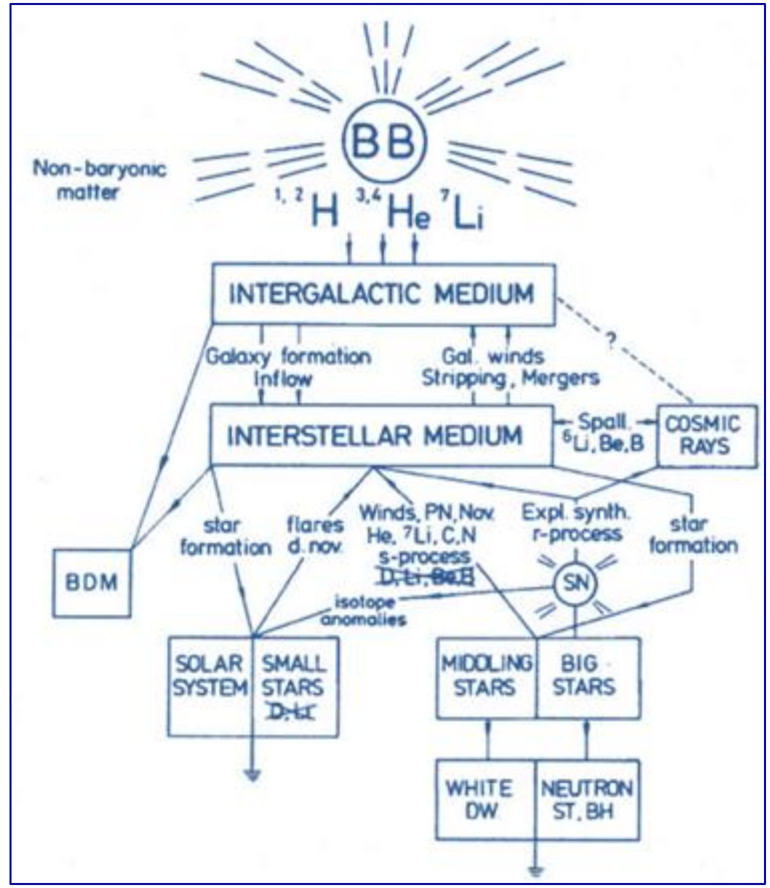
CHEMICAL EVOLUTION PRINCIPLES

MODEL INGREDIENTS

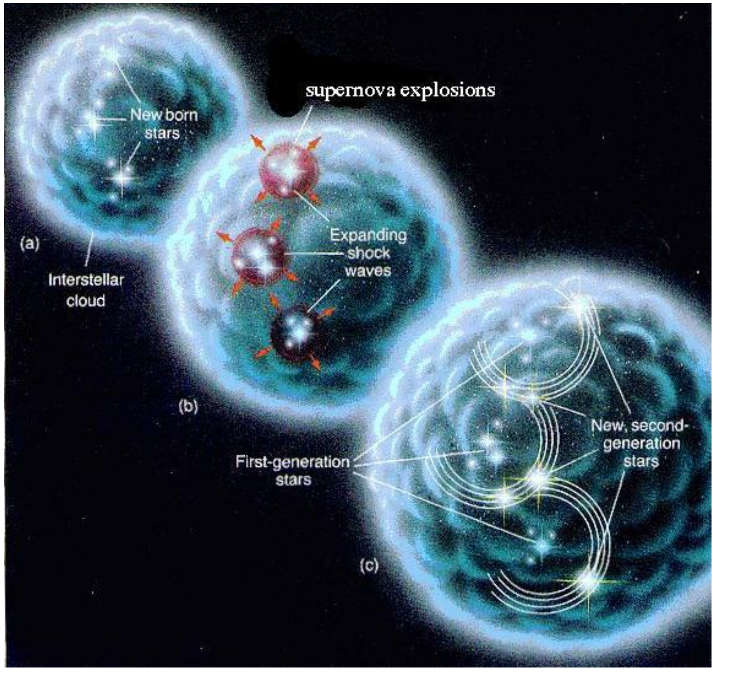
Chemical evolution goals

- The chemical evolution studies the origin and the distribution of the nuclear species (chemical elements) in the observed stars and interstellar medium.

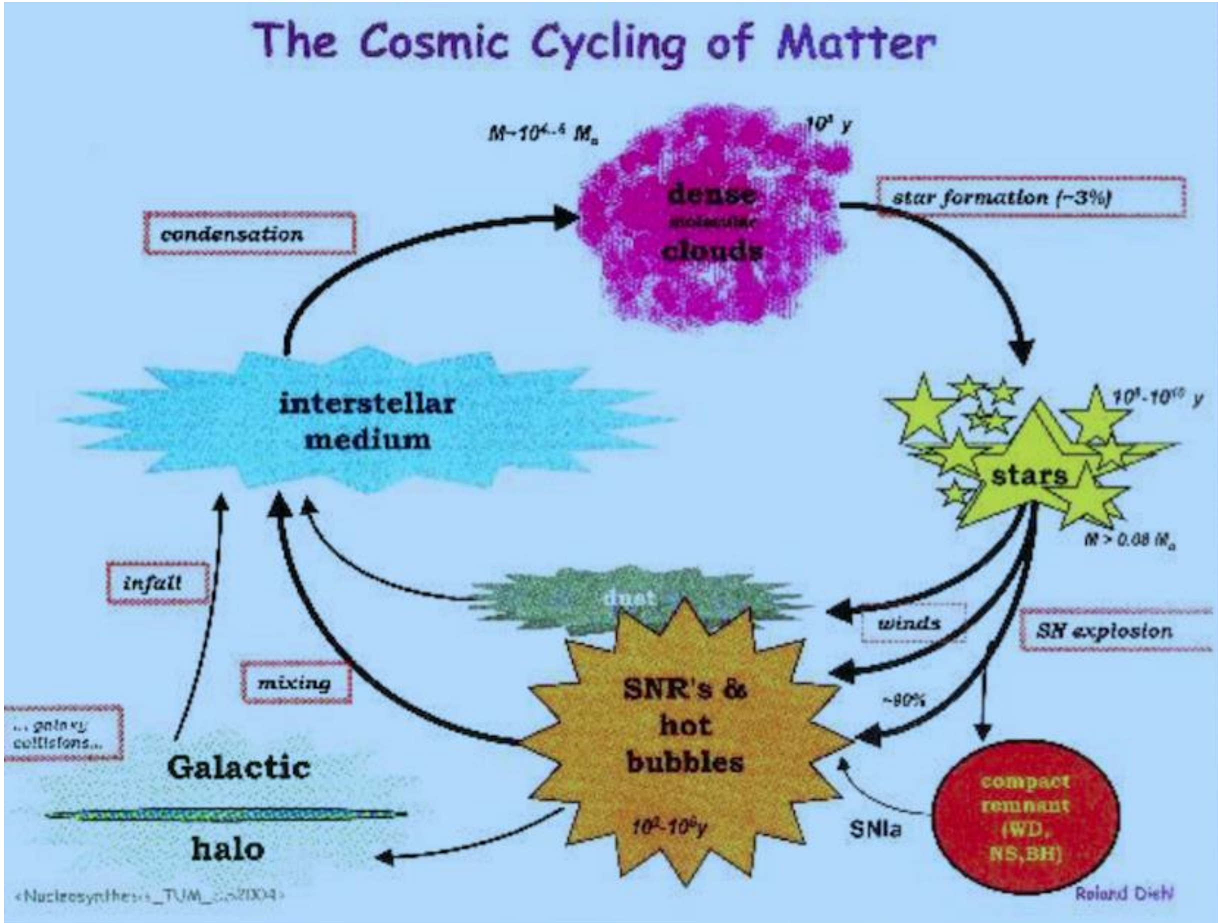


Metals and Stellar evolution

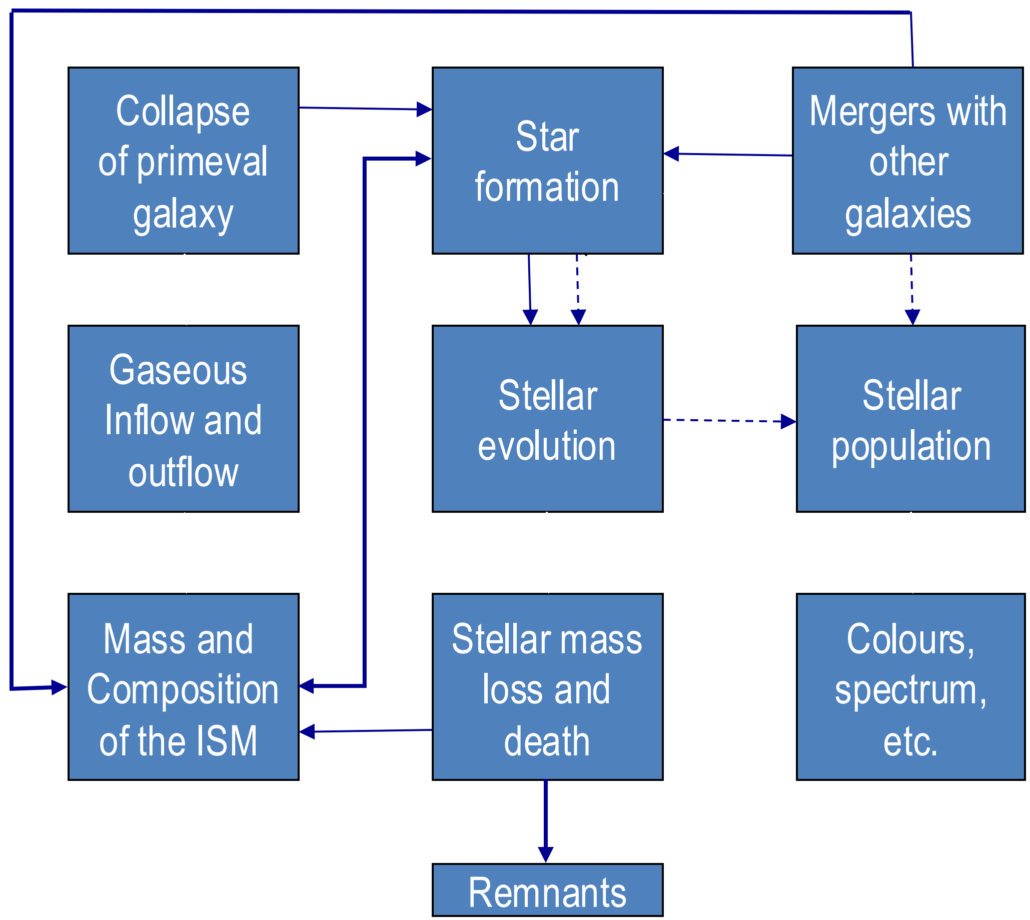
- Chemical elements are produced as result of stellar nucleosynthesis. These elementes are:
  - ejected to the ISM during or at the end of stellar evolution,
  - mixed with the ISM,
  - incorporated to next stellar generations.
- As a result, the ISM gets progressively chemically enriched.



