Unconventional views of stellar populations

Part I
Fundamentals of stellar population synthesis

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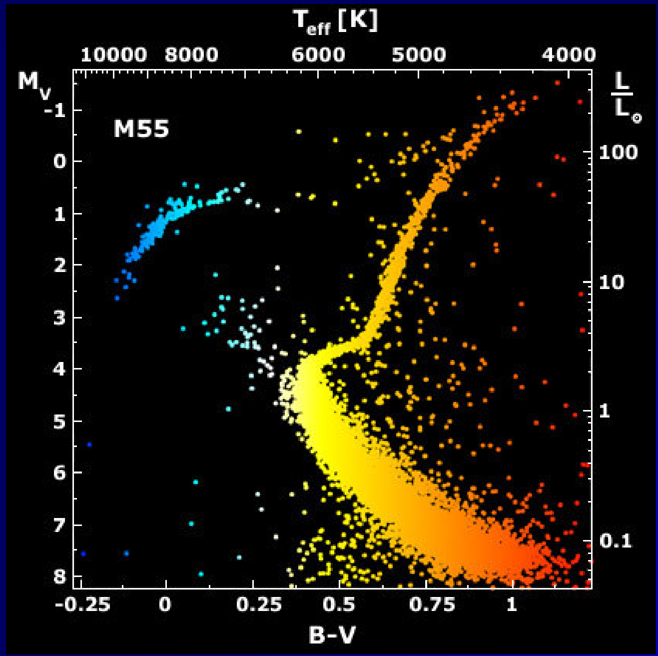
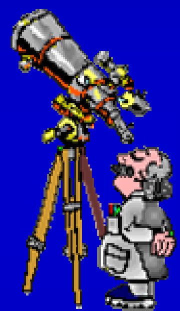
Star Trackers

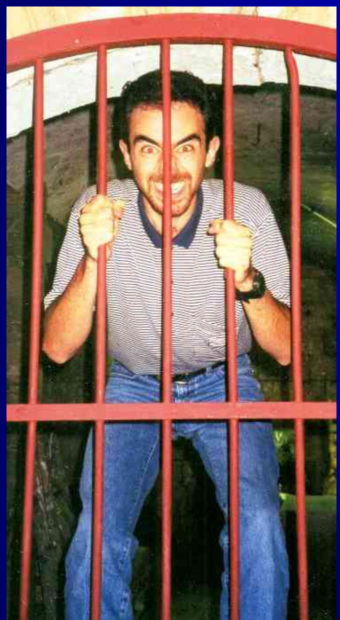
Ejnar Hertzsprung
Denmark (1873-1957)

Henry Norris Russell
USA (1877-1957)



From stars to star clusters





←Psychology

Sociology →

The "Color-Luminosity Array" (1915)

TABLE 2

COLOR LUMINOSITY ARRAY IN MESSIER 13

Limits of Photovisual Magnitude	Color-Class b0 to b5	b5 to a0	a0 to a5	a5 to f0	f0 to f5	f5 to g0	g0 to g5	g5 to k0	k0 to k5	k5 to m0	All Colors
11.80-.99											
12.00-.19								1	3	2	6
.20-.39									1	1	2
.40-.59								3	2		5
.60-.79				1	1		1	2			5
.80-.99							4	2			6
13.00-.19	1					1	8	3			13
.20-.39						1	4	2	1		8
.40-.59						1	6	1			8
.60-.79						2	3	1		1	7
.80-.99		3		2	6	14	6	2			33
14.00-.19					1	9	3	2			15
.20-.39			1			10	13	4			28
.40-.59		1	1	7	3	24	16	4			56
.60-.79			6	2	1	6	12	1	1		29
.80-.99		5	3		2	5	8	2			25
15.00-.19		24	9	3	3	19	10	2			70
.20-.39	10	21	7	5	12	28	15				98
.40-.59	4	11	6	4	11	11	5	1	1		54
.60-.79	1	5	3	3	10	4	1				27
.80-.99											
Total	16	70	36	27	50	135	115	33	9	4	495

evidence that the giant red stars were much brighter than the giant blue stars in the globular cluster Messier 13, that attention was called at once to the contrast between this color-luminosity diagram and the one

Harlow Shapley
USA (1885-1972)

(1930)

manent in spectral composition. Is this because the time units we use in measuring stellar evolution are still too anthropocentric, or because the clusters are timeless?

