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The Faint Young Sun Paradox: A Resolution

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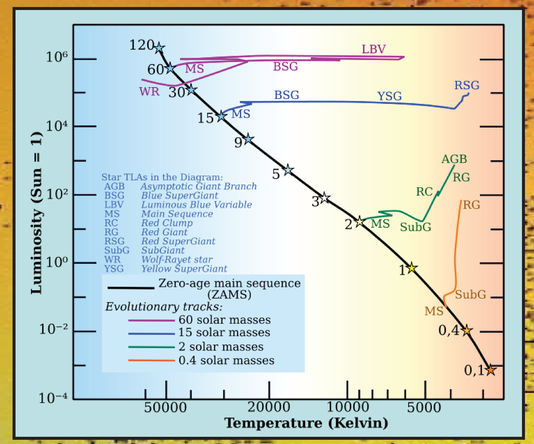
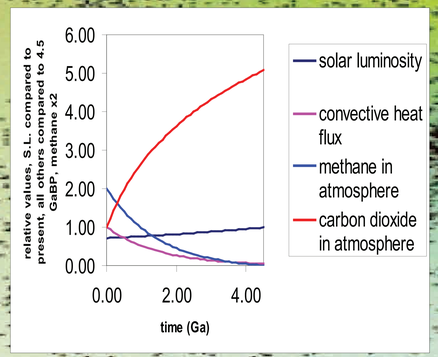
The nature of the Faint Young Sun Problem

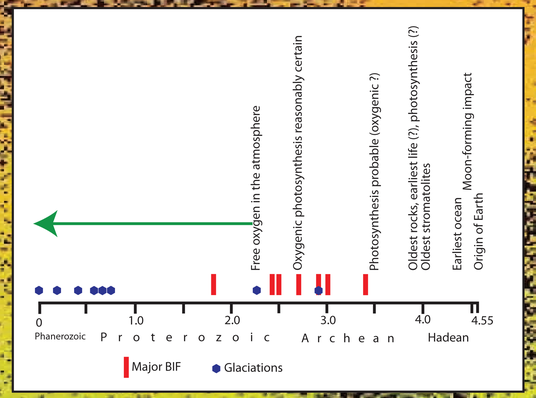
The track of the sun is similar to that of the 0.4 mass star, but starting at mass = 1.
The sun at 4.5 Ga is still on the short, near-vertical branch.



Present-day solar luminosity is about 25% greater than during the Hadean and early Archean. Scaling for all other parameters is qualitative/illustrative only.



The geologic record shows ice-age conditions sporadically since at least 2.9 BYBP, but evidence from the rock record and oxygen isotopes in earliest zircons indicates liquid oceans were present.



The Carbon Dioxide solution ?

Increasing the greenhouse effect with higher levels of CO_2 could counteract the faint young sun, but:

Problems with an early CO_2-N_2 atmosphere

How to produce pre-biotic compounds

Lack of evidence for Archean severe weathering

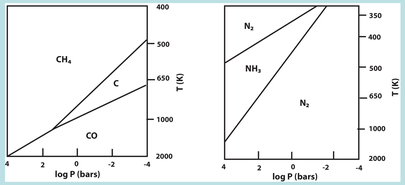
Lack of early Archean carbonate sediments

Carbon isotope record

Delay in oxidation of the atmosphere following cyanobacteria

But there is reason to believe that Earth's early atmosphere and the surface environment were dominated by reduced organic compounds.

Carbon and Nitrogen species in equilibrium with chondritic solids in near-surface environments.
(After Schaefer and Fegley, 2007)



And reprocessing of condensed organic compounds at ocean ridge hydrothermal systems could maintain moderate levels of the more effective greenhouse gases (methane and ammonia) in the atmosphere, in spite of photolytic processes that remove them rapidly.