The chemical evolution cycle



The chemical evolution cycle



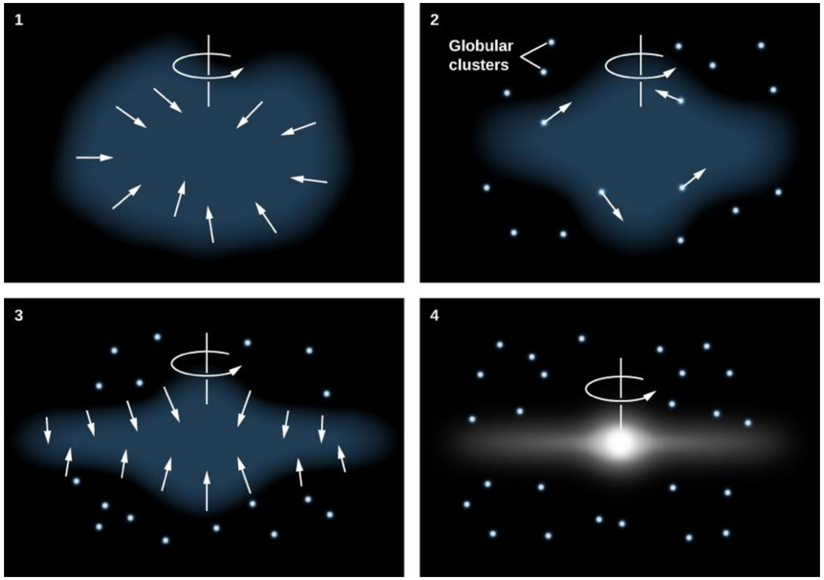
Tinsley (1980)

The ingredients of chemical evolution

- Initial conditions.
- Stellar birthrate.
- Initial mass function.
- Star formation rate.
- Stellar nucleosynthesis products.
- Evolutionary scenario.

Ingredients: the initial conditions

- Inicially, the gas has a primordial chemical composition: H, D, ^{3}He, ^{4}He y ^{7}Li (see the previous lecture)
- The gas is condensed into galaxies that initially consist of gas (probably inside dark matter haloes) that cools down and collapse while forming stars.
- Stars form according to a given mass distribution: the initial mass function (IMF).



Ingredients: the stellar birthrate

- The "***Stellar Birthrate Function***" (SBF) is defined as the number of stars crated per unit time.
- In principle, this function will depend on stellar mass (m) and time (t) $\Rightarrow B(m,t)$
- For analytical work (and in most cases …) this function is assumed to separable $\Rightarrow\ B(m,t) = \psi(t)\ .\ \phi(m)$
- The function $\psi(t)$ is the : "***Star Formation Rate***" (SFR) and refers to the mass which is transformed into stars.
- The function $\phi(m)$ is the : "***Initial Mass Function***" (IMF) and defines the mass distribution of stars at formation.

Ingredients: the initial mass function

- The initial mass function gives the number of stars that are formed in a given mass range.
- Usually it is reprsented by a power law of the form:
  - $\phi(m) = A\, m^{-(1+x)}$

  where x is called the IMF slope.
- The first value for x was given by Salpeter (1955) as x = *1.35*.
- The IMF is normalised to unity in mass:

$$\int_{m_l}^{m_u} m f(m)\, dm = 1$$

- m_l and m_u are the lower and upper limits of the stars than can form.

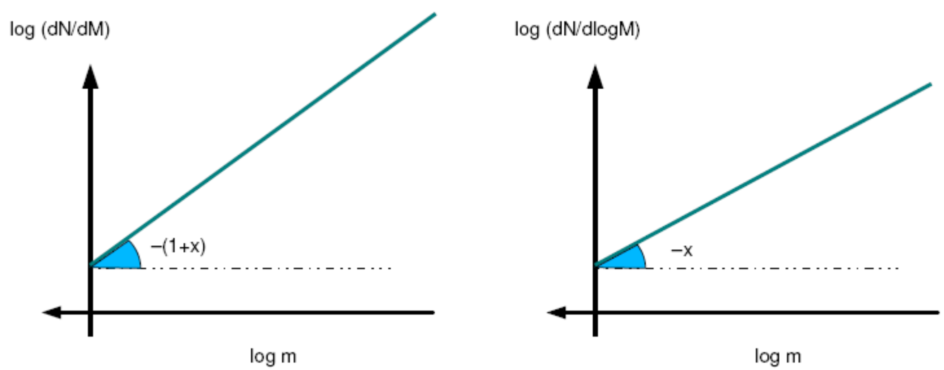
The functional form of the IMF

$$\phi(m) = A\, m^{-(1+x)}$$

$$x = 1.35$$

Salpeter 1955, 121, 161

$$\int_{m_l}^{m_u} m\phi(m)\,dm = 1 \rightarrow A = \frac{1}{\int_{m_l}^{m_u} m\phi(m)\,dm}$$



The "Salpeter" IMF

Salpeter Mass Function

The Initial Mass Function for stars in the Solar neighborhood was determined by Salpeter in 1955. He obtained:

$$\xi(M) = \xi_0 M^{-2.35} \qquad \textbf{Salpeter IMF}$$

$\uparrow$ constant which sets the local stellar density

Using the definition of the IMF, the number of stars that form with masses between M and M + ΔM is: $\xi(M)\Delta M$

To determine the total number of stars formed with masses between M_1 and M_2, integrate the IMF between these limits:

$$N = \int_{M_1}^{M_2} \xi(M) dM = \xi_0 \int_{M_1}^{M_2} M^{-2.35} dM$$

$$= \xi_0 \left[\frac{M^{-1.35}}{-1.35} \right]_{M_1}^{M_2} = \frac{\xi_0}{1.35} \left[M_1^{-1.35} - M_2^{-1.35} \right]$$

(From P. Armitage)

UNIVERSIDAD AUTONOMA DE MADRID

The Salpeter IMF

Grupo de Astrofísica
Universidad Autónoma de Madrid

Can similarly work out the total **mass** in stars born with mass $M_1 < M < M_2$:

$$M_* = \int_{M_1}^{M_2} M\xi(M)dM$$

Properties of the Salpeter IMF:

- most of the stars (by number) are low mass stars
- most of the **mass** in stars resides in low mass stars
- following a burst of star formation, most of the **luminosity** comes from high mass stars

Salpeter IMF must fail at low masses, since if we extrapolate to arbitrarily low masses the total mass in stars tends to infinity!

Observations suggest that the Salpeter form is valid for roughly $M > 0.5\ M_{sun}$, and that the IMF `flattens' at lower masses. The exact form of the low mass IMF remains uncertain.

(From P. Armitage)

The derivation of the IMF

- The IMF is derived from the stellar luminosity function (LF), $\Phi(M_v)$, which gives the number of stars per unit volume with absolute magnitude within a given range.
- From the LF, the present day mass function (PDFM) with mass within a given range.
- Finally, we have to estimate the number of stars which have already evolved out of the MS.

UAM UNIVERSIDAD AUTONOMA DE MADRID

The Present Day Mass Function (PDMF)

Grupo de Astrofísica
Universidad Autónoma de Madrid

- It is the base of the IMF determination.
- It is defined as the number of stars in the Solar Neighbourhood (SN) per logarithmic unit of mass interval, per parsec, $F\ (log\ m)$
- It is related to the LF by:

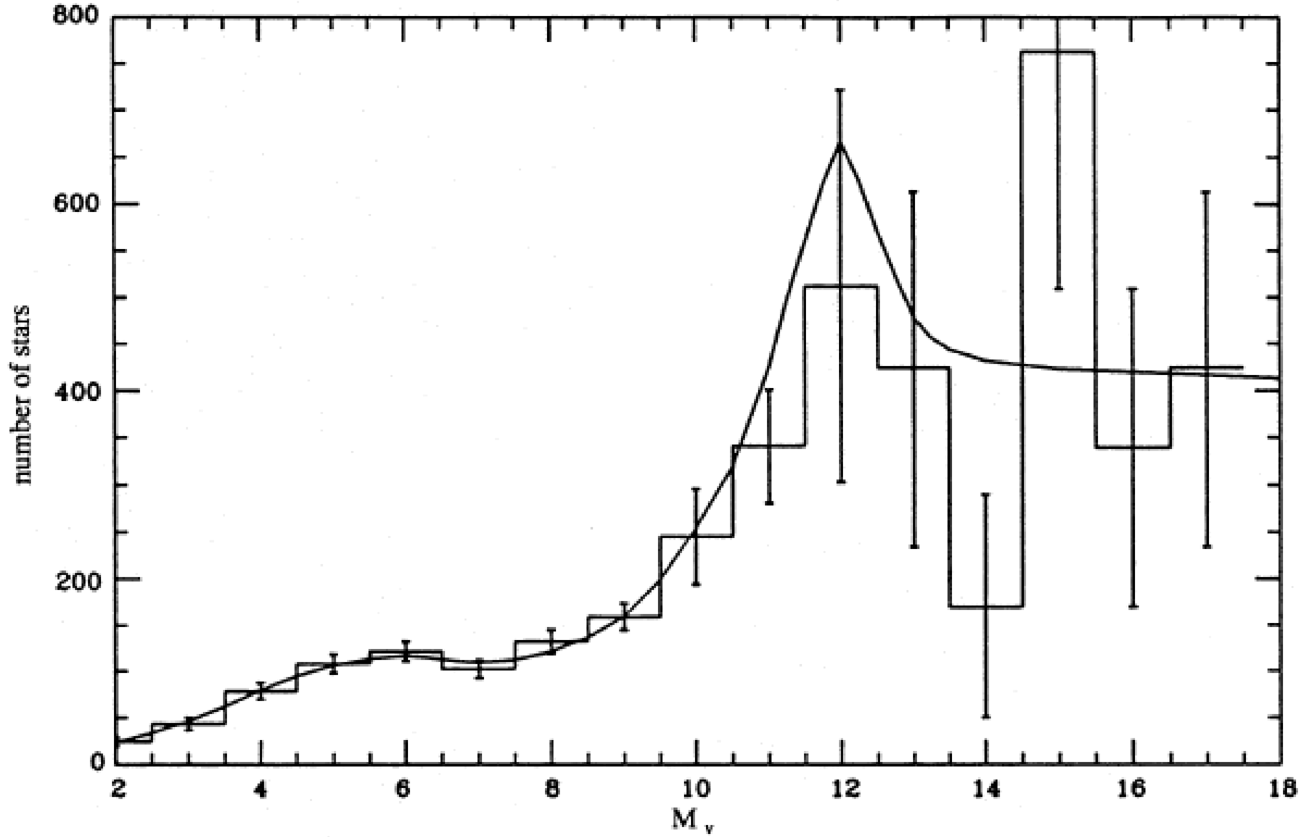
$$F(\log m) = F(M_V) \times \left| \frac{dM_V}{d\log m} \right| \times 2H(M_V) \times f_{MS}(M_V)$$