B^{2}FH (1956)

5 October 1956, Volume 124, Number 3223 **SCIENCE**

Origin of the Elements in Stars

F. Hoyle, William A. Fowler,
G. R. Burbidge, E. M. Burbidge

Experimental (*1, 1a*) and observational (*2–6*) evidence has continued to accumulate in recent years in support of the theory (*7–10*) that the elements have been and are still being synthesized in stars. Since the appearance of a new and remarkable analysis by Suess and Urey (*11*) of the abundances of the elements, we have found it possible to explain, in a general way, the abundances of practically all the isotopes of the elements from hydrogen through uranium by synthesis in stars and supernovae. In this article we wish to outline in a qualitative fashion the essentially separate mechanisms which are required in stellar synthesis (*12*).

Thermal Conversion of Pure Hydrogen through Helium to Iron

As long as extremely high temperatures in excess of 5×10^9 degrees Kelvin are not under consideration, the general tendency of nuclear reactions inside stars is to increase the average binding energy per nucleon. For a given temperature and density and for a given time scale of op-

in some cases by resonance penetration. Since barrier effects become less severe as the temperature increases, it follows that the binding energies increase with temperature. This will become clear from the following examples.

At temperatures from about 10^7 to 5×10^7 degrees in main-sequence stars, hydrogen is transformed to helium, $4H^1 \rightarrow He^4$, with an average binding energy of 7.07 million electron volts (Mev) per nucleon. We emphasize that the proton-proton sequence of reactions makes possible the production of helium starting only with hydrogen. The recent discovery of the free neutrino as reported by Cowan *et al.* (*1a*) leads to increased confidence in the existence of the primary proton-proton interaction which proceeds through prompt electron-neutrino emission. At temperatures from 10^8 to 2×10^8 degrees in red giant stars, He^4 is transformed principally to C^{12}, O^{16}, and Ne^{20} with an average binding energy of 7.98 Mev per nucleon. The important roles of the ground state of Be^8 and of the second excited state of C^{12} in expediting the primary process of helium fusion, $3He^4 \rightarrow C^{12}$, have recently been

appreciably greater atomic weight than Fe^{56}.

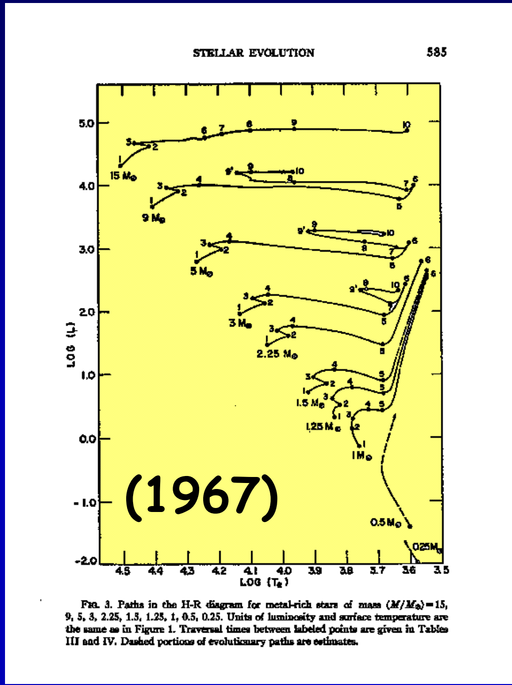
The situation, then, is that a thermal "cooking" of pure hydrogen yields principally He^4 and the α-particle nuclei with $A = 4n$, $Z = 2n$, $n = 3$, 4, 5, 6, 7, 8, 9, and
10 (C^{12} to Ca^{40}), to
centered around Fe^{56}.
abundant nuclei. Mor
abundances that hav
for these nuclei, and
20-odd isotopes of ti
chromium, manganese
nickel, show good ag
served abundances. Th
rium calculations by
been considerably im
into account the low-l
of the iron-group nucl
active nuclei which u
them, and by statistica
state according to its
that expected on nu
Typical results for the
dances of the chro
3.8×10^9 degrees are in
We regard results si
sented in Table 1 as gi
to the view that the el
sideration were synth
and that they became
tributed in space, eith
from late-type giants
explosion, as for insta


Scanned at the American Institute of Physics

Thermal Reactions of ... and Helium with Ligh...

