Planet Earth, seven milliard years ahead

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Rybicki K.R. & Denis C., 2001: Icarus **151**, 130–137

Ball Ph., 2001: *The end is shy*, Nature (Science Update), 9 May

Where do we come from?
Where do we go to?
Who are we?

The first two questions have to do with the birth and evolution of the Sun and the solar system

Formation of the solar nebula

Region of η Car

Gravitational collapse

$$\boxed{\rho > 1.5 \times 10^{14}\, T\, R^{-2}}$$

very cool original cloud (dark matter)

$\rho \approx 10^{-18}$ kg m^{-3}

$T = 10$ K

$\rightarrow$ $R > 3.85 \times 10^{16}$ m

(= 260 000 AU= 4.12 ly)

$\rightarrow$ $M = 120\, M_{\odot}$

$\rightarrow$ **hierarchy of smaller and smaller clouds**

primeval solar nebula

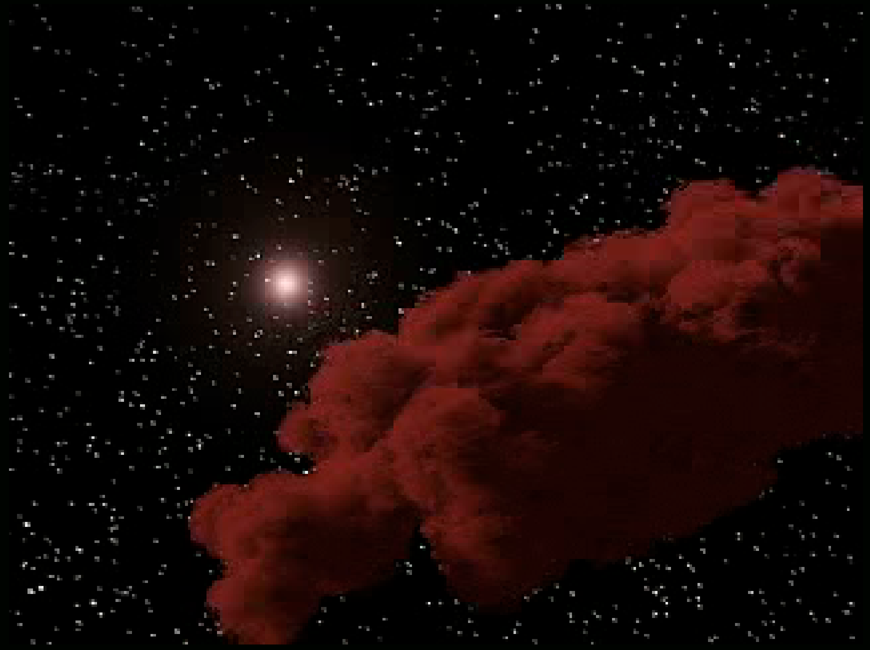
$\rho \approx 10^{-14}$ kg m^{-3}

$\rightarrow$ $R > 3.84 \times 10^{11}$ m

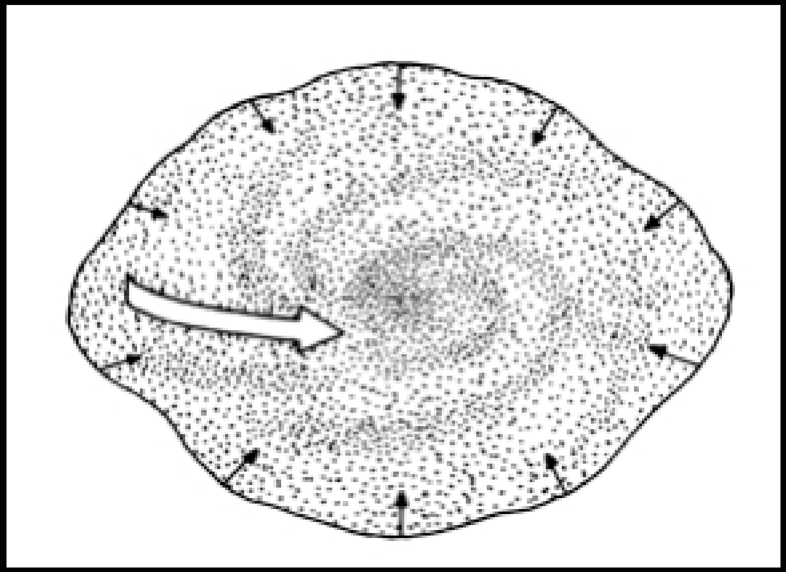
(= 2577 AU = 65 x now)

$\rightarrow$ $M = 1.19\, M_{\odot}$

Effect of the explosion of a supernova in the vicinity of or within the primitive nebula

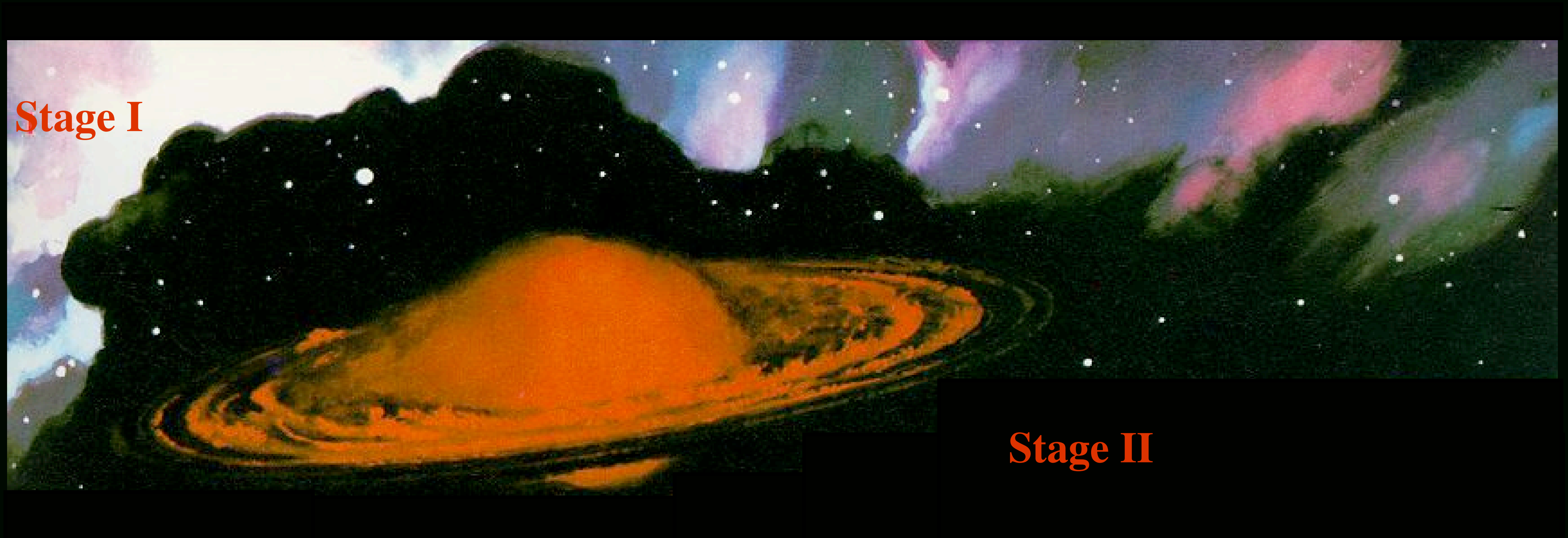


triggers the formation of the solar nebula



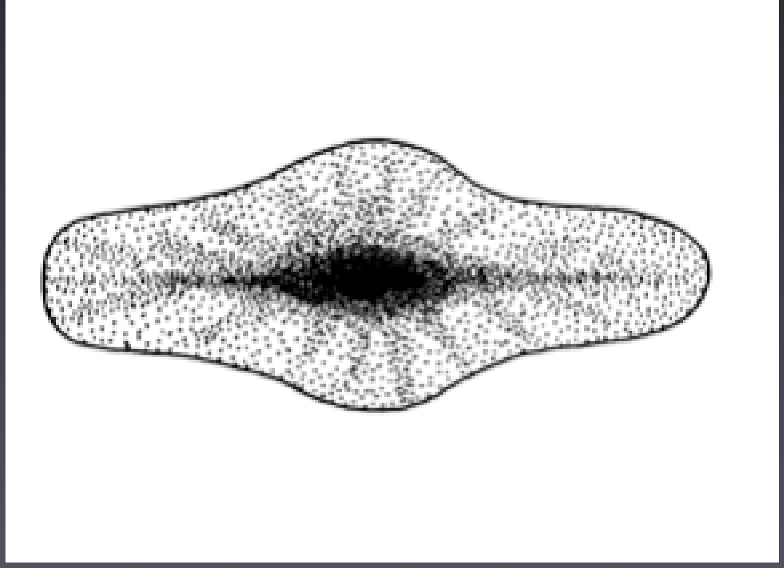
Stage I : First dynamical collapse

The nebula is transparent to IR radiation, implying that it is essentially isothermal. Duration: about 100 years !