- In this expression $\Phi(M_v)$ is the number of stars with absolute magnitude between M_V y $M_V + dM_V$, per pc^3; H is the galactic disc length scale; and f_{MS} is the fraction of stars in the main sequence.

The parameters of the PDMF

- The PDMF depends on:
  1. The LF, $\Phi(M_v)$: number of stars of all types per unit of absolute magnitude and pc^3 in the galactic disc of the SN.
  2. The mass-luminosity relation for MS stars, $|dM_v/d(\log m)|$, which depends on the stellar evolutionary tracks.
  3. The luminosity fraction coming from MS stars, f_{ms}
  4. $2H(M_v)$, which is the result of the integration of the LF through the dimension perpendicular to the hgalactic disc, assuming this has an expontentially decreasing distribution with a scale height H.

The local stellar Luminosity Function



Bright stars **Faint stars**

Kroupa, Tout & Gilmore, 1993, MNRAS, 262, 545

Local Stellar Luminosity Function

open dots: photometric parallaxes

light: $L_V \, \Phi_V(M_V)$

light from MS stars only

solid dots: Hipparcos data

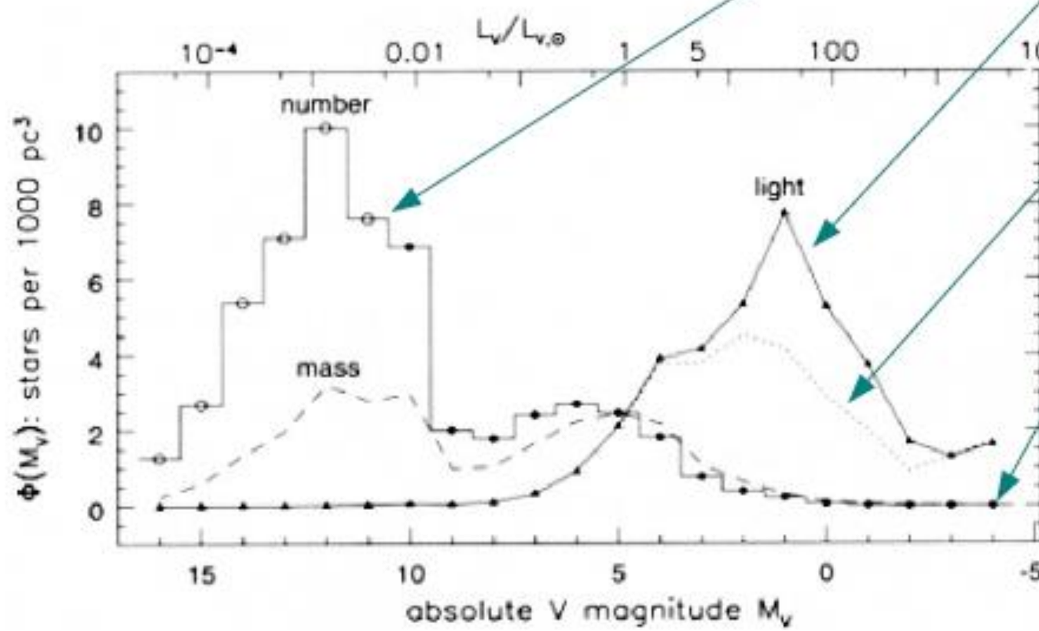
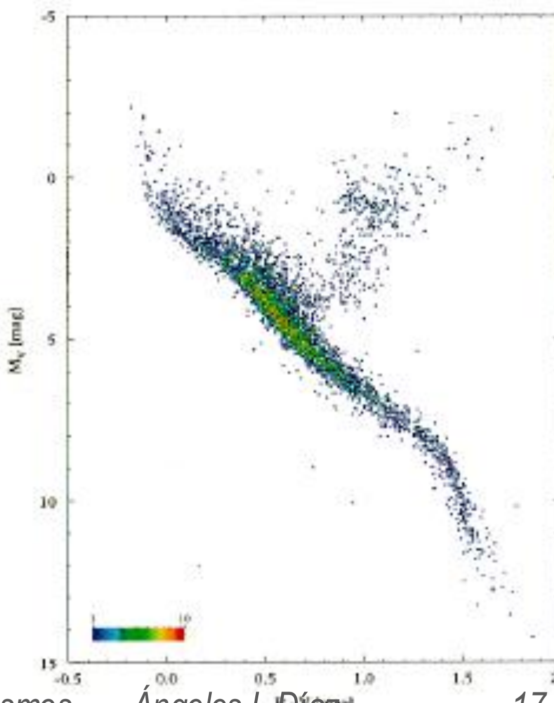


Figure from Sparke & Gallagher

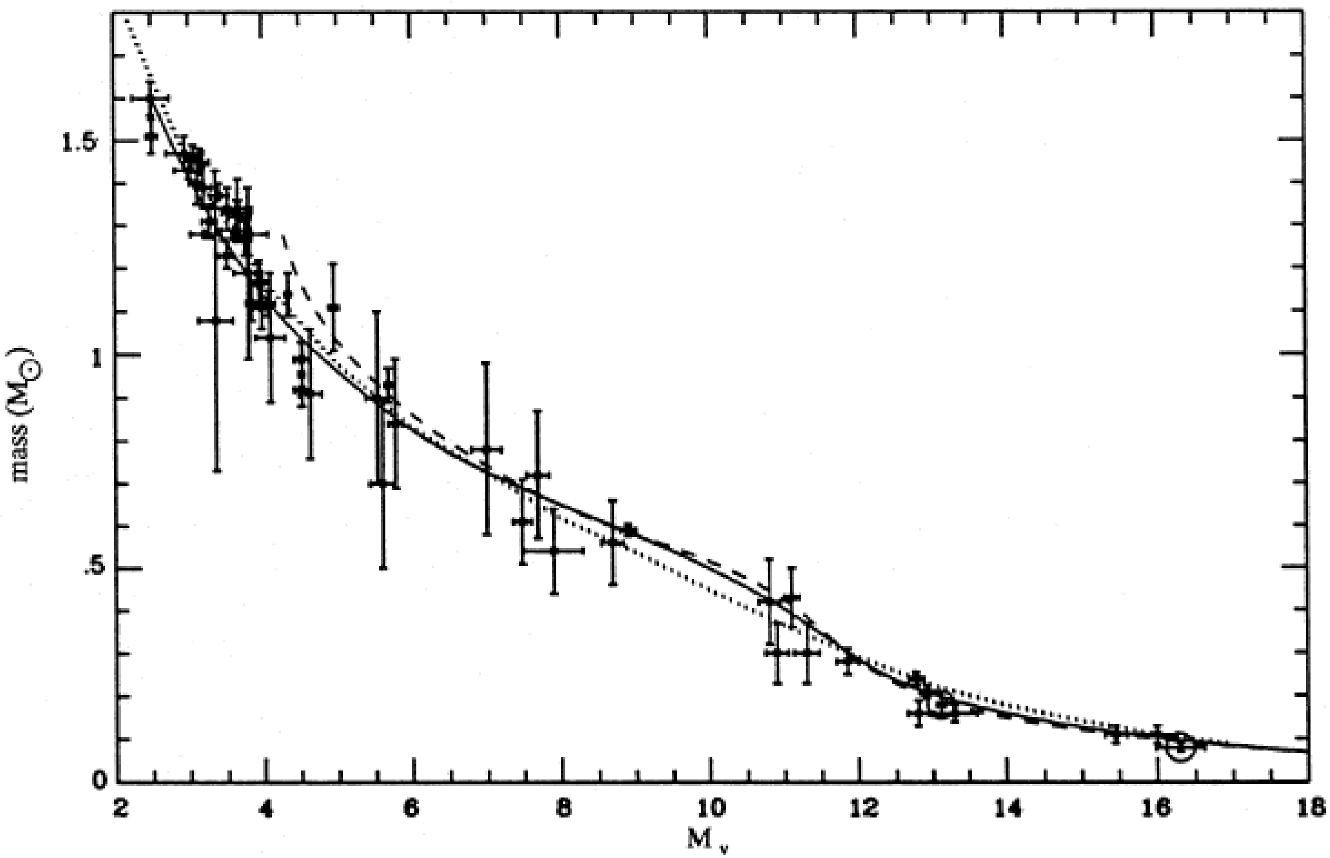


The characteristics of the LF in the SN

- The majority of stars in the SN are intrisically faint.
- Bright stars are rare, but most of the luminosity comes from them.
- Most of the stellar mass comes from the faint stars.
- The mass is didtributted in a roughly uniform way in stars with M_V between 3 y 15.
- The mass density in SN stars is ~ 0.039 $M_\odot\, pc^{-3}$.
- The mean mass-luminosity relation in the SN is

$$\Gamma_V \sim 0.67\ (M_\odot / L_\odot)$$

The mass-luminosity relation



Kroupa, Tout & Gilmore, 1993, MNRAS, 262, 545

Luminosity fraction coming from MS stars

TABLE 2

FRACTION (f_{ms}) OF STARS OF A GIVEN ABSOLUTE MAGNITUDE ON THE MAIN SEQUENCE

M_v	Salpeter 1955	Sandage 1957	Schmidt 1959	Upgren 1963	McCuskey 1966
−6......	...	0.46	...	...	0.40
−5......	...	0.48	0.41	...	0.42
−4......	0.18	0.48	0.41	...	0.43
−3......	0.36	0.50	0.46	...	0.44
−2......	0.50	0.51	0.48	...	0.45
−1......	0.47	0.53	0.52	0.12	0.47
0......	0.41	0.56	0.46	0.29	0.51
+1......	0.47	0.62	0.33	0.62	0.56
+2......	0.65	0.71	0.69	0.91	0.66
+3......	0.76	0.86	0.87	1.00	0.82
+4......	0.95	1.00	1.00	1.00	0.98
+5......	1.00	1.00	1.00	1.00	1.00