(from Cruse and Seewald, 2006)

Vent	Sample	Exit T (C)	Mg (mmol/kg)	Cl (mmol/kg)	NH4 (mmol/kg)	H2 (mmol/L)	CO2 (mmol/kg)
Dead Dog Field							
H'ken Hollow	BGT-3597-1		51	544	0.064	0.03	2.7
	BGT-3597-2		11.3	589	2.792	1.5	7
	M-3596-12C		3.11	581	2.855		
	M-3596-1C		2.25	576	2.996		
	M-3597-12		45.9	557	0.282		
	M3597-15		27.9	554	1.35		
	Endmember	67-187	0	583	3.18	1.9	8.2
Chowder Hill	BGT-3596-3		1.9	572	3.045	2.5	7.5
	BGT-3596-4		1.12	576	3.103	2.6	9
	Endmember	281		575	3.164	2.6	8.4
Insp. Mounds	BGT-3597-3		34.4	551	0.993	0.8	5.7
	BGT-3597-4		41	542	0.524	0.5	4.2
	M-3597-6C		30.3	541	1.251		
	M-3597-11C		41	557	0.551		
	Endmember	255-261	0	546	2.866	2.3	12
Puppy Dog	BGT-3599-3		6.16	582	2.646	1.8	7.7
	BGT-3599-4		44.6	544	0.351	0.3	3.4
	Endmember	202	0	586	2.986	2	8.4
ODP Mound Field							
1035F	BGT-3598-3		43.2	527	0.232	0.39	3.4
	M-3598-6C		46.7	542	0.16		
	M-3598-11C		46.7	528	0.121		
	Endmember	40	0	448	1.263	2.1	8.2
Shiner Bock	BGT-3595-1		1.61	435	2.262	8	11
	BGT-3595-2		3.4	439	2.099	7.6	11
	M-3595-11C		5.99	444	2.13		
	M-3595-6C		12.7	467	1.8		
	M-3595-1C		26.7	495	1.07		
	M-3595-12		3.1	443	2.24		
	Endmember	272	0	434	2.34	8.2	12
Spire	BGT-3595-3		1.64	434	2.107	2.1	13
	BGT-3595-4		22.5	479	1.264	1.2	8.5
	M-3595-15		4.12	442	2.215		
	Endmember	263	0	432	2.27	2.2	13
1035H	BGT-3599-1		17	479	1.446	4.2	7.9
	BGT-3599-2		20.9	481	1.262	3.7	7.6

Table 2
Concentrations of organic aqueous species in vent fluids from Dead Dog and ODP Mound fields, Middle Valley, northern Juan de Fuca Ridge (from Cruse and Seewald, 2006)