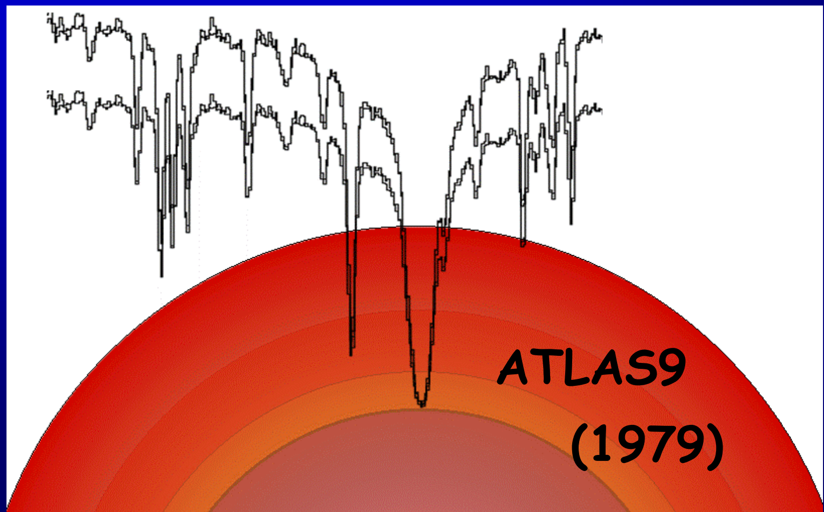
More complicated effects arise when the thermal cooking is considered, not of completely pure hydrogen, but of hydrogen adulterated with a small proportion of the elements mentioned in the previous paragraphs. When a second-genera-

Star builders



Icko Iben USA (1931-)

Robert L. Kurucz USA (1946-)



Star synthesizers

Beatrice M. Tinsley
New Zealand/USA
(1941-1981)

Sandra M. Faber (USA)

Most popular synthesis codes (→ 2008)

'90

- Leitherer (et al.), 1999
- Maraston, 1998, 03, 05
- Granato & Silva, 1998
- Vazdekis (et al.), 1997, 99, 01, 03
- Poggianti (et al.), 1996, 97, 03
- Bressan & Chiosi (et al.), 1994, 96
- Worthey, 1994
- Fritze v. Alvensleben (et al.), 1992, 95, 99
- Brocato (et al.), 1990

'80

- Barbaro & Olivi, 1989
- Buzzoni, 1989, 95, 02, 05
- Bica (et al.), 1988, 90
- Rocca-Volmerange (et al.), 1988, 97
- Arimoto & Yoshii, 1986, 87
- Pickles, 1985
- Bruzual (& Charlot), 1983, 93, 03, 07

'70

- Tinsley (et al.), 1976, 78
- O'Connell, 1976, 80
- Faber, 1972
- Spinrad & Taylor, 1969, 71