Integration through the disc

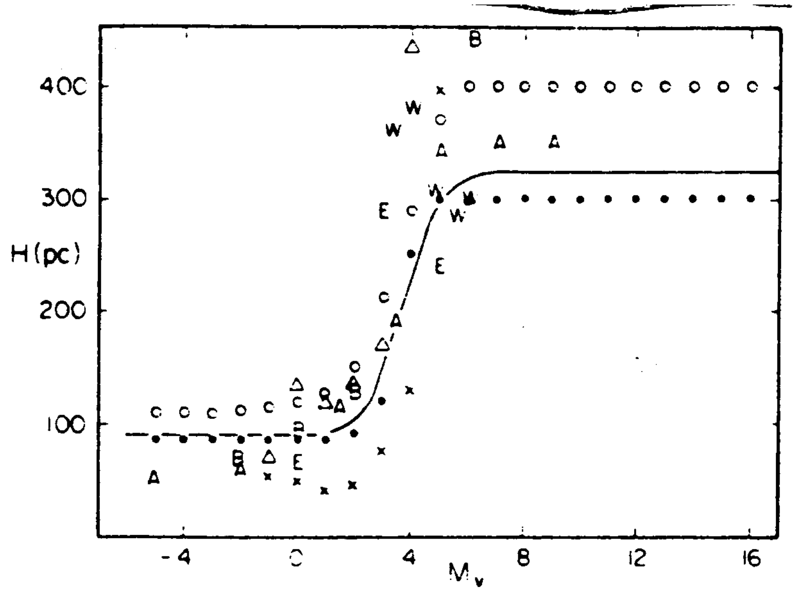


FIG. 3. Relationship between scale height H (pc) and absolute visual magnitude M_v. ●, Schmidt (1963); ○, Schmidt (1959); ×, Upgren (1963); ▲, McCuskey (1966); *W*, Weistrop (1972); *B*, Bok and MacRae (1941); *E*, Elvius (1951, 1962); *A*, Allen (1973); *solid line*, adopted relation.

$$\int_{-\infty}^{\infty} F(z)\,dz = 2F_o \int_0^{\infty} e^{-z/H}\,dz = 2F_o H \int_0^{\infty} e^{-y}\,dy = 2HF_o$$

Generally adopted relations

TABLE 1

ADOPTED RELATIONSHIPS

M_v	$\phi(M_v)$ (stars pc^{-3} mag^{-1})	log $M/M_\odot$	$\frac{-dM_v}{d \log M}$	$2H$ (pc)	log T_{ms} (yr)
−6.	1.78 (−8)	+1.79	4.0	180	6.50
−5.	7.94 (−8)	+1.55	4.2	180	6.57
−4.	3.55 (−7)	+1.33	4.6	180	6.76
−3.	1.58 (−6)	+1.11	4.9	180	7.02
−2.	7.08 (−6)	+0.91	5.3	180	7.32
−1.	3.16 (−5)	+0.72	5.8	180	7.68
0.	1.20 (−4)	+0.54	6.4	180	8.11
+1.	3.31 (−4)	+0.40	7.1	185	8.50
+2.	7.24 (−4)	+0.27	8.1	210	8.90
+3.	1.41 (−3)	+0.16	9.2	300	9.28
+4.	2.19 (−3)	+0.07	10.6	465	9.63
+5.	2.95 (−3)	−0.01	12.8	590	9.93
+6.	3.98 (−3)	−0.08	15.4	635	10.18
+7.	5.25 (−3)	−0.14	15.6	650	. . .
+8.	6.61 (−3)	−0.21	15.0	650	. . .
+9.	8.13 (−3)	−0.27	13.5	650	. . .
+10.	9.55 (−3)	−0.35	11.6	650	. . .
+11.	1.12 (−2)	−0.44	10.4	650	. . .
+12.	1.26 (−2)	−0.54	10.0	650	. . .
+13.	1.41 (−2)	−0.65	10.0	650	. . .
+14.	1.41 (−2)	−0.75	10.0	650	. . .
+15.	1.38 (−2)	−0.85	10.0	650	. . .
+16.	1.26 (−2)	−0.96	10.0	650	. . .

Uncertainties associated to the derivation of the PDMF

- The LF gives the number of stars in a given absolute **magnitude interval**. There are bright stars (low M_v) which are not on the MS $\Rightarrow f_{ms}$ would thus not be well calculated. A solution would be the use of spectral types instead of absolute magnitudes.
- Massive stars loose mass and therefore are observed at lower luminosities that would initially correspond to them.
- Very young stars might be still embedded within molecular clouds and dust. IR observations can help solve this problem.
- Chemical composition variations affect all the used relations.

The derivation of the IMF

- Stars with MS mean lifetimes, τ_m, longer than the age of the Galaxy, t_0, are on the MS at the present time. Their masses are: $m_* \leq 1\,M_\odot$. For them :

$$B(m,t)=\int_0^{t_0}\phi(m)\psi(t)\,dt=\phi(m)\int_0^{t_0}\psi(t)\,dt=\phi(m)\,\overline{\psi_1}\cdot t_0$$

$$\phi(m, m \leq 1M_{sun})=\frac{B(m)}{\overline{\psi_1}\cdot t_0}$$

where $\overline{\psi_1}$ is the past average star formation rate.

The derivation of the IMF

- Stars with $\tau_{ms} \leq t_0$ will be on the MS if they formed at a time $t_0 - \tau_{ms}$. Their masses are: $m_* \geq 2\,M_\odot$. For them:

$$B(m,t) = \int_{t_0-\tau_{ms}}^{t_0} f(m)\psi(t)\,dt = f(m)\int_{t_0-\tau_{ms}}^{t_0} \psi(t)\,dt$$

- If $\tau_{ms} << t_0$, $\psi(t)$ can be considered constant and

$$f(m, m \geq 2M_{sun}) = \frac{B(m)}{\psi_1 \tau_1}$$

where ψ_1 is the present day star formation rate and τ_1 is about 1 Gyr

The derivation of the IMF

- For stars with masses $1 \leq M/M_{\odot} \leq 2$, we cannot know the IMF without knowing the details of the star formation history
- To adjust the two parts of the IMF above, the continuity hypothesis is made:

$$\frac{B(m, m \leq 1M_{sun})}{B(m, m > 2M_{sun})} = \frac{f(m, m \leq 1M_{sun})}{f(m, m > 2M_{sun})} \frac{\overline{y_1 t_0}}{y_1}$$