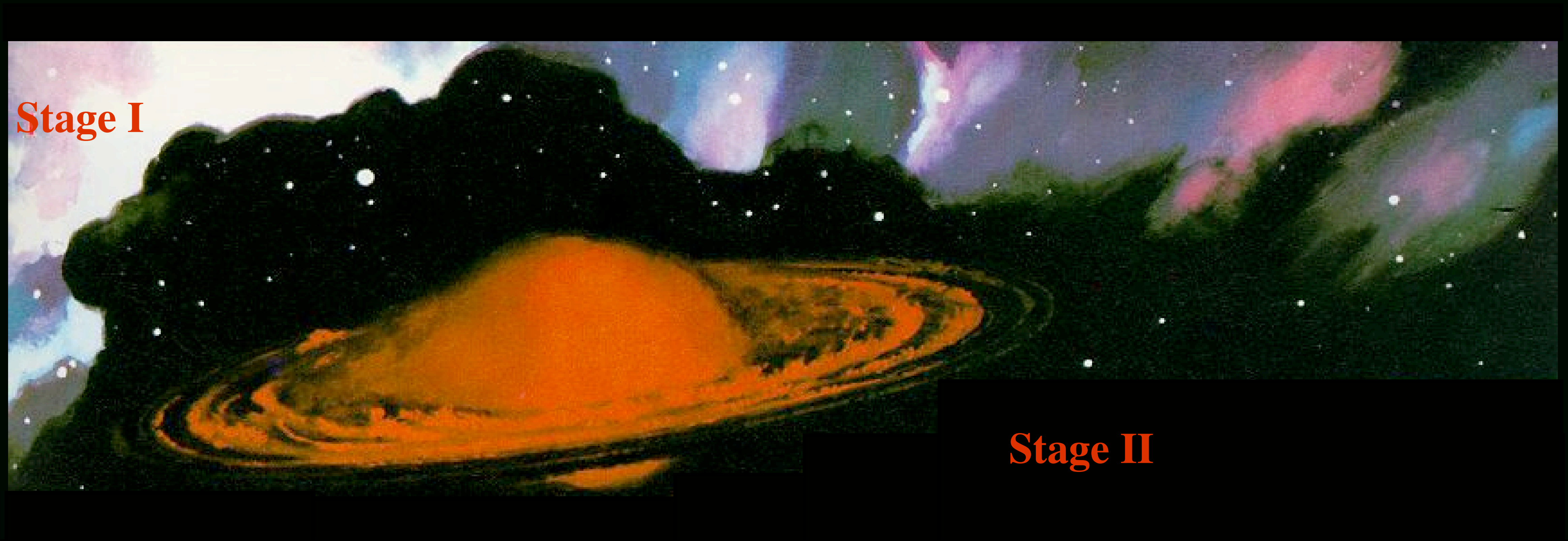


Stage IIa : First equilibrium phase

The dynamical collapse has stopped and only slow gravitational contraction occurs, forming an inner core after roughly 1000 years.

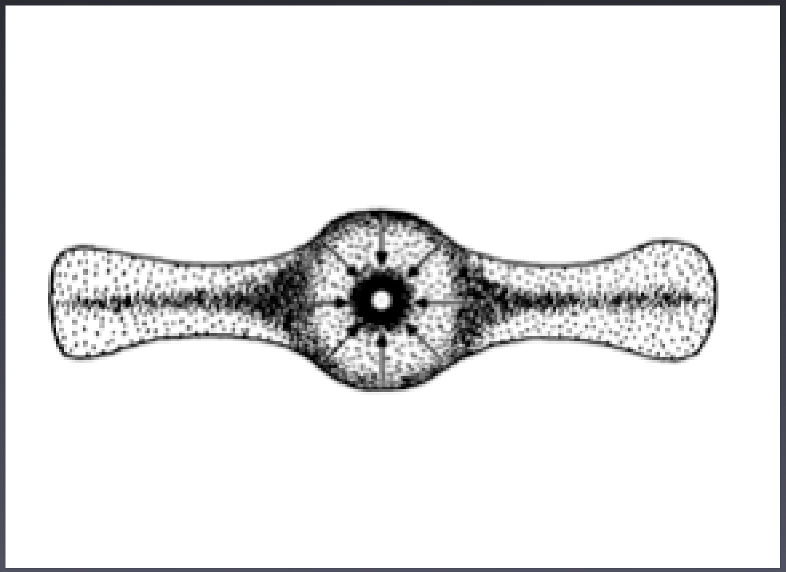


The density is now large enough to make the inner regions opaque to IR radiation, and the proto-Sun heats up. Dissociation of molecular hydrogen occurs as soon as the central temperature reaches about 1800 K.