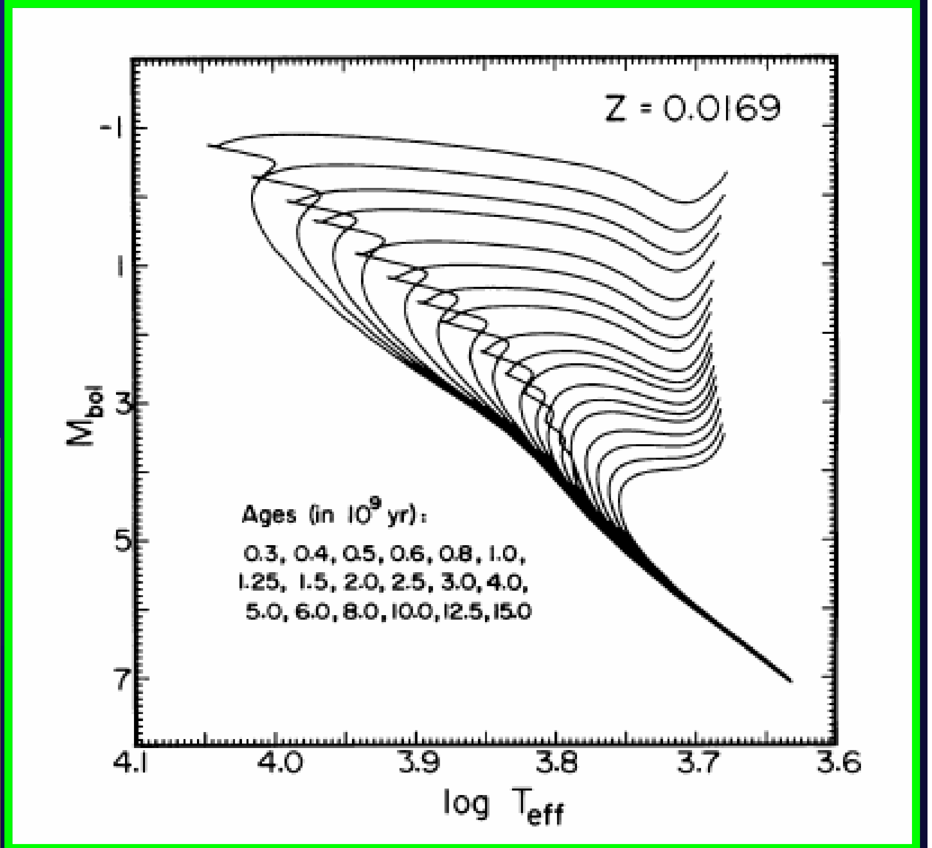
The synthesis approach…

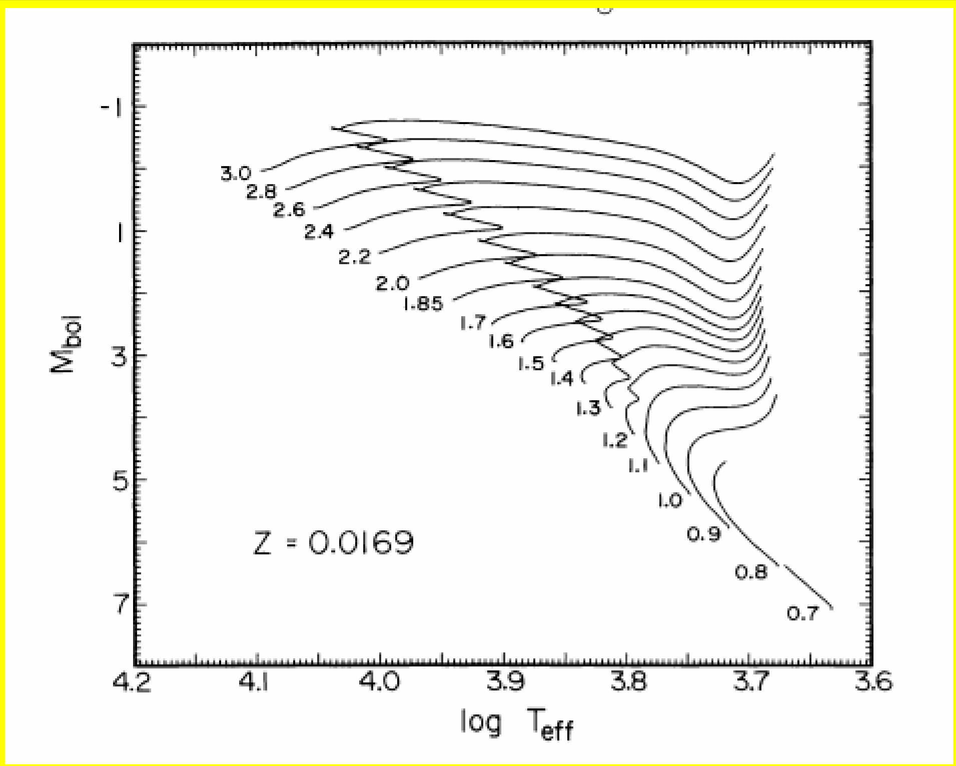
$$F(\lambda) = \int^{*} f(\lambda)_{T,L} \left[\text{HR diagram}\right]_{T,L}$$

Input	→	Output
Output	←	Input

Stellar tracks & Isochrones

Vandenberg (1985)





A Simple Stellar Population (SSP) is…

- Any <u>coeval</u> sample of stars
- With <u>fixed</u> distinctive properties (other than stellar mass)
- Its c-m diagram can be described theoretically by an <u>isochrone</u>

Composite Stellar Populations (CSPs)

$$\mathrm{CSP}(t) = \int_0^t \mathrm{SSP}(\tau) \otimes \mathrm{SFR}(t-\tau)\, d\tau$$

Evolutionary regimes

High-mass stars ($M > 7\ M_{sun}$):

End up as SN II

Intermediate-mass stars ($2 < M < 7\ M_{sun}$):

