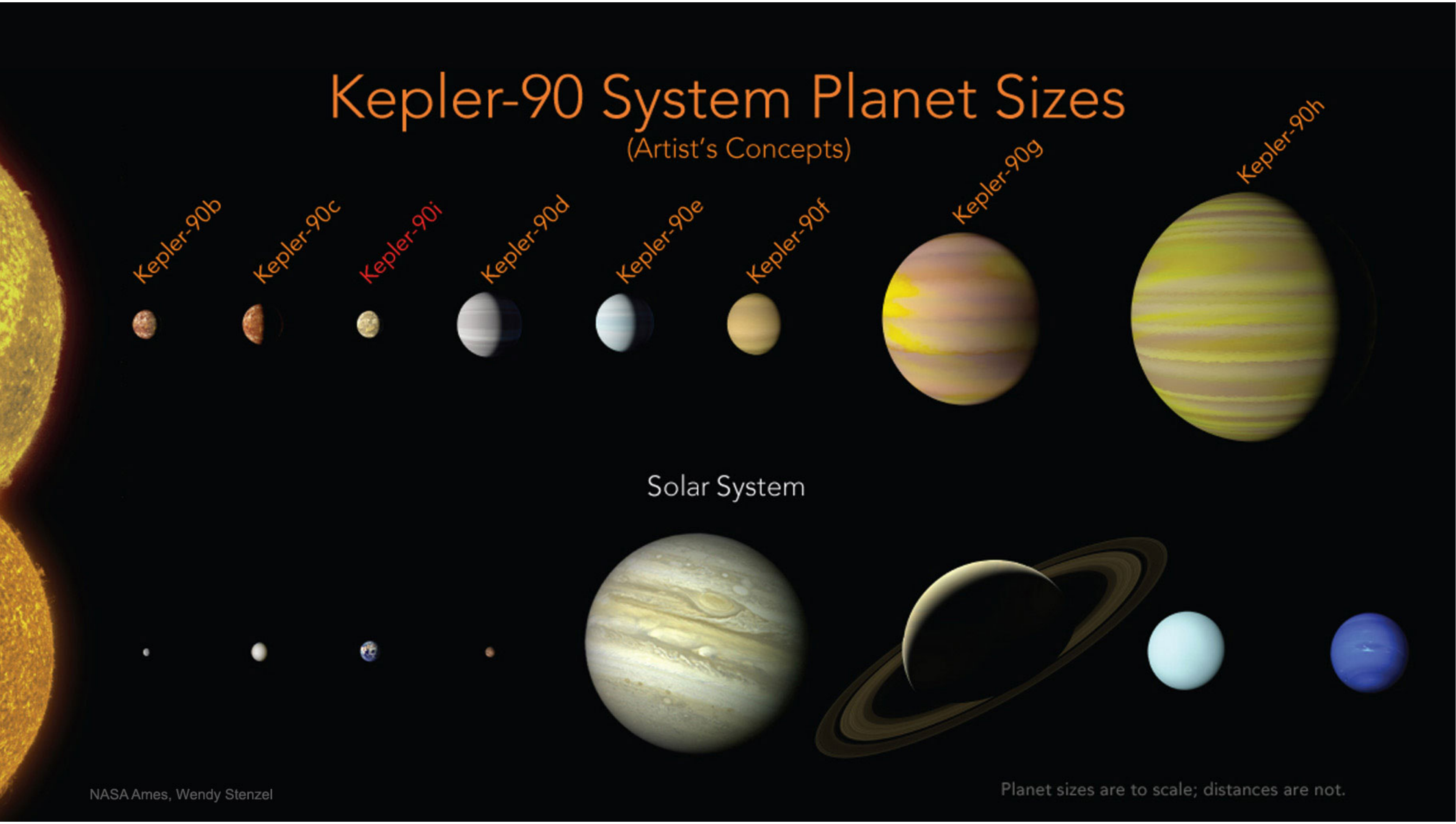
$$\frac{\Omega_{terra}}{\Omega_{sole}} = \frac{R^2_{terra}}{R^2_{sole}} \simeq 0.000084$$