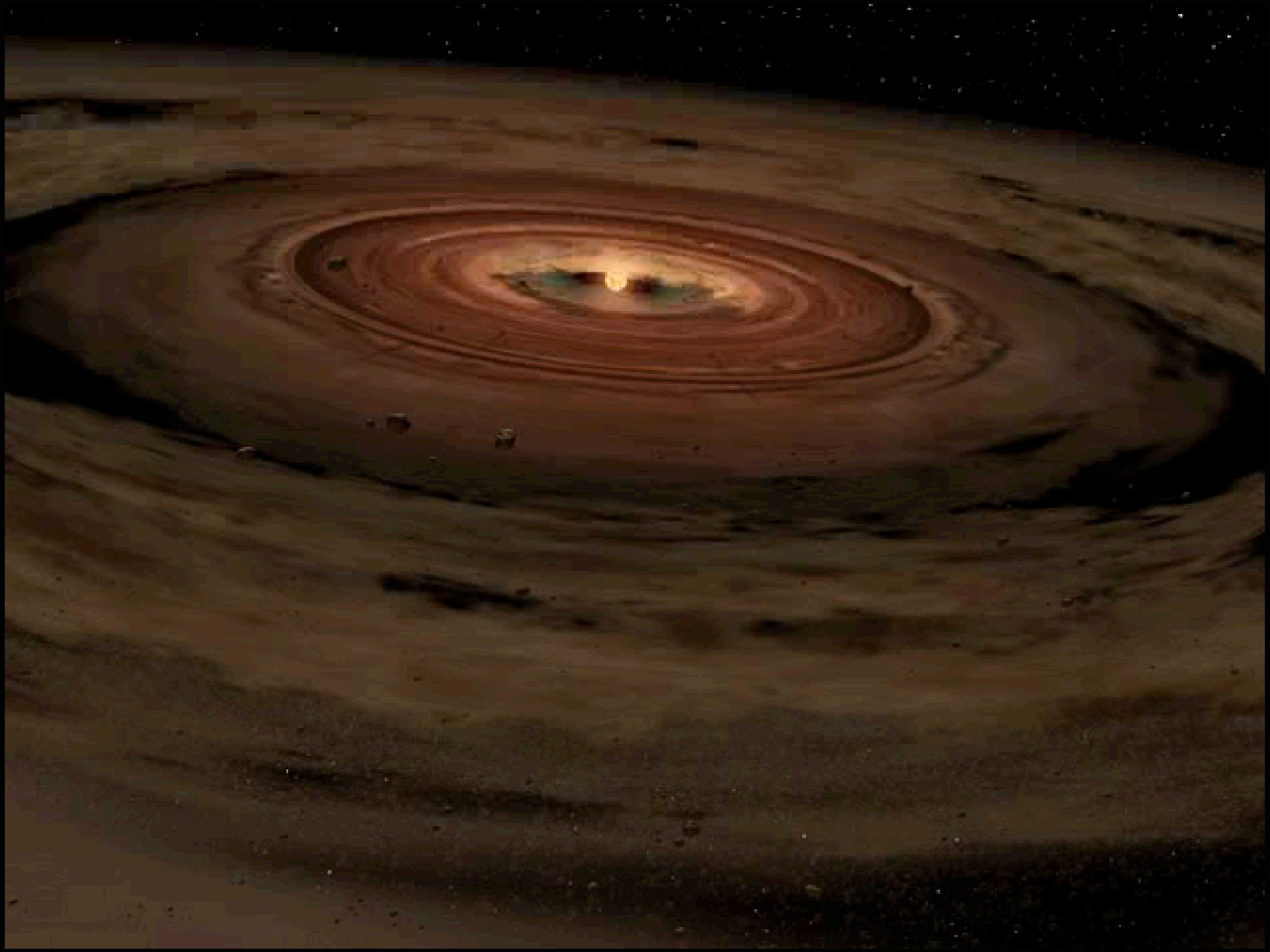
Stage IIb : Second dynamical collapse

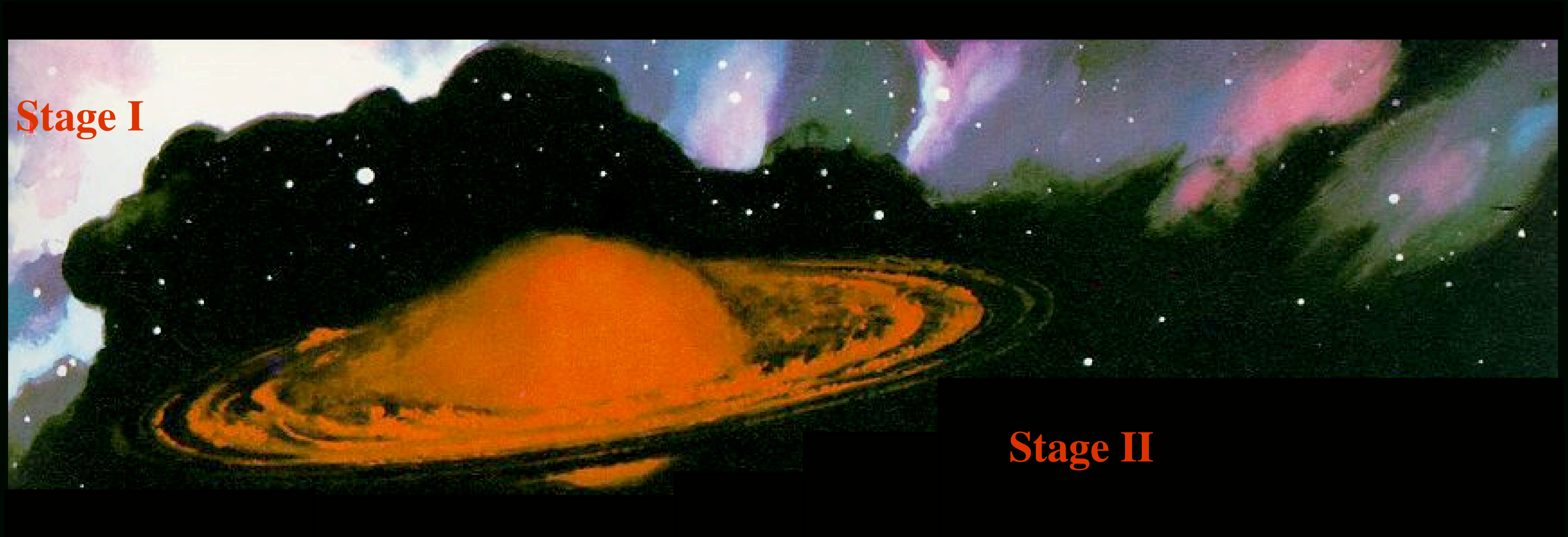
Because of the dissociation of molecular hydrogen, a second gravitational collapse starts. The proto-Sun, due to its high opacity, is wholly convective.



For this reason, the luminosity increases suddenly (begin of the 'Hayashi sequence'). The surrounding accretion disk becomes strongly heated and the dust particles in the inner zone of the disk evaporate.

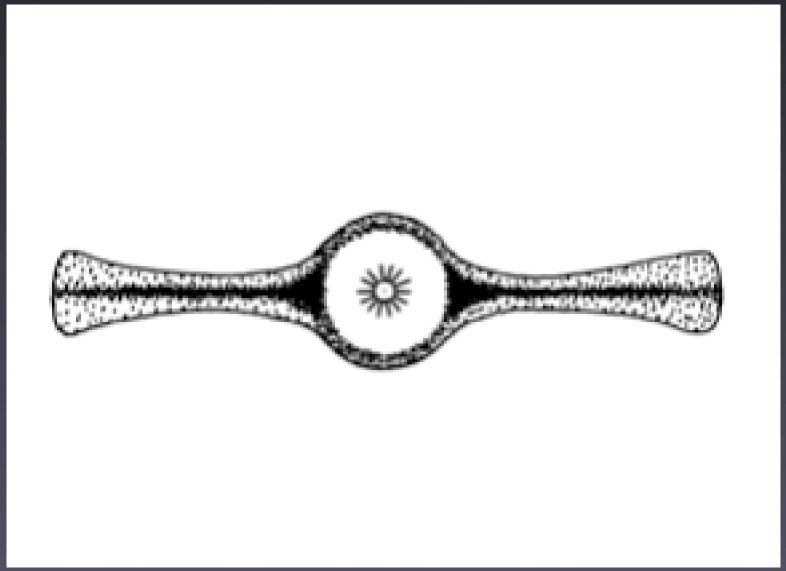
Formation of the proto-Sun and an accretion disk of gas, dust, meteoroids and planetesimals



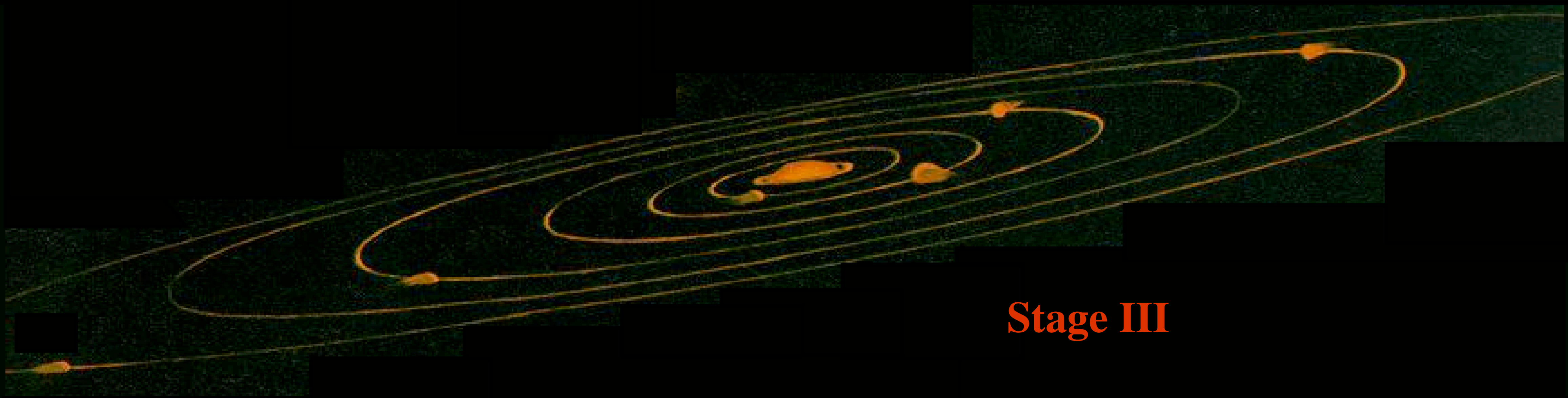


Stage IIc : Moderate contraction phase

The proto-Sun continues to contract at a more moderate rate, implying a decreasing luminosity at constant surface temperature.

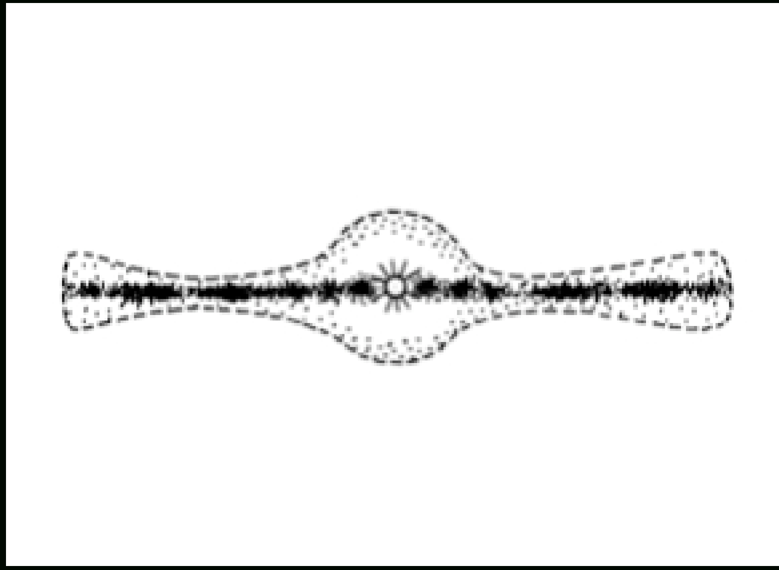


After 8 million years, the luminosity stabilizes and the surface temperature increases.