The continuity condition

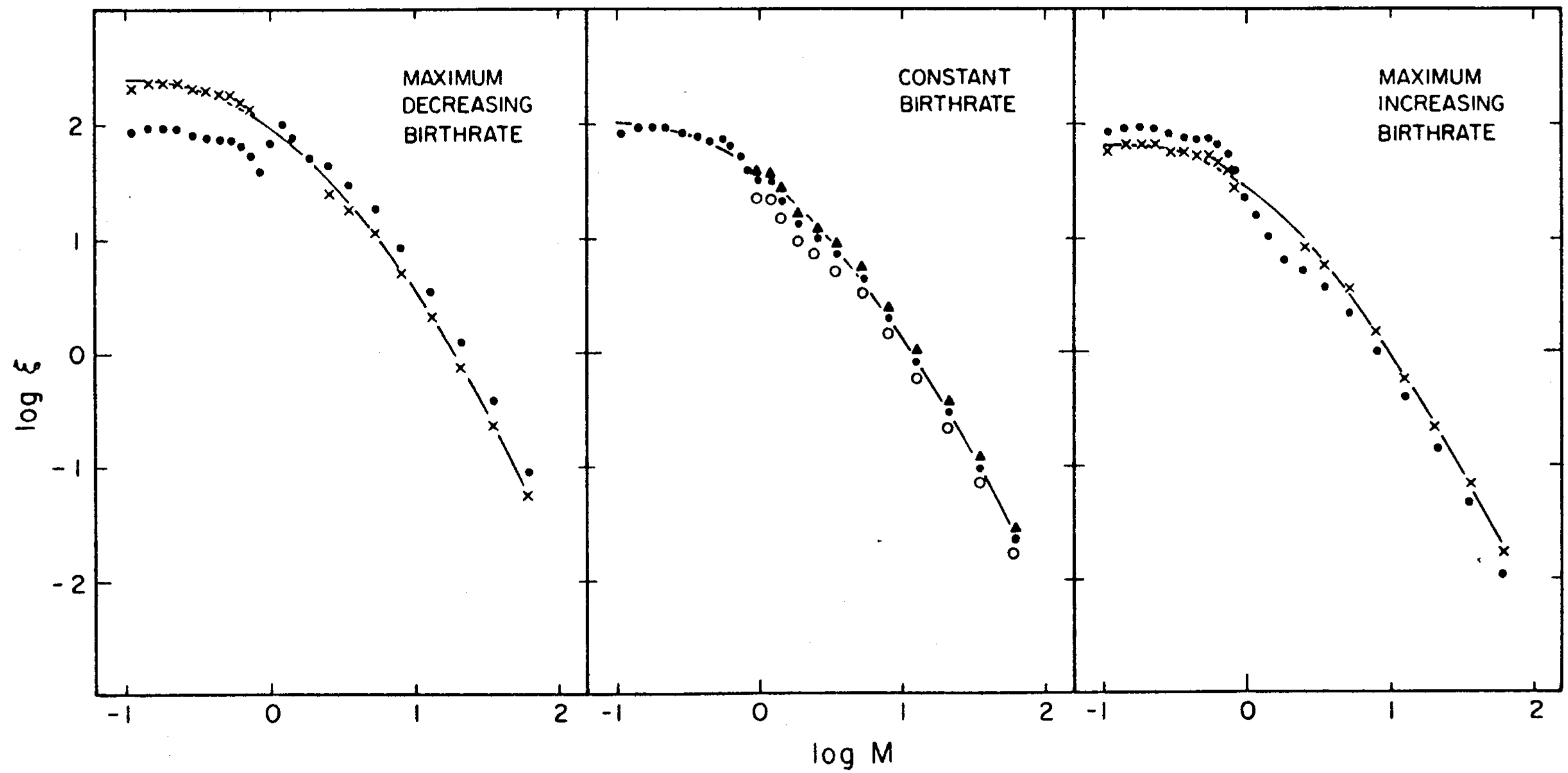


FIG. 10.—IMFs derived from the continuity constraint. For the MI and MD birthrates, the filled circles give the IMF derived from the adopted PDMF while the crosses give the IMF calculated from the PDMF adjusted by the extremes of the estimated uncertainty. This procedure was necessary because the limits on the present birthrate derived from Fig. 8 took these uncertainties into account. The IMFs for the MI and MD birthrates are independent of T_0 for 9×10^9 yr $\leq T_0 \leq 15 \times 10^9$ yr. For the constant birthrate, the IMF depends slightly on T_0. The open circles, filled circles, and filled triangles are for $T_0 =$ 9, 12, and 15×10^9 yr, respectively. For all birthrates, the solid line is an analytic fit to the IMF. For the constant birthrate, only the analytic fit for $T_0 = 12 \times 10^9$ yr is shown.

The PDMF for MS stars in the SN

The IMF and the PDMF are identical for stars with $\tau_{ms} > t_0$.

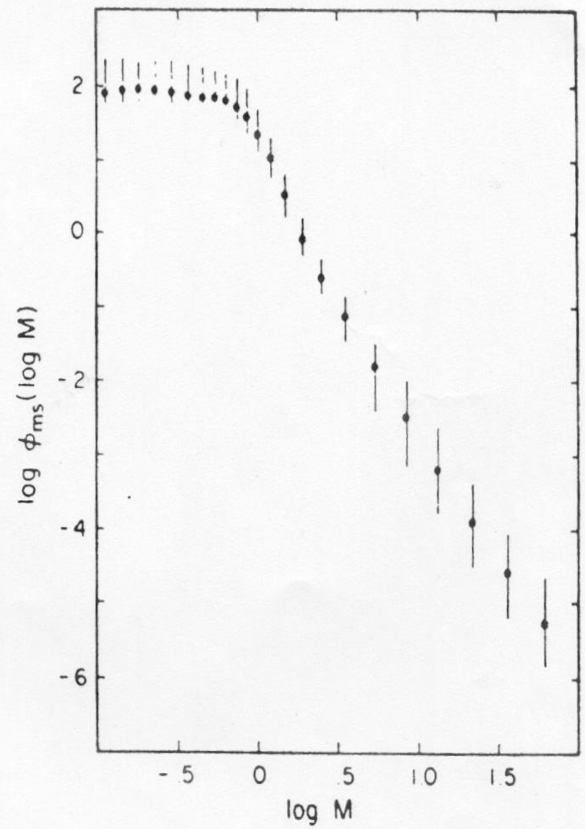


FIG. 4.—The PDMF of main-sequence field stars $\phi_{ms}(\log M)$ given as the number of stars $pc^{-2} \log M^{-1}$ in the solar neighborhood. Uncertainty bars are from Table 5.

IMF from Kroupa et al. (1993)

Low-mass stars in the Galactic disc 575

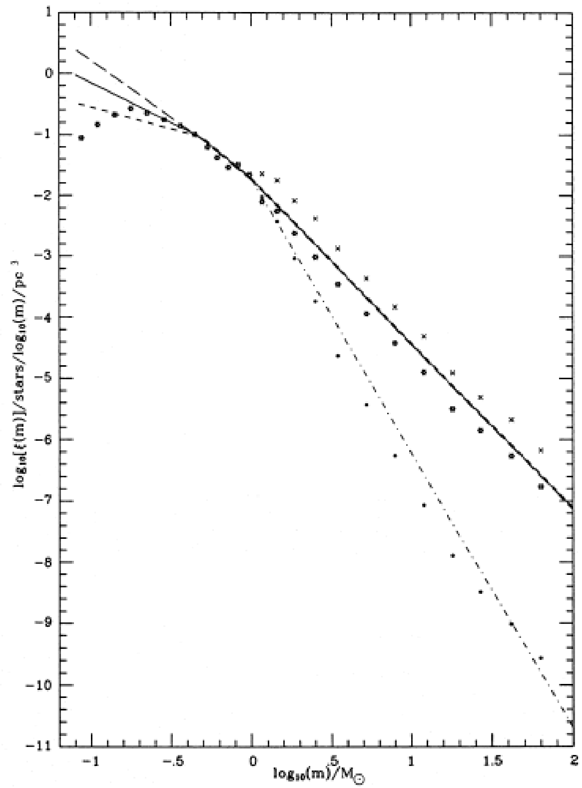
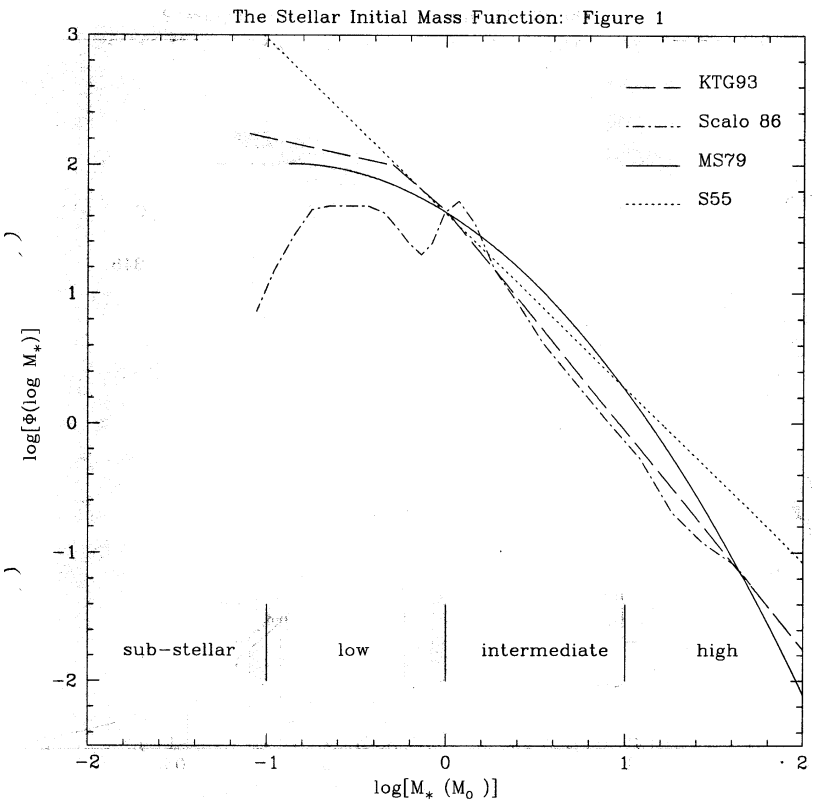


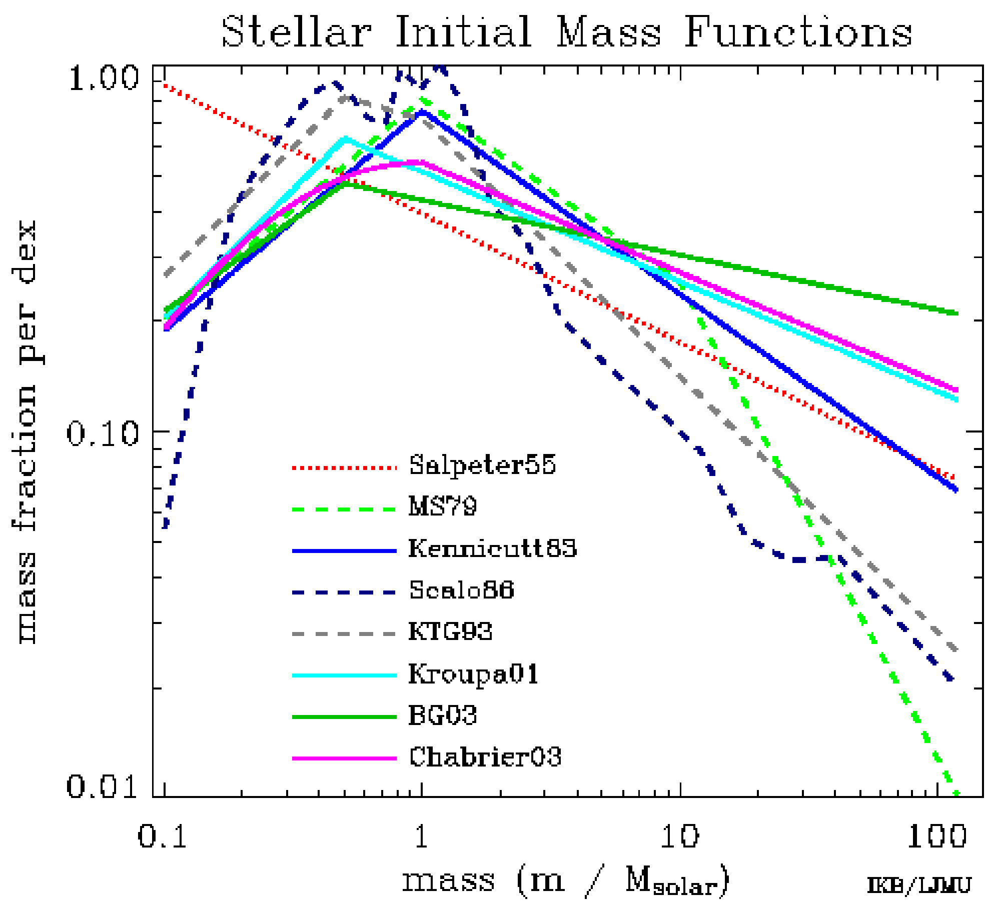
Figure 22. The stellar initial mass function (IMF) and present-day mass function (PDMF). The solid line represents the IMF given by equation (13), and the long- and short-dashed lines are for the cases $\alpha_1 = 1.85$ and 0.70, respectively. The PDMF ($\alpha_3 = 4.5$, Section 2) is indicated by the dot–dashed line. At masses below about 1 $M_\odot$ the PDMF equals the IMF. As a comparison, we show the PDMF derived by Scalo (1986) by solid dots. He corrects for stellar evolution; for a Galactic disc age of $T_0 = 9$ Gyr the IMF is indicated by stars, and for $T_0 = 12$ Gyr by crosses.