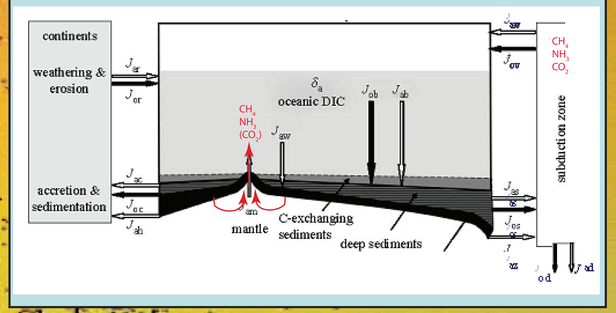
Vent	Sample (unit)	CH_4 (mmol/kg)	C_2H_6 (mmol/kg)	C_3H_8 (mmol/kg)	C_4H_{10} (mmol/kg)	C_5H_{12} (mmol/kg)	i-C_4H_{10} (mmol/kg)	n-C_4H_{10} (mmol/kg)	Benzene (mmol/kg)	Toluene (mmol/kg)
Dead Dog Field										
H'ken Hollow	BGT-3597-1	0.45	—	4.74	1.6	1.21	0.12	0.1	0.5	0.08
	BGT-3597-2	17.7	3.9	186	—	47.7	4.9	5.3	22	4.7
	Endmember	22.6	4	236	41	60.7	6.2	6.8	28	6
Chowder Hill	BGT-3596-3	19.2	6	219	4.7	53.2	5.8	6	24	4.6
	BGT-3596-4	20.3	2.9	231	2.4	56.8	6.1	6.2	22	5
	Endmember	20.3	4.6	232	3.7	56.6	6.2	6.2	23	4.9
Insp. Mounds	BGT-3597-3	7.58	4.8	219	4.7	53.2	2.1	6	24	4.6
	BGT-3597-4	4.88	4.3	231	2.4	56.8	1.4	6.2	22	5
	Endmember	21.6	14	232	16	57.5	5.9	6.1	24	4.5
Puppy Dog	BGT-3599-3	16.4	3.4	175	—	44.3	4.4	5.2	19	3.8
	BGT-3599-4	2.88	—	31.6	—	7.77	0.75	0.83	3.1	0.56
	Endmember	18.5	3.8	198	—	50.1	5	5.9	22	4.3
ODP Mound Field										
1035F	BGT-3598-3	0.56	5.6	2.07	2.2	0.48	—	—	0.19	0.09
	Endmember	2.99	30	11.1	12	2.58	—		0.99	0.09
Shiner Bock	BGT-3595-1	6.92	8.4	23.2	4	4.47	0.35	0.98	2.6	0.19
	BGT-3595-2	6.56	7.5	23.1	3	4.36	0.33	0.98	2.5	0.2
	Endmember	7.07	8.4	24.3	3.7	4.63	0.36	1	2.6	0.2
Spire	BGT-3595-3	6.52	19	23.4	5.7	4.26	0.31	0.8	2.2	0.15
	BGT-3595-4	3.84	13	14.3	3.9	2.74	0.23	0.59	1.5	0.12
	Endmember	6.71	20	24.3	6.1	4.48	0.34	0.87	2.3	0.17
1035H	BGT-3599-1	3.98	9.4	15.6	3.5	3.09	0.24	0.71	1.5	0.12
	BGT-3599-2	3.54	—	14.3	—	2.72	0.2	0.65	1.3	—
	Endmember	5.85	14	23.2	5.2	4.52	0.34	1.1	2.1	0.18
Bottom Sea Water		0	0	0	0	0	0	0	0	0

Table 2. Concentration (mmole/kg fluid) of selected aqueous species and pH (25C) during experiment SED-SW at 325C, 500bars and 400C, 400 bars, and an initial fluid/sediment mass ratio of 1.56. (adapted from Seewald et al., 1994)

Hours	Na	Ca	Mg	K	SiO_2	Cl	pH	H_2	NH_3	SO_4	H_2S	CO_2	CH_4	C_{org}
0	475	10.9	58.2	16.4	1	542	7	<0.01	<2	37.3	<0.05	-	-	-
98	409	33.6	0.14	195	28	516	5.5	1.5	50.4	0.19	14.9	388	30	138
241	348	47.5	0.36	35.1	21.2	508	5.4	1.6	52.7	0.14	8.92	449	40	110
410	346	46.9	0.37	36.6	22.6	511	-	1.7	55.3	0.16	8.65	478	46	89
414	Temperature increased to 400C, pressure reduced to 400 bars													
533	193	59.3	0.38	68.3	21.9	478	-	5.1	-	0.06	13.8	570	105	47
1161	269	38.3	0.13	94.1	23.6	508	-	6.9	88.5	0.07	14.1	65	33	27

A model of early carbon cycling.

(Modified from Hayes and Waldbauer, 2006.
Note addition of reduced gas production at ocean ridges, and presence of same in atmosphere)



Conclusions

The Faint Young Sun Problem is real: a mechanism must be found to explain the presence of moderate climatic conditions on the early Earth to counteract the lower luminosity of the early sun.

Elevated carbon dioxide is not a viable solution given the evidence from geological observations.

Large reduced carbon compound reservoirs on Earth's early surface are very likely.

Regeneration of methane and ammonia through hydrothermal activity at ocean ridges is a viable route to maintain atmospheric levels of these potent greenhouse gases sufficient to conteract the FYS.

Reprocesssing of reduced compounds by deep subduction and magmagenesis at high temperature in the mantle produces CO_2, and eventually leads to an oxidized surface environment.