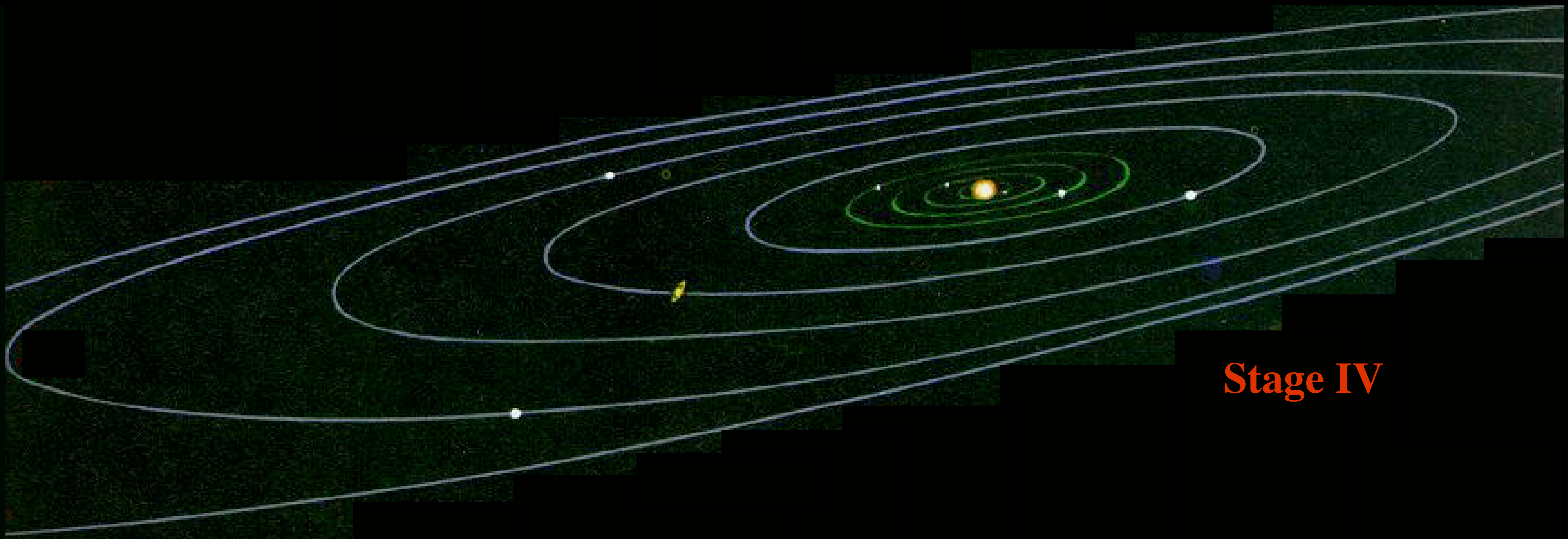
Stage III : Second moderate contraction phase

The proto-Sun continues to contract and heat up at a moderate rate, thus increasing continuously the temperature in the central regions.



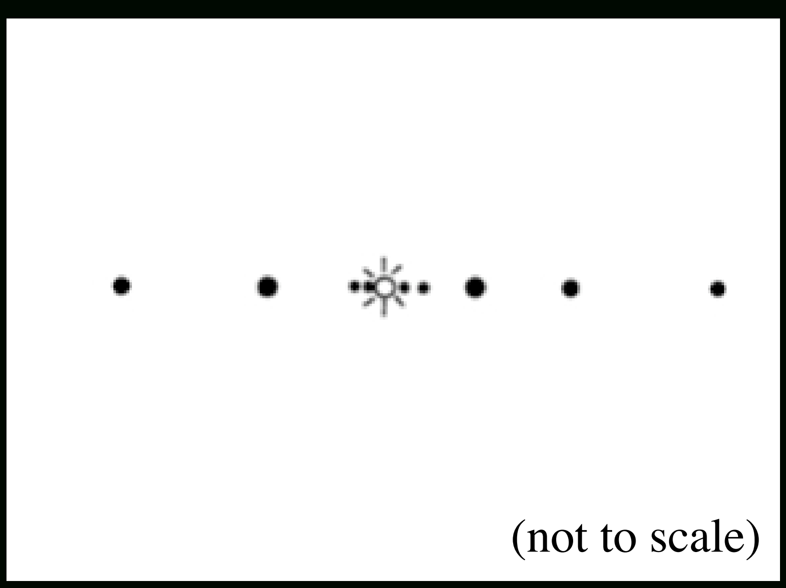
In the surrounding accretion disk, the central zone cools down again, letting the dust recondense again into planetesimals of all sizes. The latter are the main building blocks that allow, by myriads of collisions, the planets and their satellites to form.

Evolution of the accretion disk

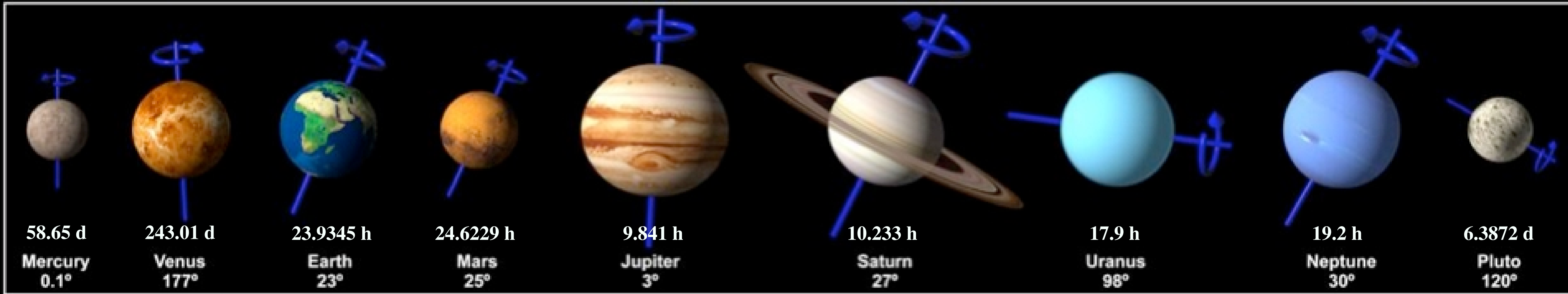


Stage IV : Sun in the hydrogen-burning phase

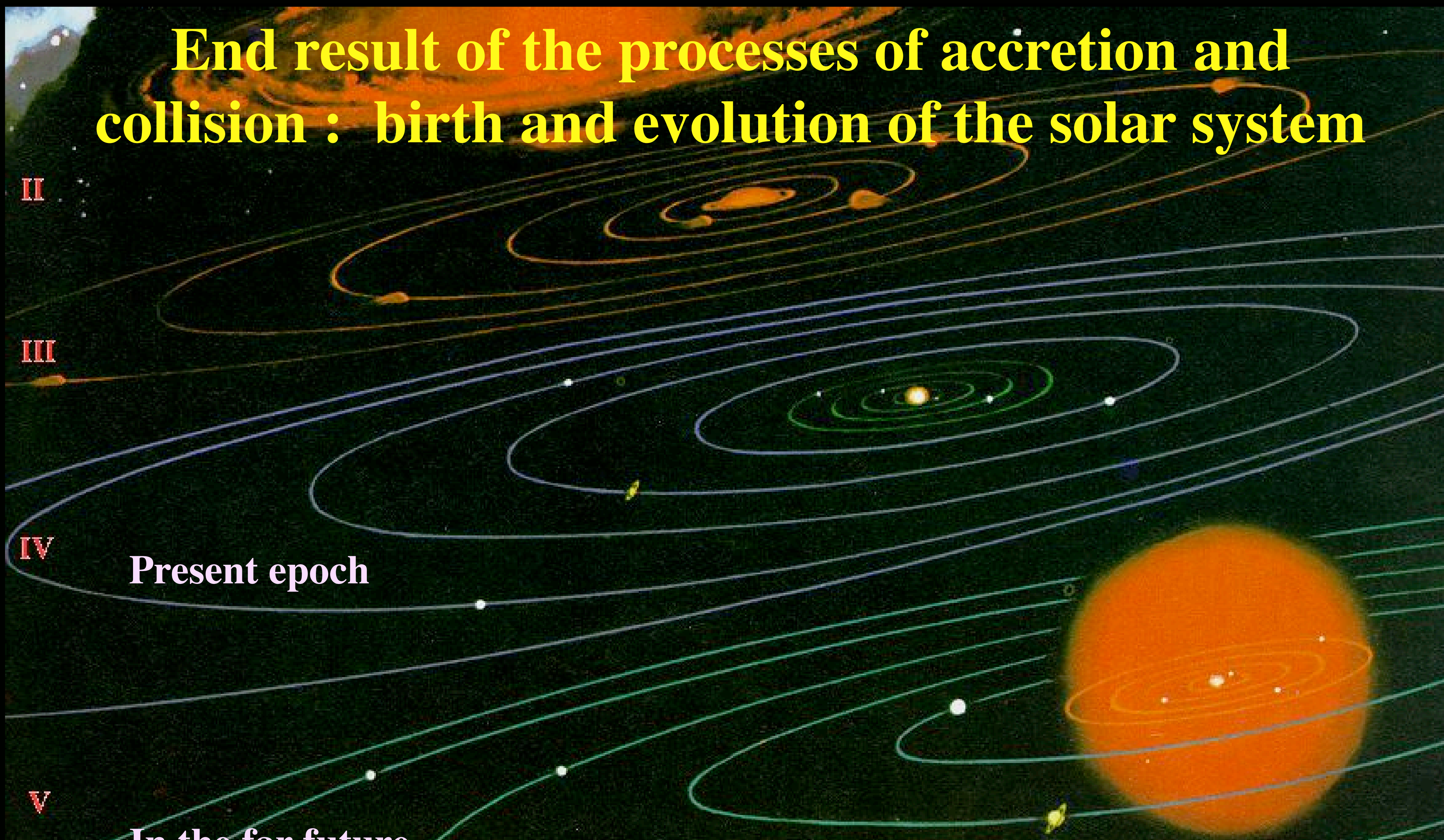
After 30 to 50 million years, the Sun has reached the so-called ‘main sequence’ on the H-R diagram and is now converting hydrogen into helium in its central regions for about 11 milliard years.