Helium ignites in a non-degenerate core

No HB (blue loops) No AGB

Nucleosynthesis up to C-O

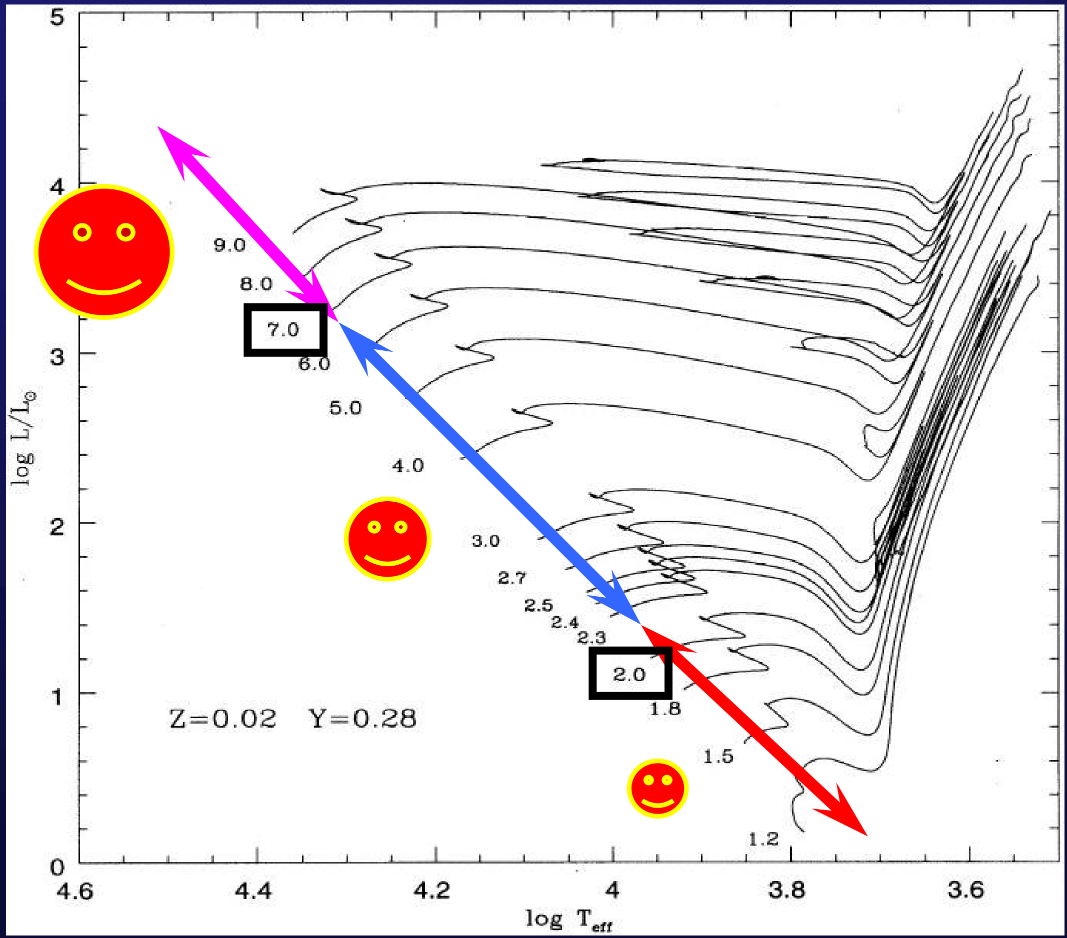
Low-mass stars ($M < 2\ M_{sun}$):

Helium ignites in a degenerate core (He flash)

Full HB - Full AGB

Nucleosynthesis up to C

Dominguez, Chieffi, Limongi, & Straniero (1999)



The Fuel Consumption Theorem

Renzini & Buzzoni (1986)