IMF comparison



- For stars with mass $M > 10\ M_\odot$ it is valid to use a general slope of x= 1.35 (Salpeter).
- Between *1* and $5\ M_\odot$ there is a flattening.
- Below $0.5\ M_\odot$ it seems totally flat (x=0).
- The mass at which the curve begins t o flatten seems to depend on metallicityZ, according to some studies of globular clusters with different

Different derived IMFs



Other functional forms of the IMF

- Power law:

$$\phi(m) = A\, m^{-(1+x)}$$

- Several power laws:

$$\begin{cases} m\,\Phi(m)\,\phi_1 = 1.00\, m^{-0.25} & 0.4 < m < 1 \\ m\,\Phi(m)\,\phi_1 = 1.00\, m^{-1} & 1 < m < 2 \\ m\,\Phi(m)\,\phi_1 = 1.23\, m^{-1.3} & 2 < m < 10 \\ m\,\Phi(m)\,\phi_1 = 12.3\, m^{-2.3} & m > 10 \end{cases}$$

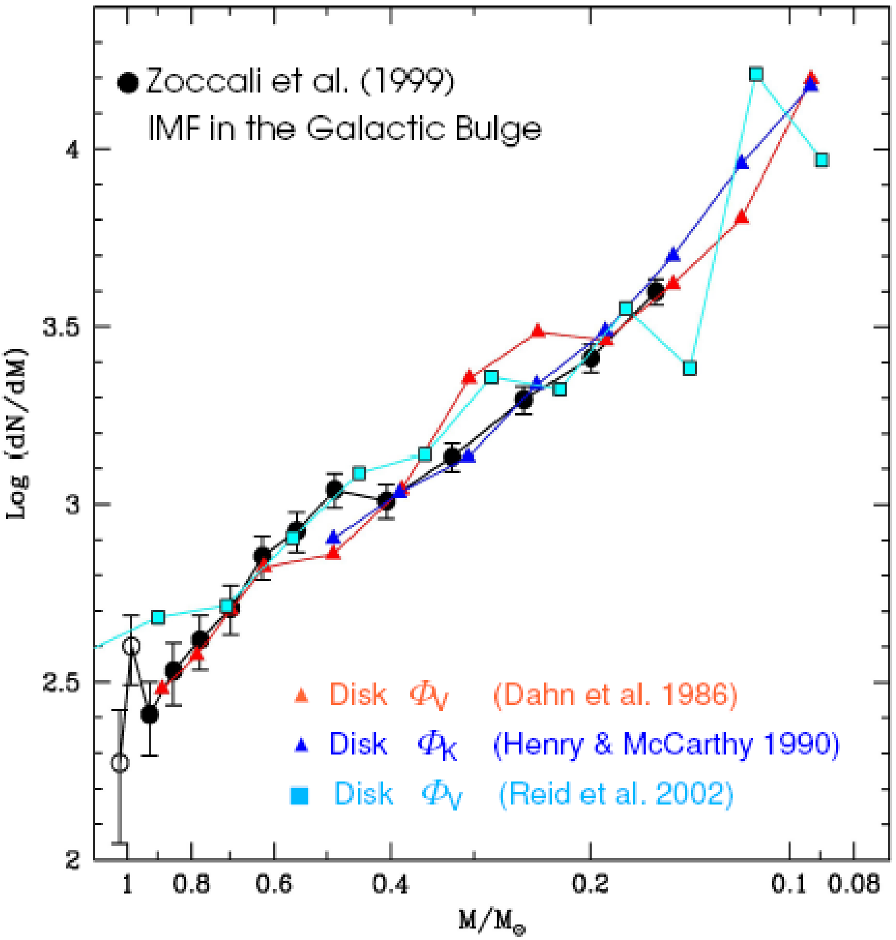
- Quadratic fit:

$$\log f\,(\log m) = 1.53 - 0.96 \log m - 0.47\,(\log m)^2$$

- Half-Gaussian fit:

$$f\,(\log m) = C_0 \exp\left[-C_1(\log m - C_2)\right]^2$$

Is the IMF "universal" ?



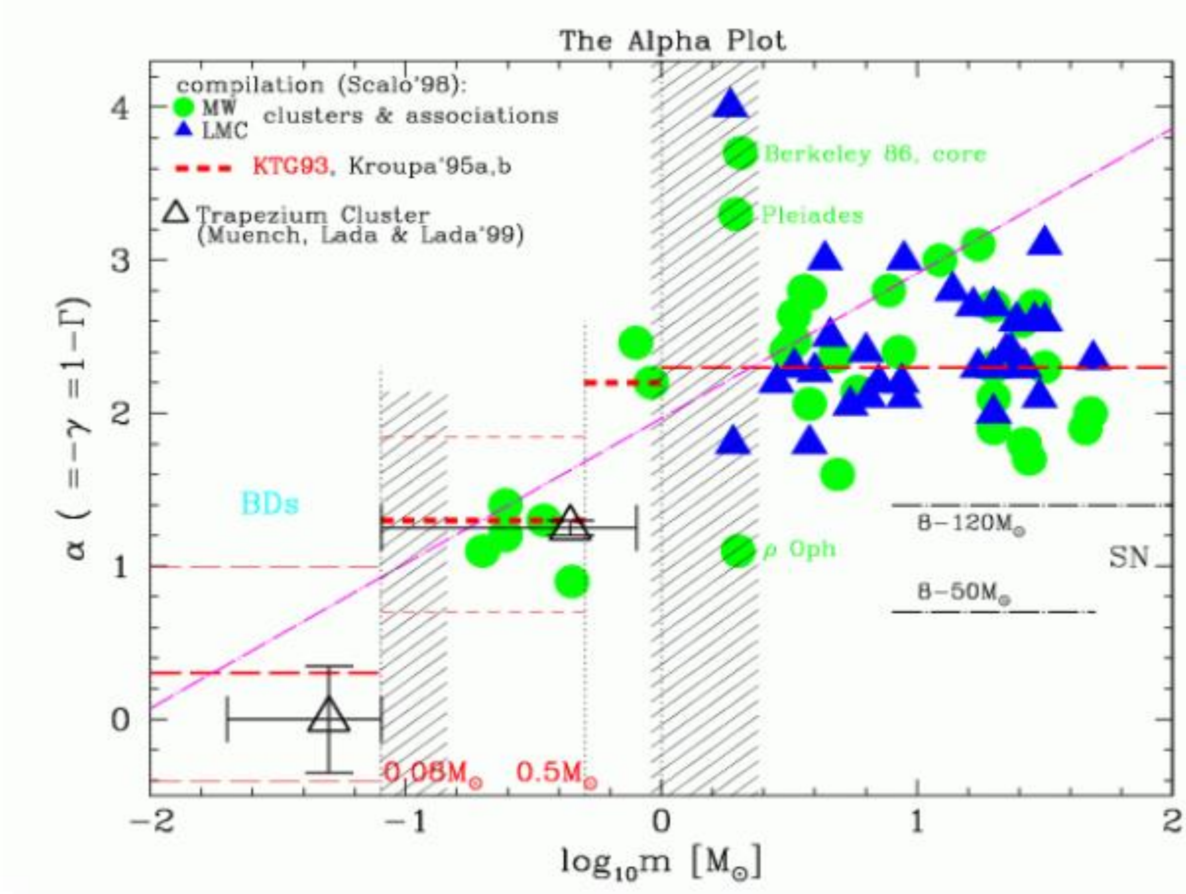
Dahn et al. (1986)
stars with d<5.2 pc and δ>-20°
MLR from Delfosse et al. (2000)

Henry & McCarthy (1990)
stars with d<5 pc and δ>-30°
MLR from Baraffe et al. (1998)

Reid et al. (2002)
HIPPARCOS stars
δ>-30° and 8<M_V<16
Empirical MLR

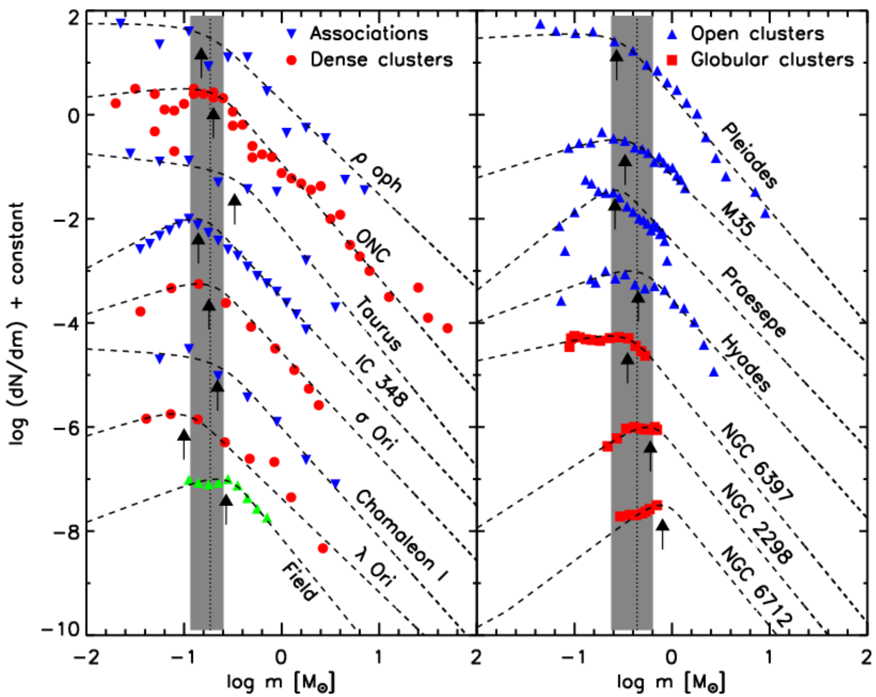
DISK IMF = BULGE IMF
⇒ <u>universal IMF</u>

Is the IMF “universal” ?