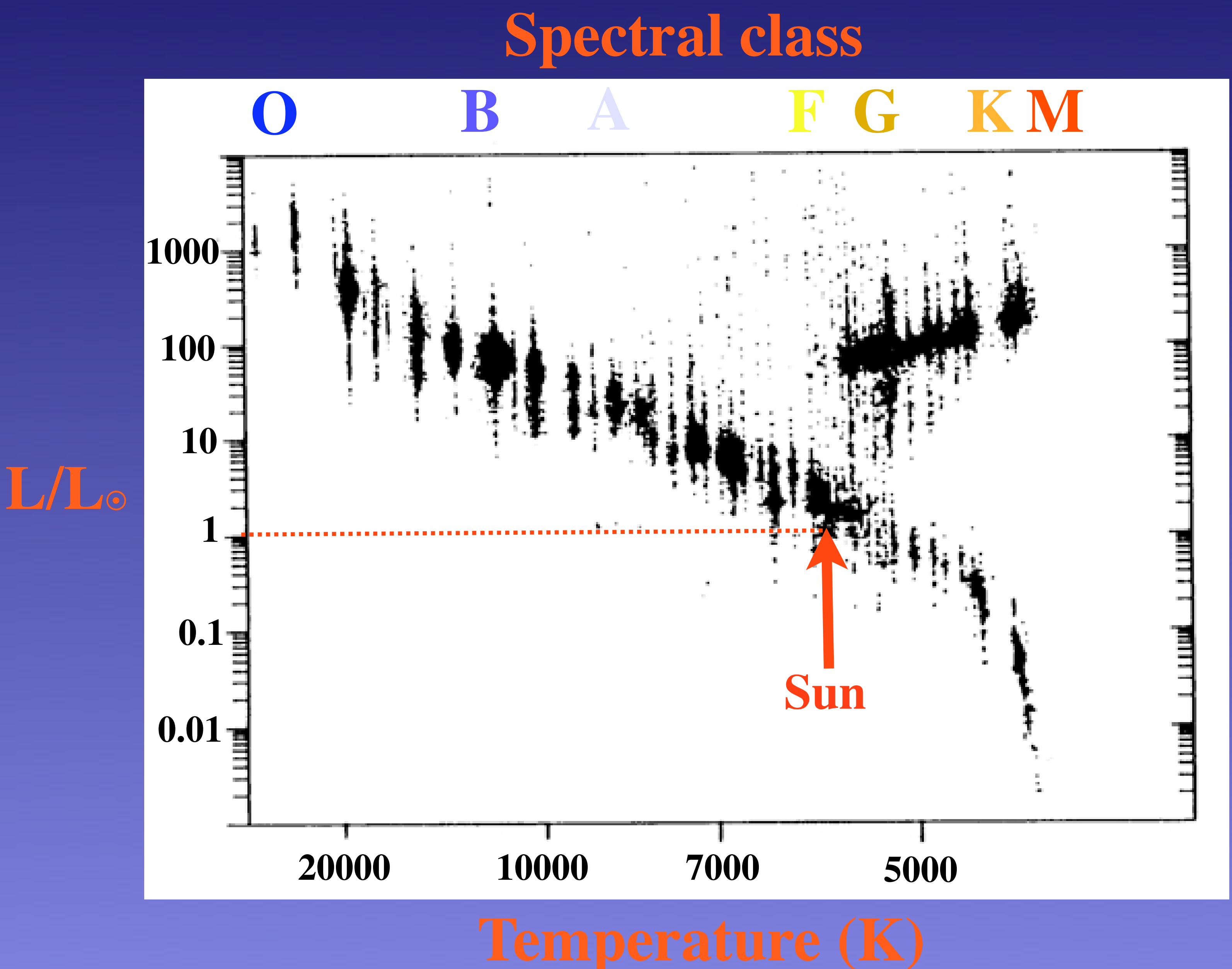
When the Sun reaches the main sequence, after having left the ‘Hayashi track’, its luminosity is about 70% of its present value. At the same time, the planetary accretion is essentially completed, and the solar system exists more or less in its present-day configuration.

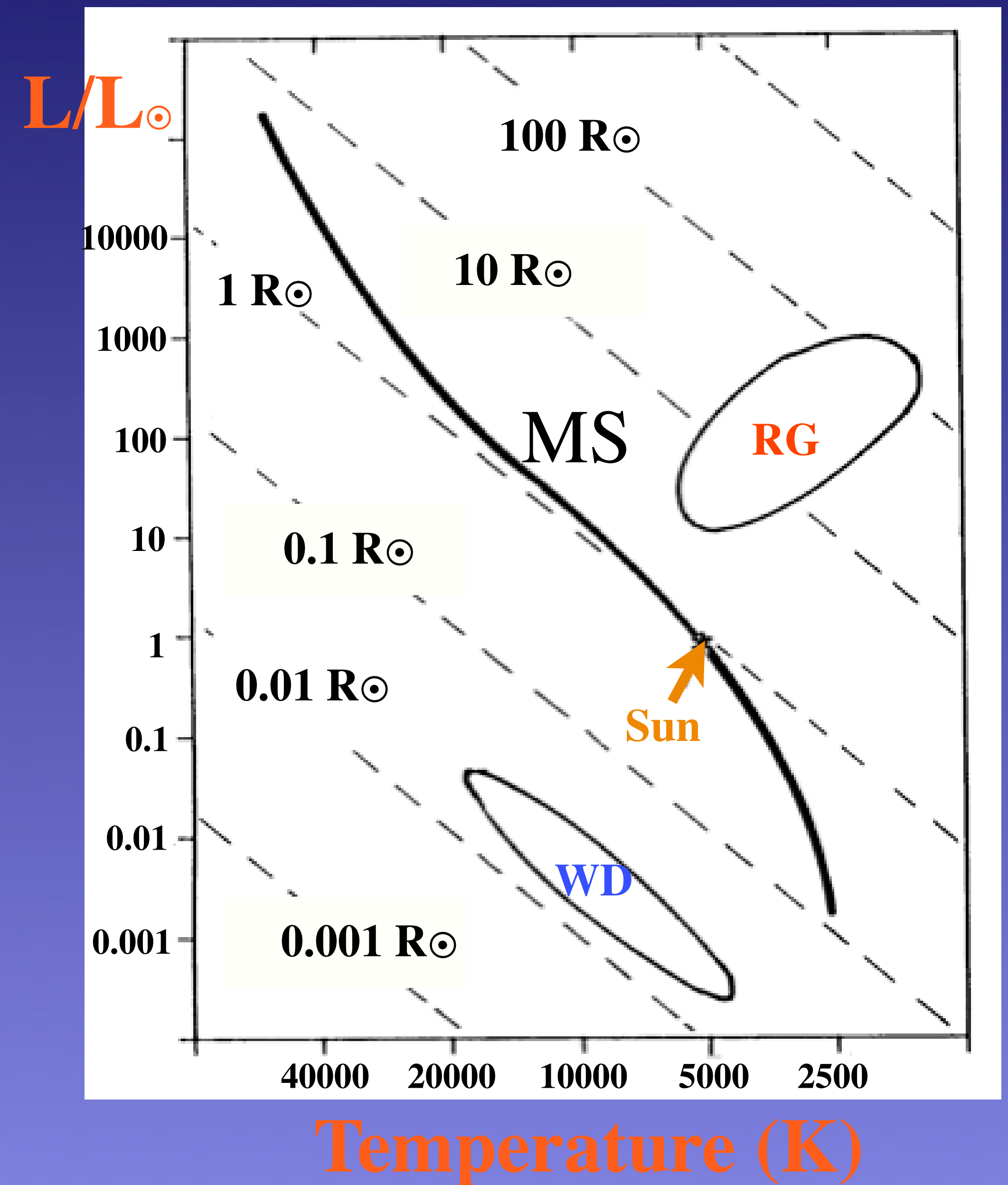


End result of the processes of accretion and collision : birth and evolution of the solar system