Post-MS luminosity contribution: $L = \int \ell_* N(M) dM_*$

IMF → $N(M)\, dM = A\, M^{-s}\, dM$

$$L_{PMS} = \int \ell_* [A\, M^{-s}_{TO}\, dM/dt] d\tau$$

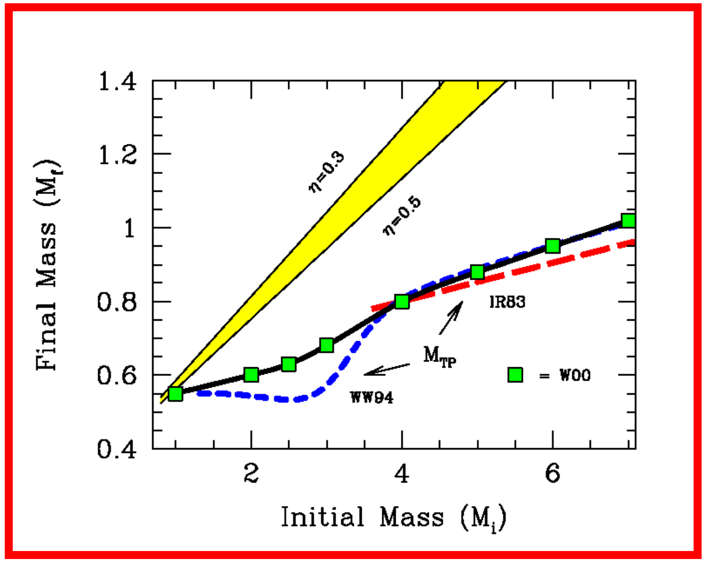
$A \rightarrow M_{tot}$ $\quad L_{PMS} = A\, M^{-s}_{TO}\, dM/dt \int \ell^* d\tau$

Evolutionary flux (b) ↑ Fuel!

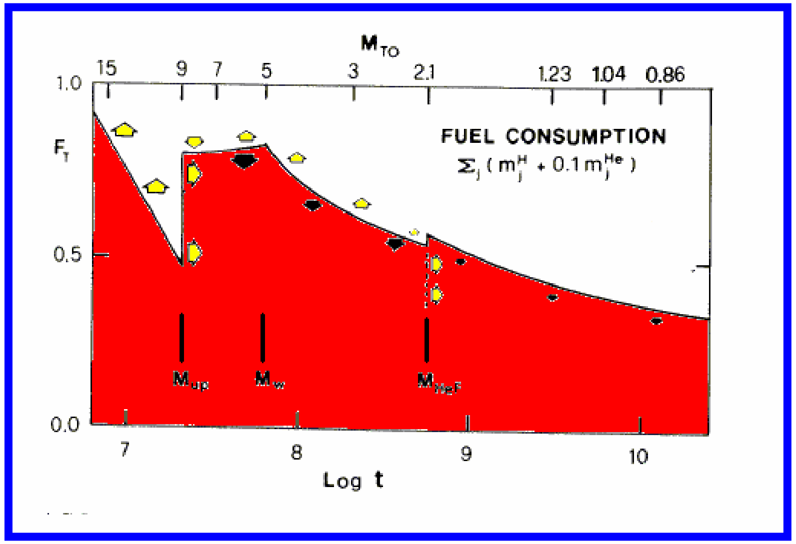
$$L_{PMS} / L_{TOT} = B \text{ Fuel}$$

↑

$B = b/L_{TOT}$ (Specific evolutionary flux)