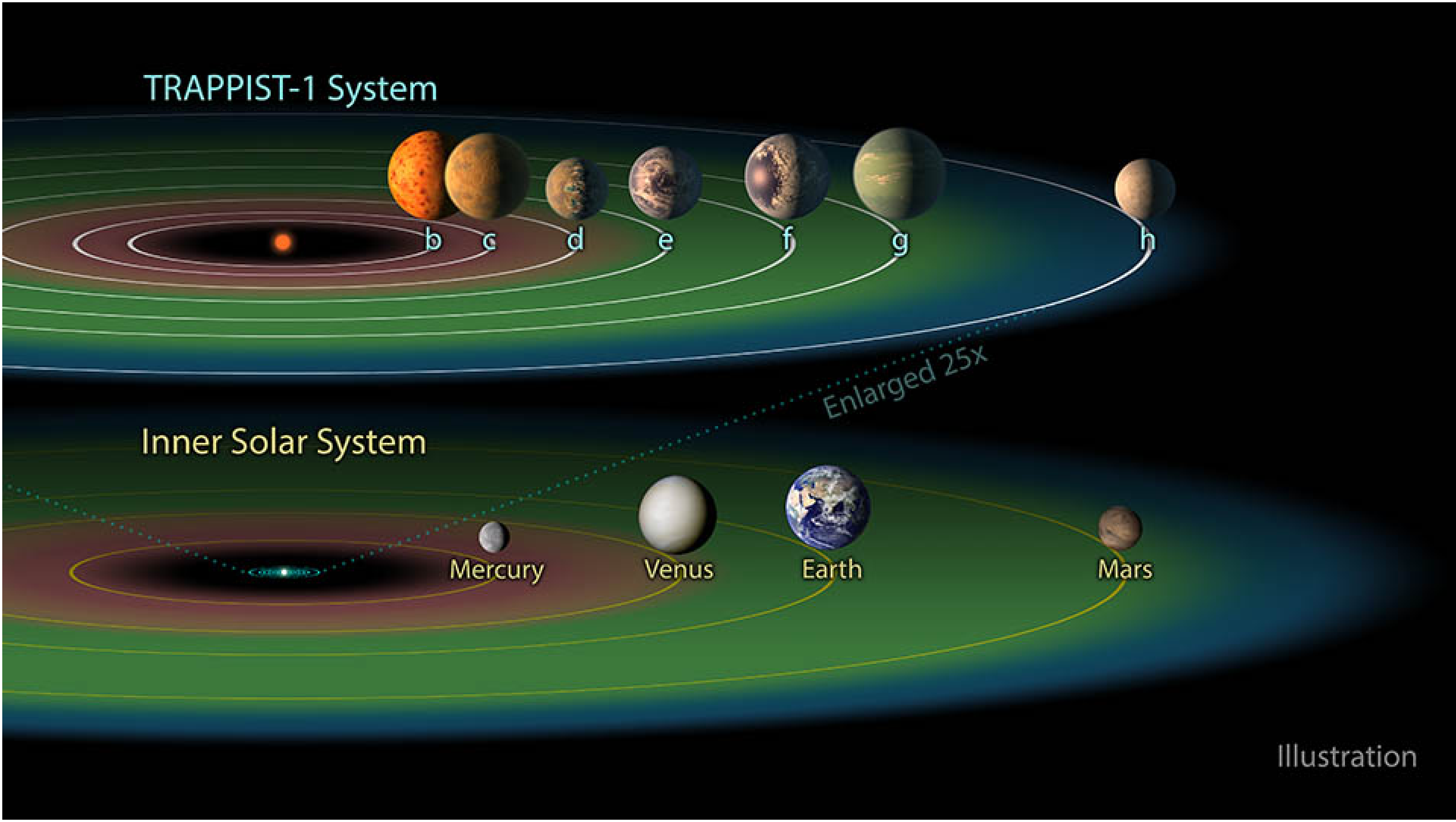
$$\Delta m_{sole} = -2.5 \log\left(1 - \frac{\Omega_{terra}}{\Omega_{sole}}\right) \simeq 0.0001$$

2950 pianeti confermati + 2337 candidati




Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale


Kepler-90 System Planet Sizes
(Artist's Concepts)
Kepler-90b
Kepler-90c
Kepler-90i
Kepler-90d
Kepler-90e
Kepler-90f
Kepler-90g
Kepler-90h
Solar System
NASA Ames, Wendy Stenzel
Planet sizes are to scale; distances are not.


TRAPPIST-1 System
b
c
d
e
f
g
h
Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars
Illustration