Hertzsprung-Russell diagram

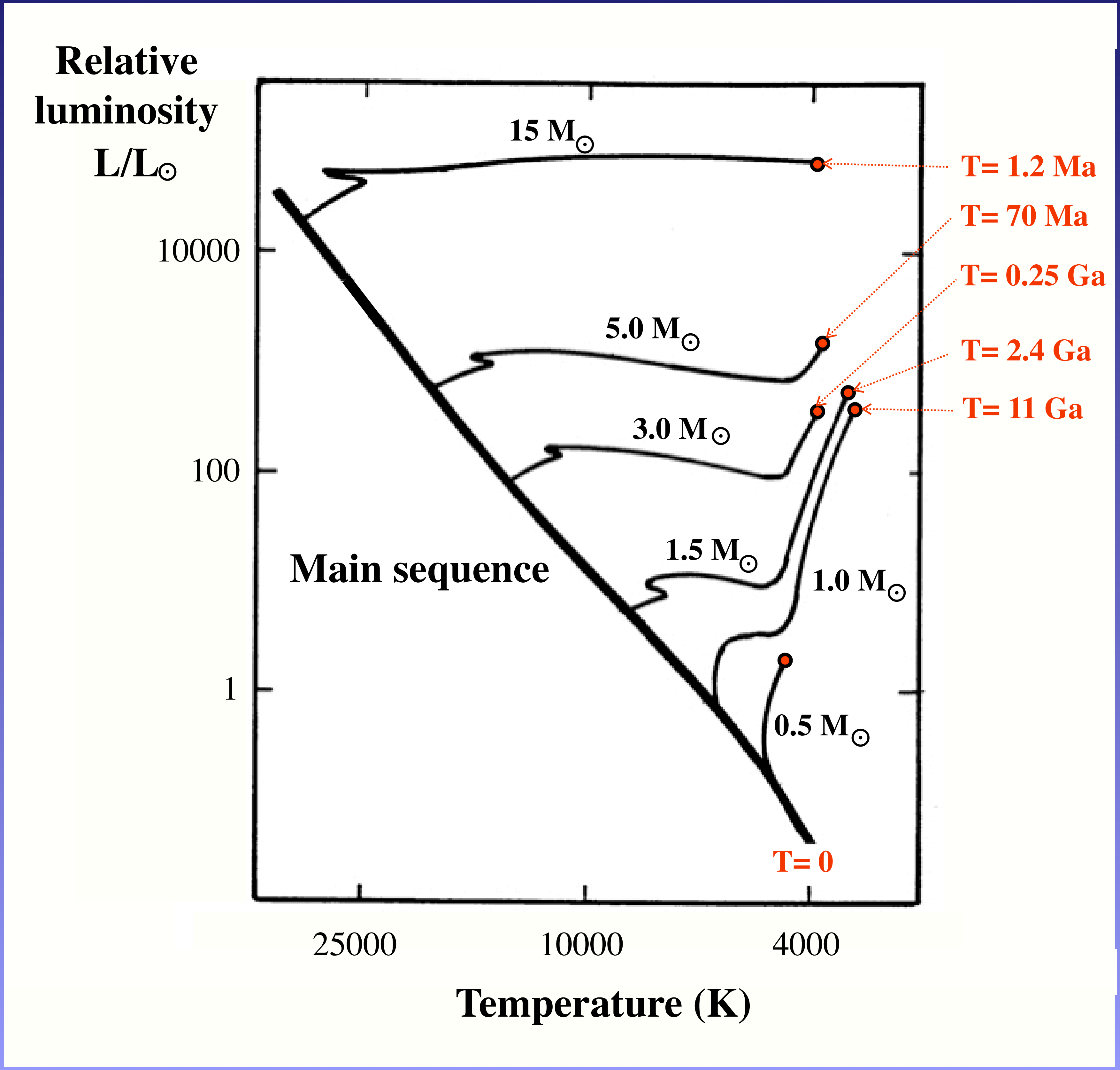


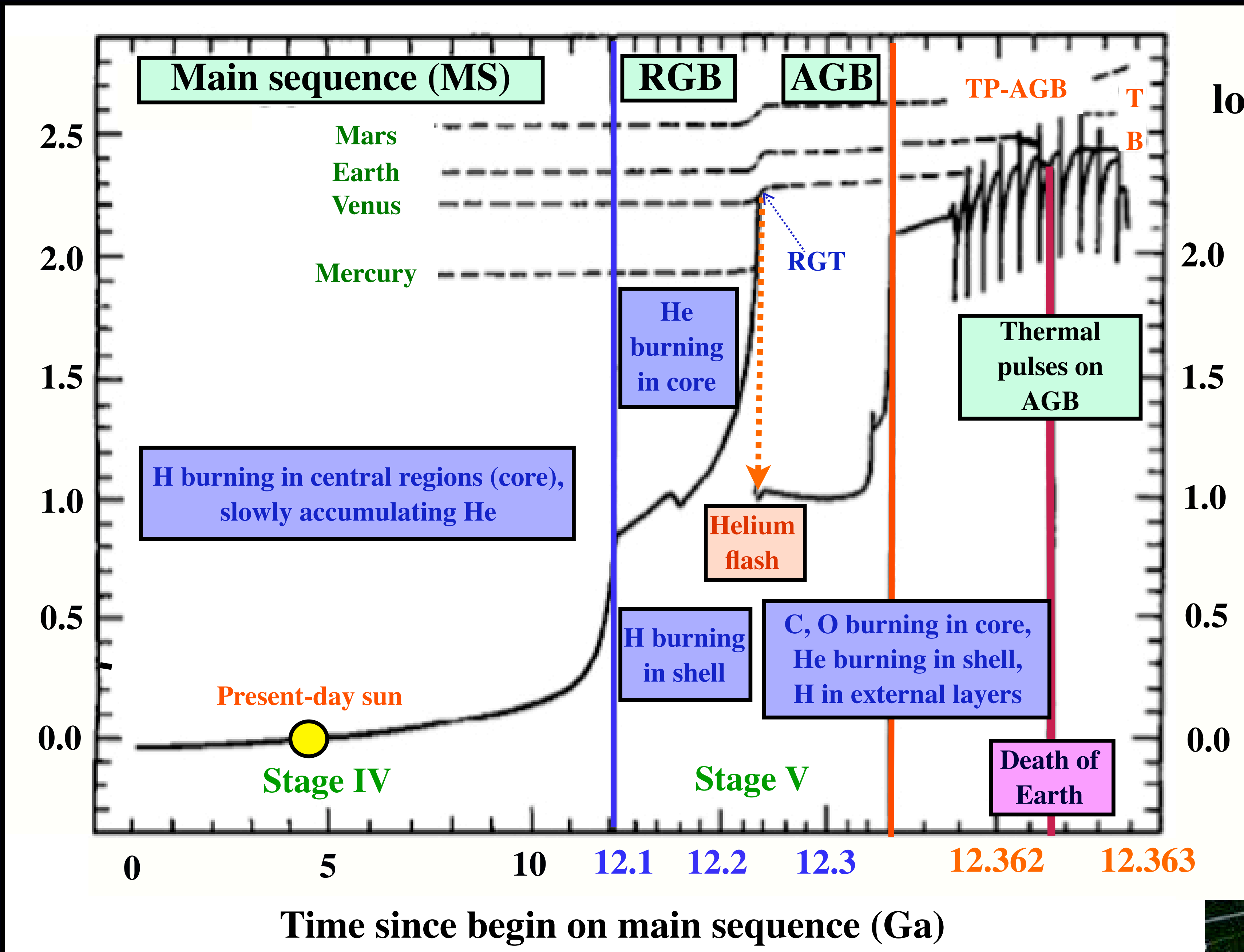


Original Hertzsprung-Russell (H-R) diagram

Schematic H-R diagram

Stellar evolution





Prevailing processes are different according to
- ☀ $r > R$: the planet is *outside* the Sun
- ☀ $r < R$: the planet is *within* the Sun

Processes:

— mass loss of the Sun by solar wind

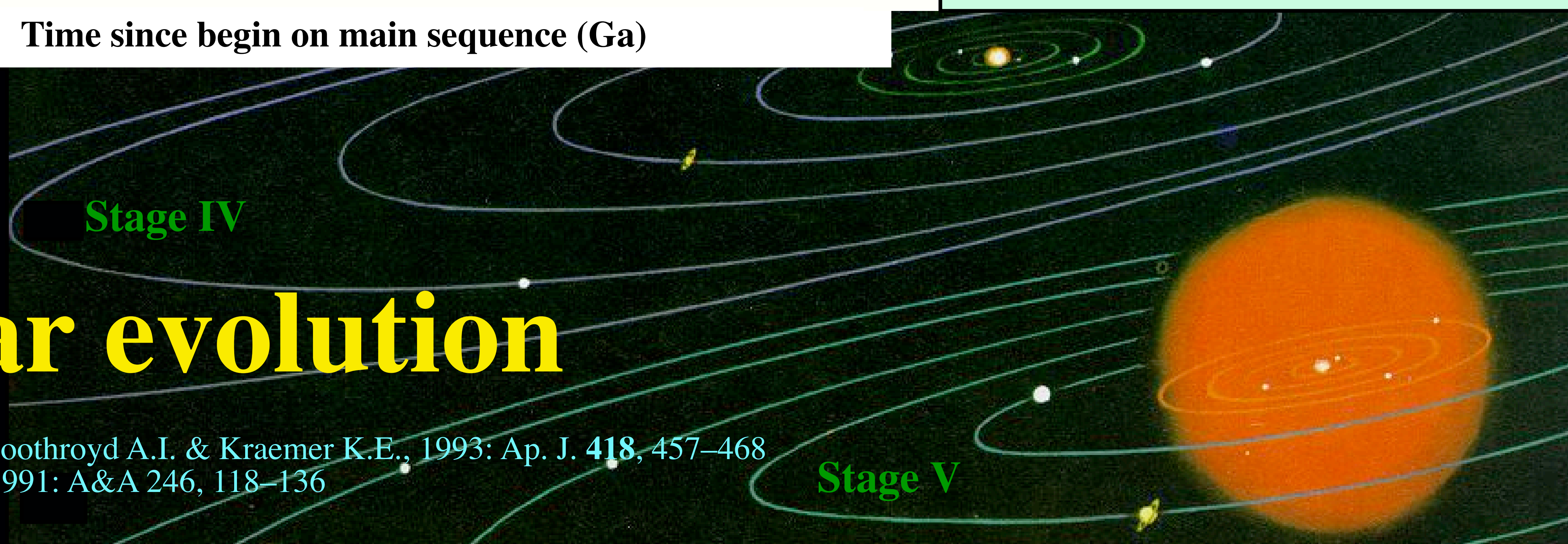
$$dM/dt = -\,0.0004\ \eta\ L\ R\ /\ M$$

(in present-day solar masses per milliard years; L, R and M in solar units)

$\eta \cong 0.4$: mass-loss parameter

— drag forces acting on the planet
- “gravitational drag” (accretion)
- “bow shock drag”
- “tidal drag”

Problem: **Evaluate the evolution of the ratio R/r for the two opposing processes.**



Solar evolution

Sackmann I.-J., Boothroyd A.I. & Kraemer K.E., 1993: Ap. J. **418**, 457–468
Jørgensen U.G., 1991: A&A 246, 118–136

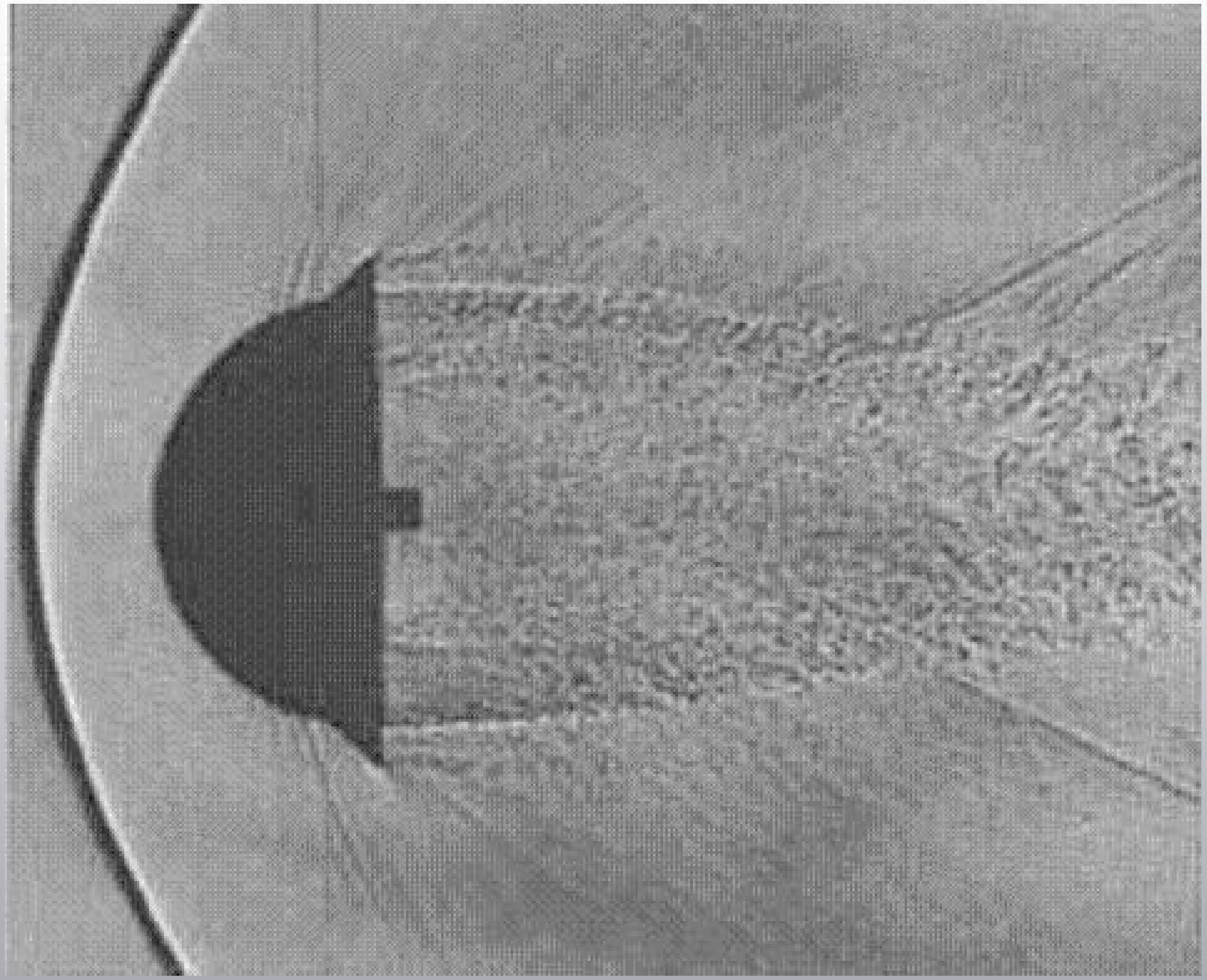
R < r

Owing to the small density of the solar wind, both gravitational and bow shock drags are negligible.

$$dr/dt = -\,(r/M)\, dM/dt - 12\, K_2\, m\, R^8/(M\, \tau\, r^7)$$

— M and R are Sun's mass and radius
— m and r are the planet's mass and distance to Sun
— K_2 is the apsidal motion constant of the Sun (on the RGB, $K_2 = 0.01 .. 0.1$)
— τ is a characteristic eddy viscosity time

(Zahn J.-P., 1977: A&A **57**, 383–394; Erratum: **67**, 162)



R > r

In the case of engulfment, the situation becomes more complicated, yet tidal forces may still play an important rôle.