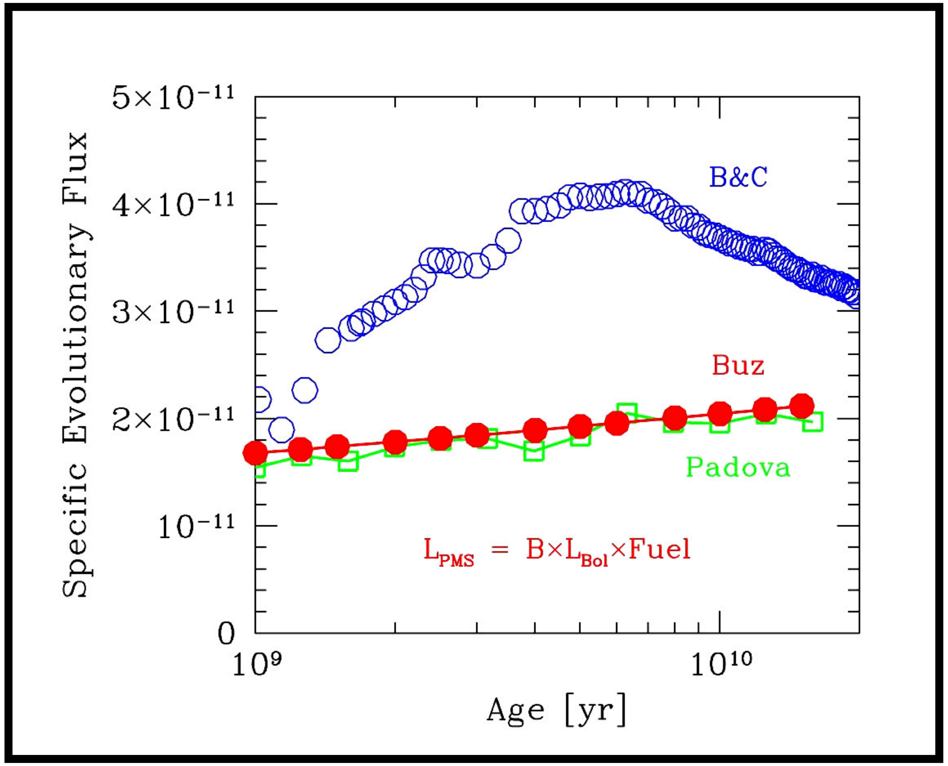


Buzzoni, Arnaboldi & Corradi (2006)



Fuel

B



Clock, Fuel…

& Energy conservation!…

...a straightforward consequence on number counts....

$$N_{PMS} = AM^{-s}dM = \left[AM_{TO}^{-s} \frac{dM_{TO}}{dt} \right] \tau = b \times \tau$$

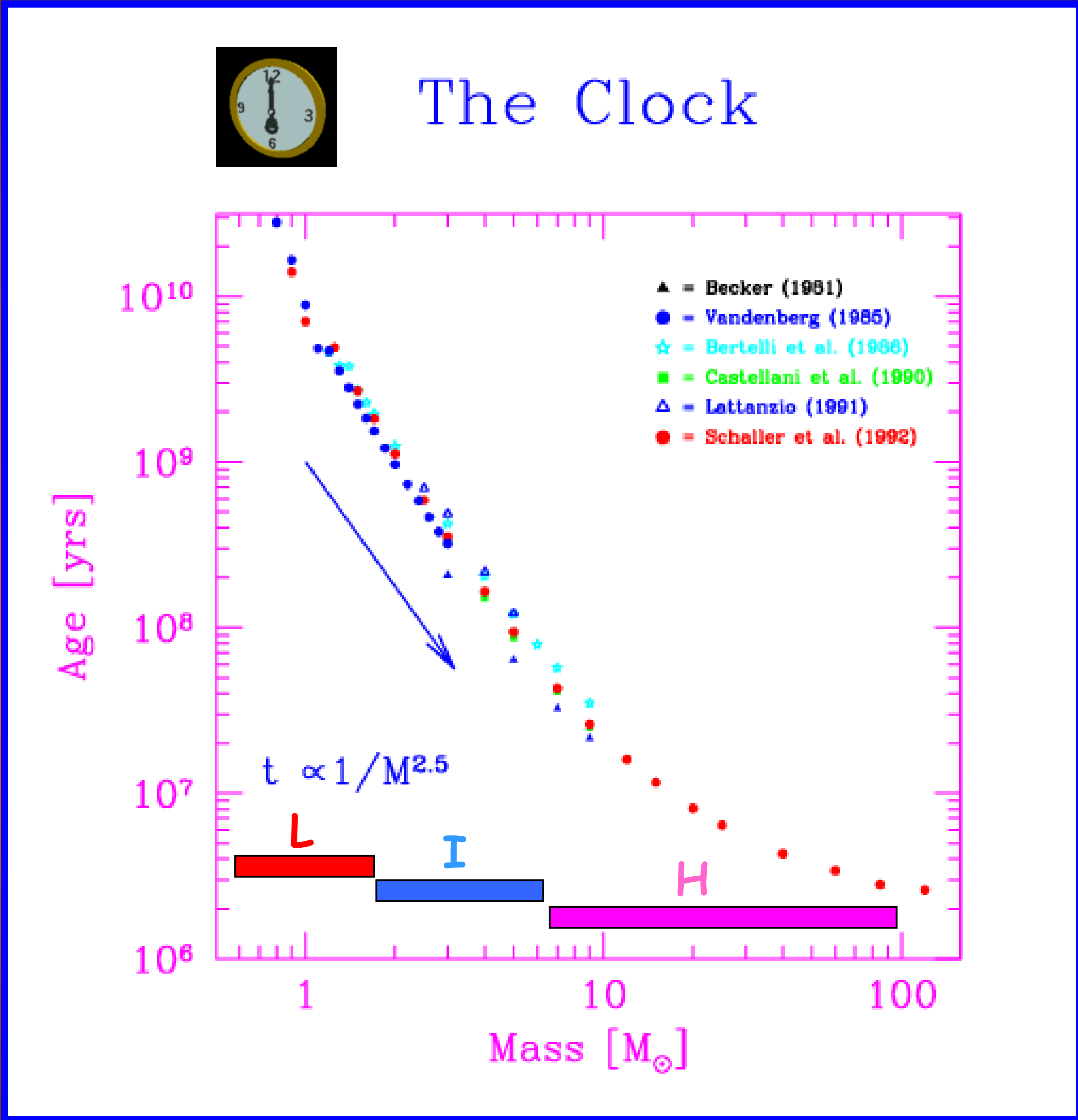
$$N_{PMS} = \left[\frac{AM_{TO}^{-s} \frac{dM_{TO}}{dt}}{L_{TOT}} \right] L_{TOT} \, \tau = B \times L_{TOT} \times \tau$$