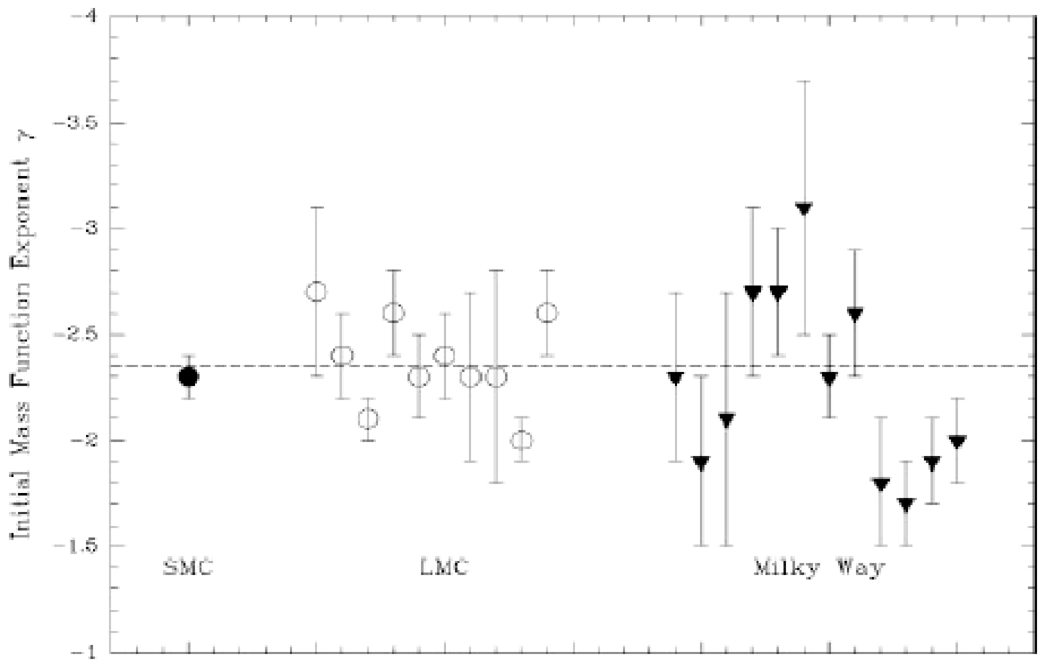
Is the IMF “universal” ?

Bastian et al, 2010, ARAA, 48, 339

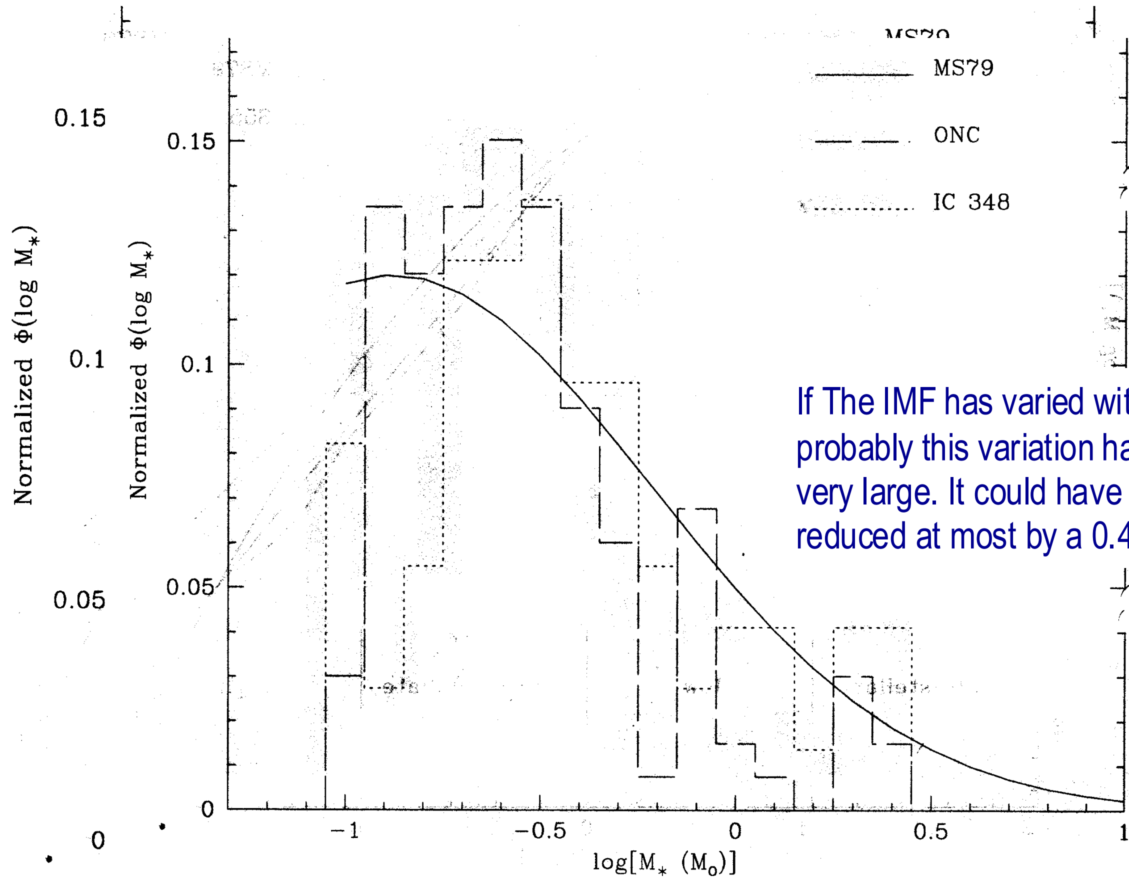


“The observations are consistent with a single underlying IMF, although the scatter at and below the stellar/sub-stellar boundary clearly calls for further study.”

IMF slope variation



IMF time variation



If The IMF has varied with time, probably this variation has not been very large. It could have been reduced at most by a 0.4 factor .

IMF references

- The initial mass function and stellar birthrate in the solar neighborhood, *Miller, G.E. & Scalo, J.M. 1979, ApJS, 41, 513*
- The stellar initial mass function, Scalo, J.M. 1986, *Fundametals of Cosmic Physics, 11, 1*
- The distribution of low-mass stars in the Galactic disc , Kroupa,Tout & Gilmore, 1993, *MNRAS 262, 545*
- The Stellar Mass Function (invited review),Kroupa, P. 1998, *ASP Conference Series, Vol. 134, eds. R. Rebolo, E. L. Martin & M. R. Zapatero Osorio, p. 483.*
- The Local Stellar Initial Mass Function, Kroupa, P. 2001, *ASP Conference Series, Vol. 228, eds S. Deiters, B. Fuchs, R. Spurzem, A. Just, and R. Wielen, p. 187*
- The relationship between the prestellar core mass function and the stellar initial mass function, Goodwin, S. P., Nutter, D., Kroupa, P., Ward-Thompson, D., Whitworth, A. P. 2008, *A&A, 477, 823*
- The Galactic Disk Mass Function: Reconciliation of the Hubble Space Telescope and Nearby Determinations, Chabrier, G. 2003, *ApJ, 586L, 133*

Stellar mass ranges of interest for stellar evolution and nucleosynthesis

- ***Non stellar objects (brown dwarfs):*** $m_* \leq M_L$ where M_L is the limiting mass for H burning.
- ***Low mass stars:*** $m_* \leq M_{HeF}$
  - M_{HeF} is the limiting mass for the formation of a stellar He with degenerate electrons immediately after the Main Sequence (MS) phase.
  - These stars burn He in an electron degenerate core.
- ***Intermediate mass stars***: $M_{HeF} \leq m_* \leq M_{C\text{-}O}$
  - $M_{C\text{-}O}$ *is the limiting mass for the formation of a C-O core with degenerate electrons.*
  - These stars burn He in a core with non-degenerate electrons and, after He exhaustion, develop a C-O core with degenerate electrons
- ***Massive stars:*** $m_* \geq M_{C\text{-}O}$
  - Stars that do not develop a C-O core with degenerate electros.

Brown Dwarfs

- $m_* \leq M_L$
- The value of M_L depends on the initial metallicity of the star, on the physics of stellar models and the models atmospheres.
- Most models give M_L~ 0.08-0.09 $M_\odot$
- Brown dwarfs are relevant as a dark matter component.
- Regarding chemical evolution, they remove gas from the ISM thus preventing its processing.

Low mass stars

- Stars with $M_L \leq m_*/M_\odot \leq 0.5$ burn H in their centres, but develope a core of degenerate electrons and never reach the central temperatures required for the ignition of He.
- Stars with $0.5 \leq m_*/M_\odot \leq M_{HeF}$ go through the MS and Red Giant (RG, H shell burning) phases and ignite He in an electron degenerate core (He flash).
- After this, they go through the Horizontal Branch (HB), Asymptotic Giant Branch (AGB) and Planetary Nebulae (PN).
- They end their lives as C-O White Dwarfs