$$dr/dt = -\,2\pi\, \rho\, \upsilon\, r\, (C_1\, R_1^2 + C_2\, R_2^2)\, /\, m$$

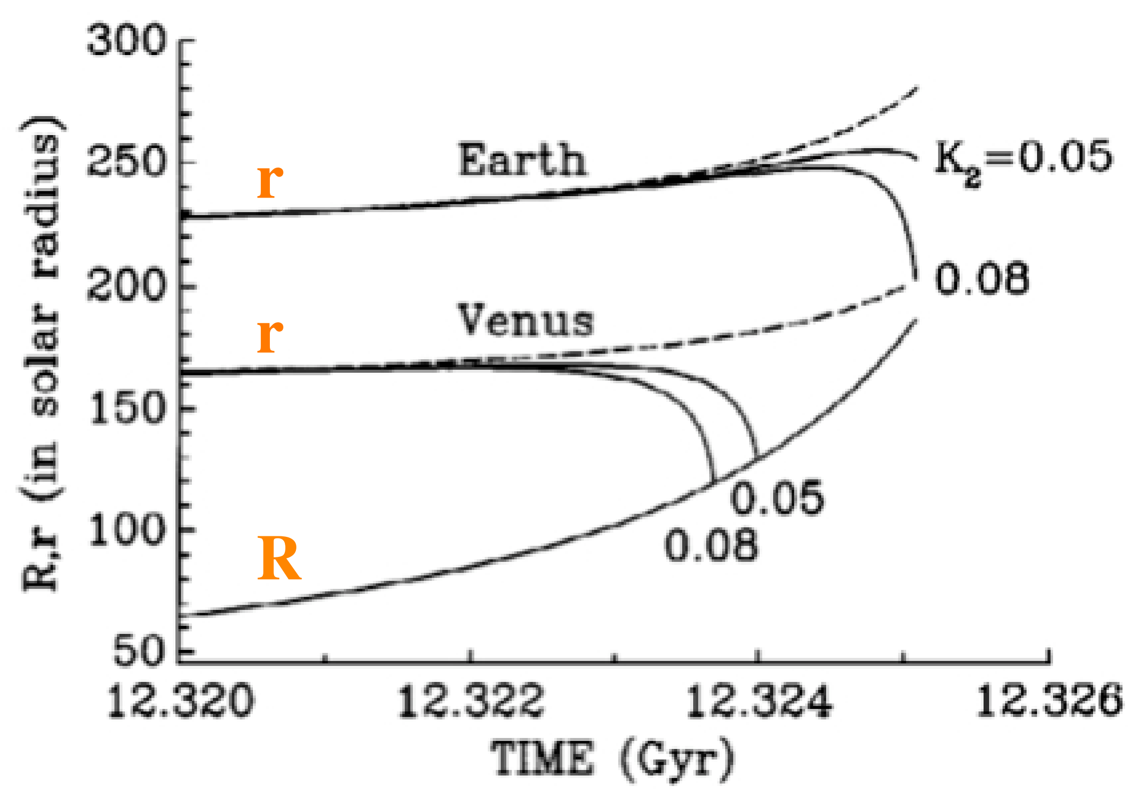
— m, r, υ, R_1 and R_2 are the planet's mass, distance to Sun's centre, Keplerian velocity, radius and accretion radius, respectively
— ρ is the density of the solar envelope at the position of the planet
— $C_1 \approx 1$ is the bow shock drag coefficient
— $C_2 \approx 1 .. 4$ is the accretion coefficient

(Ruderman M.A. & Spiegel E.A., 1971: Ap. J. **165**, 1–15

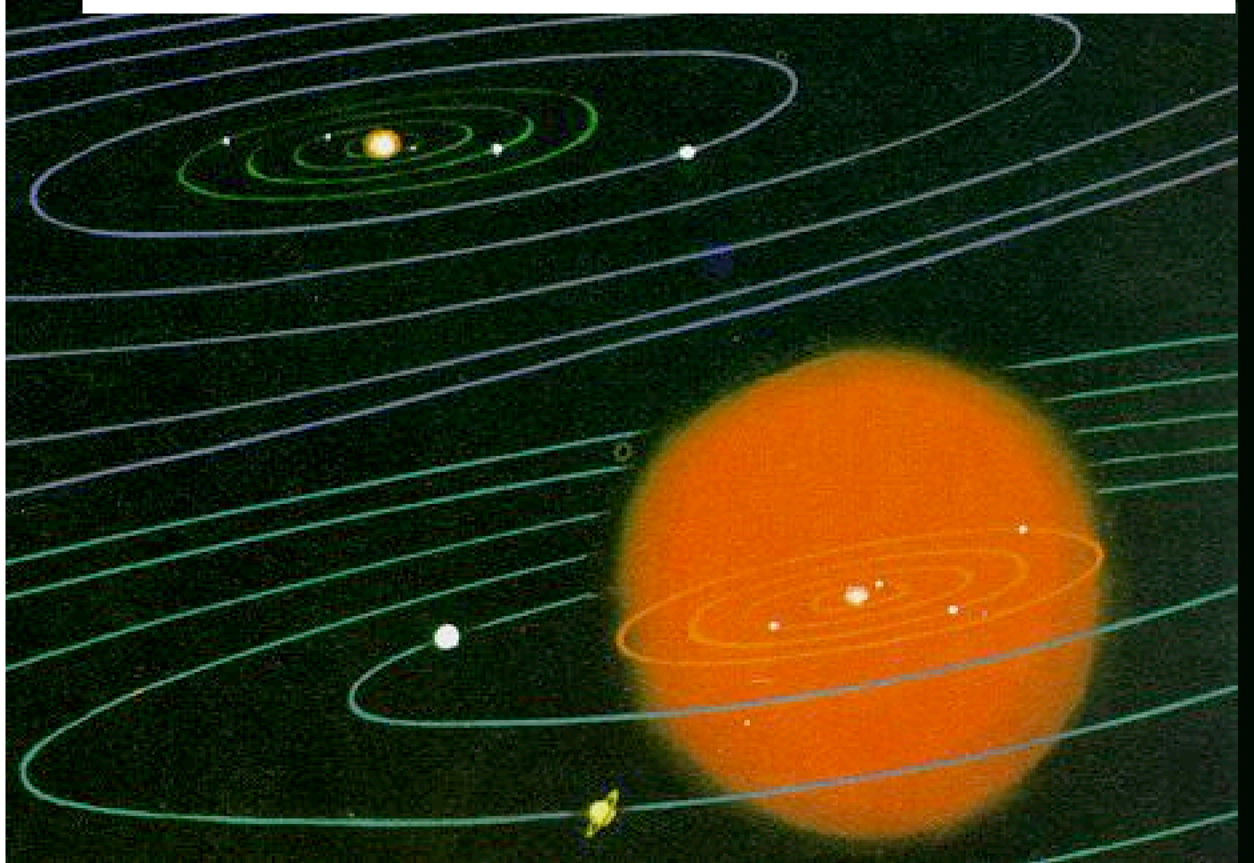
Mass, Luminosity, and Radius at the RGT and AGB for Nine Selected Models of Solar Evolution[a]

No.	M	L	R	R_{max}	r Venus	r Earth	r Mars	Time
1	0.71	2570	0.97		1.02	1.41	2.15	RGT
	0.65	4266	1.31	1.64	1.11	1.54	2.35	PN
	0.60	4786	1.46	1.83	1.21	1.67	2.54	AGT
2	0.87	2512	0.91		0.83	1.15	1.75	RGT
	0.75	7079	1.81	2.26	0.96	1.33	2.03	PN
	0.66	8710	2.12	2.65	1.10	1.52	2.31	AGT
3	0.60	2692	1.02		1.21	1.67	2.54	RGT
	0.52	1479	0.68		1.39	1.92	2.93	AGB
4	0.88	1862	0.56		0.82	1.14	1.73	RGT
	0.66	5754	1.14	1.43	1.10	1.52	2.31	PN
	0.62	6166	1.21	1.51	1.17	1.61	2.46	AGT
5	0.93	1905	0.56		0.78	1.08	1.64	RGT
	0.74	7244	1.29	1.61	0.98	1.35	2.06	PN
	0.66	8318	1.42	1.78	1.10	1.52	2.31	AGT
6	0.76	1698	0.54		0.95	1.32	2.01	RGT
	0.57	3548	0.86	1.08	1.27	1.75	2.67	PN
	0.55	3631	0.88	1.10	1.32	1.82	2.77	AGT
7	0.72	2349	0.77		1.00	1.38	2.10	RGT
	0.59	2999	0.84	0.99	1.22	1.69	2.58	AGB
8	0.79	2483	0.92		0.92	1.27	1.93	RGT
9	0.77	2752	0.87		0.94	1.30	1.97	RGT

[a] Mass (M) and luminosity (L) are both expressed in present-day solar units $M_\odot$ and $L_\odot$, respectively. Radius R is expressed in present-day astronomical units AU. The distances r (in AU) for Sun–Venus, Sun–Earth, and Sun–Mars are provided for the considered models, assuming that only solar mass loss is taken into account, tidal interaction being neglected. The models are from Bressan *et al*. (1993), Hurley *et al*. (2000), Jorgensen (1991), and Sackmann *et al*. (1993).



Evolution of the solar radius in the vicinity of the red giant tip according to the evolutionary track taken from Hurley *et al*. (2000), shown by the continuous curve at the bottom of the figure. The distances Earth–Sun (above) and Venus–Sun (below) are computed using the same model for the following three cases: (1) no tidal drag, $K_2 = 0$ (dashed lines); (2) tidal drag, $K_2 = 0.05$ (continuous lines); (3) tidal drag, $K_2 = 0.08$ (continuous lines).



Conclusions

(to be accepted with caution)

1. There is little doubt that Mercury and Venus will get engulfed and will evaporate already while the Sun is still on the RGB.

2. Mars will most probably escape evaporation and will revolve about the Sun forever.

3. The situation for the Earth is extremely tricky, but most of our models — if tidal effects are taken into account — seem to imply engulfment (not necessarily evaporation) during thermal pulses on the AGB.

4. Optimistic estimations indicate that mankind will have totally disappeared from Earth long before the Sun reaches the red giant phase.

Thanks for listening !