$1.7\ (\pm 0.3)\ 10^{-11}$ (Buzzoni 1989)

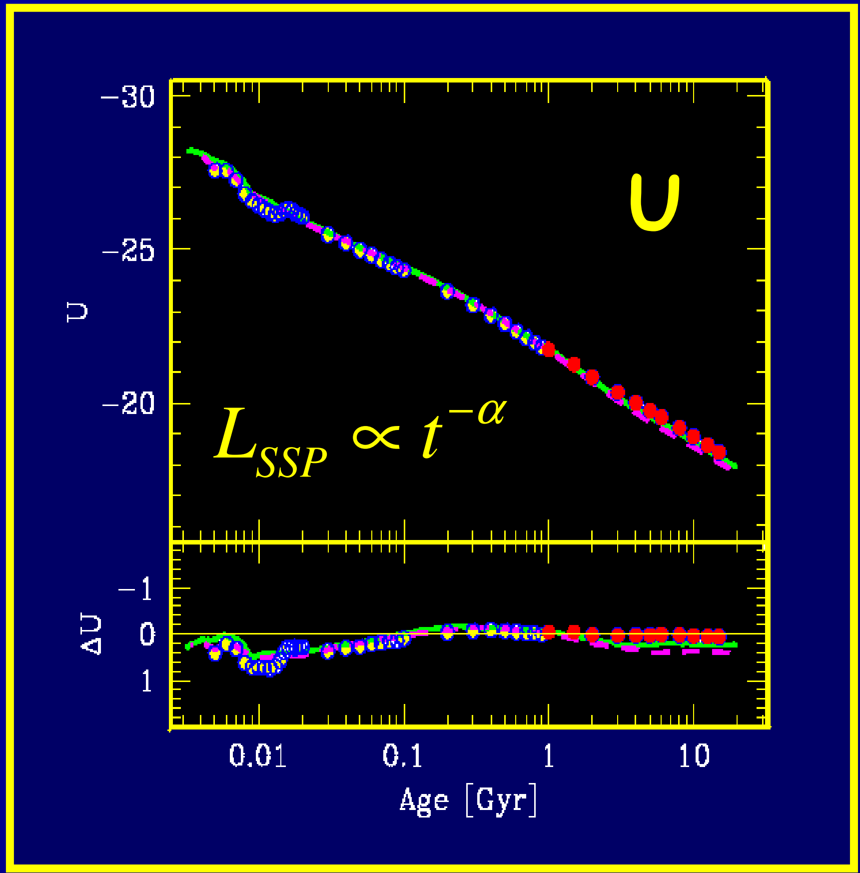
$$\frac{dt}{t} \approx -2.5\,\frac{dM_{TO}}{M_{TO}}$$

So

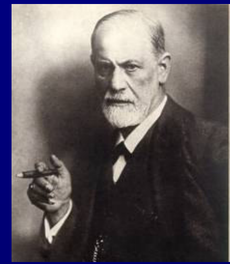
$0.1\ M_{sun} \approx \sim 3$ Gyr



Buzzoni (2002)



Short-term vs. Long-term memory



$L_U \propto t^{-1.1}$ Short α>1

$L_B \propto t^{-0.95}$

Long α<1

$L_V \propto t^{-0.85}$

$L_K \propto t^{-0.72}$

● Buzzoni (2005) ● Bruzual & Charlot (2003)
● Bressan et al. (1994) ● Leitherer et al. (1999)

$$L_{CSP}(t) = \int_{t\,\min}^{t} L_{SSP}(\tau) SFR(\tau - t) d\tau$$

$$L_{DISK} \propto [t^{(1-\alpha)} - t_{\min}^{(1-\alpha)}]$$

The End (Part I)