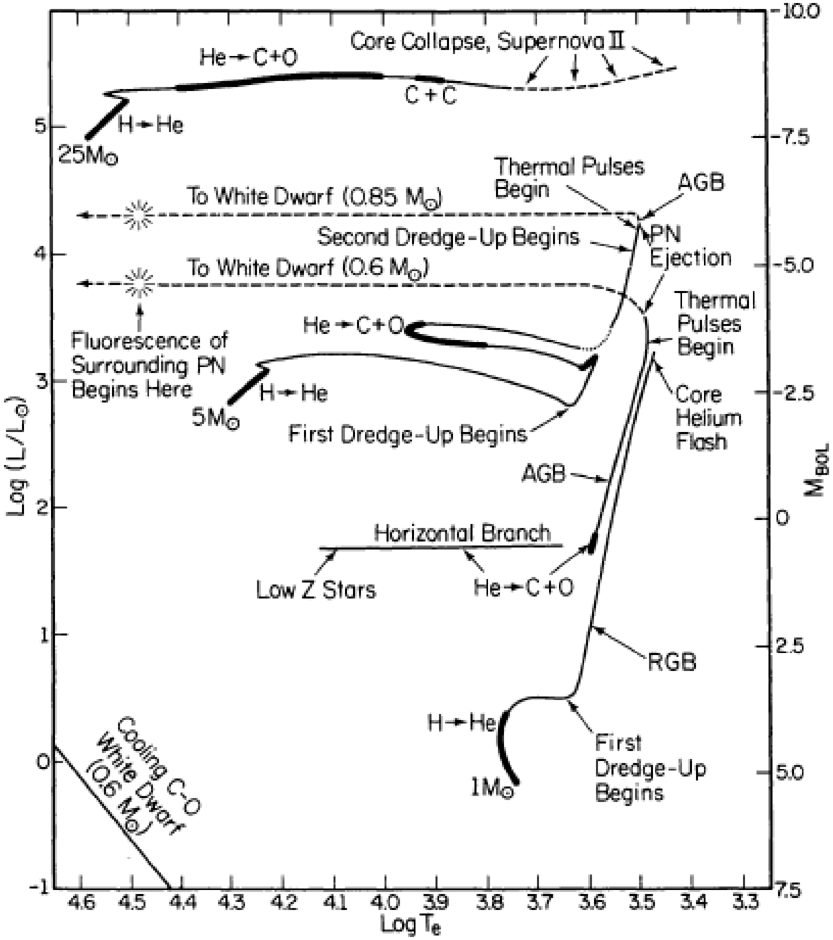
Low mass stars

- ^{12}C can be transformed into ^{13}C and ^{14}N at the base of the envelope during inter-phase pulses → *"hot bottom burning"* (HBB).
- During the phases of RGB, AGB and PN, these stars loose mass (~40%). These is the only way in which they return the processed material to the ISM.
- The exact value of M_{HeF} depends of the treatment of convection.
  - In the absence of *"overshooting"* and mass loss, M_{HeF}= 2.2 $M_\odot$
  - Taking into account overshooting, M_{HeF}= 1.85 $M_\odot$

Intermediate mass stars

- The most important phase for the ISM metal enrichment is the AGB phase. During this phase several dredge-ups are produced and the chemical elements synthesised in the stellar nucleus can be transported to the surface and ejected to the ISM. These dredge-ups take place between successive thermal pulses, i.e., He flashes in the burning shell.
- In the convective He burning shell neutron-rich nuclei are produced with the solar distribution of “s” elements.
- During dredge-ups these isotopes, and also ^{12}C are brought up to the convective envelope.

Intermediate mass stars

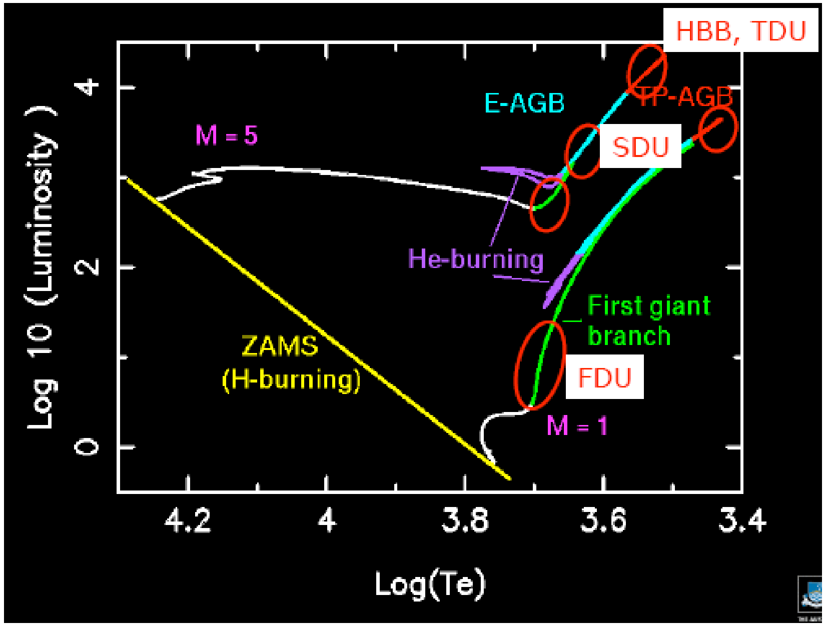


Evolutionary tracks for stars of different masses: 1, 5 y 25 $M_\odot$

Iben, I. 1985, QJRAS, 26, 1

Dredge-up processes in intermediate mass stars

- Stars experiment different dredge-up episodes during their evolution:
  - 1[est] dredge-up. It takes place at the base of the RGB for stars of all masses.
  - 2[nd] dredge-up. It happens at the beginning of the AGB phase for stars with masses M> 3.5-4 $M_{\odot}$
  - 3[erd] dredge-up. It takes place during thermal pulses in the AGB phase in stars with masses M>1.2-1.5 $M_{\odot}$
  - Hot Bottom Burning (HBB). It happens in the most massive stars of the AGB (M> 3.5-4 $M_{\odot}$)



Due to the dredge-up episodes, part of the elements synthesysed in the deep stellar ineteriors are brought up to the surface.

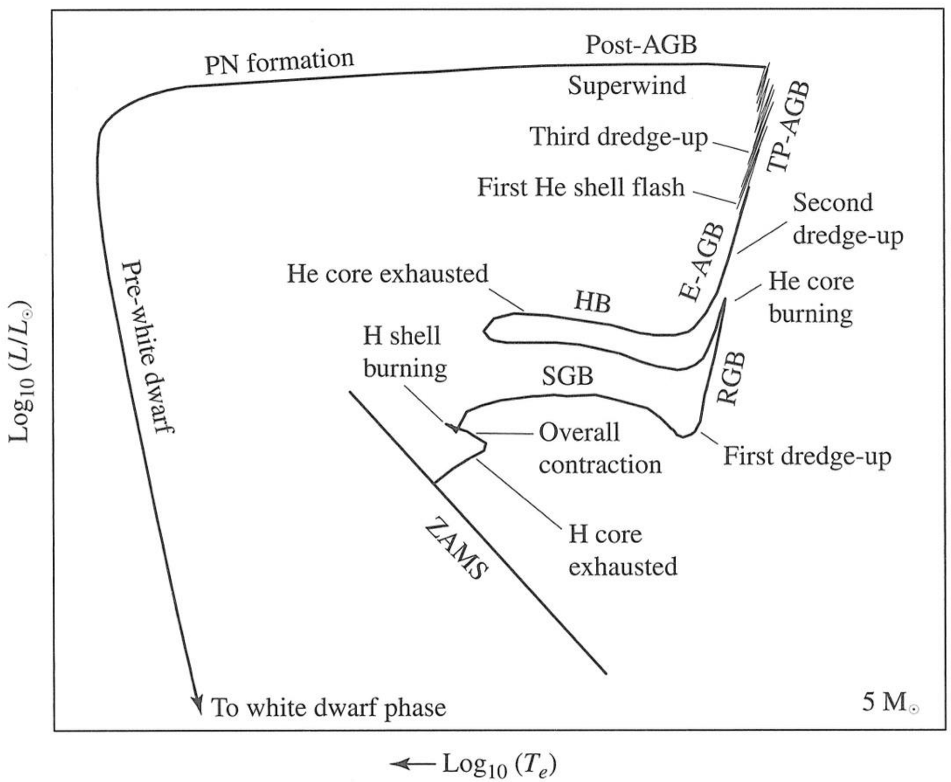
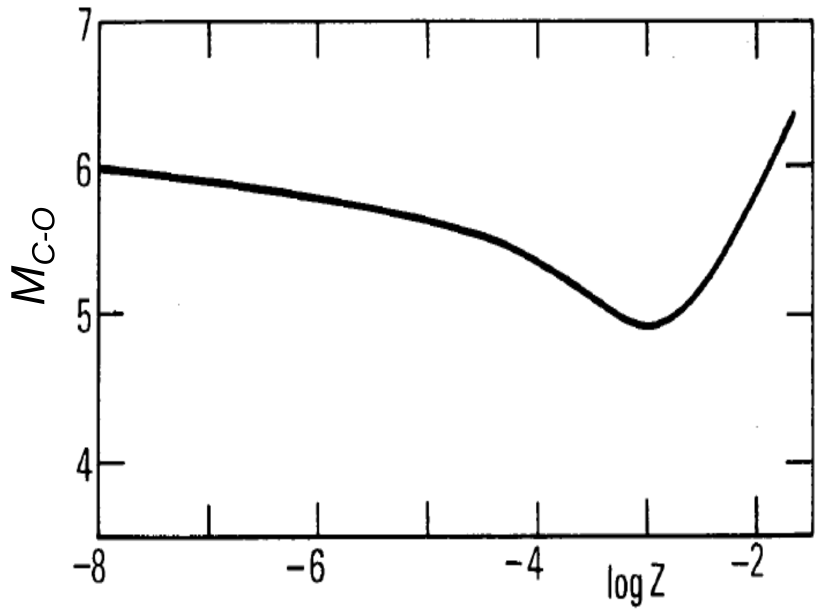


FIGURE 13.5 A schematic diagram of the evolution of an intermediate-mass star of 5 $M_\odot$ from the zero-age main sequence to the formation of a white dwarf star (see Section 16.1). The diagram is labeled according to Fig. 13.4 with the addition of the Horizontal Branch (HB).

Convective overshooting effects

- It increases the size of the stellar He core for a given value of its initial mass
- It also increases the stellar luminosity
- The importance of these effects can depend on stellar metallicity.
- The relation between the final size of the He core and the metallicity is not a monotonic function



Tornambè & Chieffi, 1986, MNRAS, 220, 129

Massive stars

- $M_{C\text{-}O} \leq m_*/M_\odot \leq$ 10-12 → They burn C in a non-degenerate core and end their lives as type II SNe.
- Those with $2.5 \leq M_{C\text{-}O}/M_\odot \leq 2.5$ ignite O in a Ne-O degenerate core. Their initial masses in classical models are 10 and 12 $M_\odot$. In models with overshooting these masses are between 6.6 y 10 $M_\odot$. They end up their lives as electro-capture SNe and leave a neutron star as remnant of ~ 1.3 $M_\odot$ (*Nomoto, 1987: ApJ, 322, 206*).
- Stars with masses between 10-12 $\leq m_*/M_\odot \leq M_{WR}$ evolve through the six hydrostatic nuclear fusion cycles up to the formation of Fe nuclei and explode as *iron-core collapse* SNe. leaving a NS or a BH as remnant. M_{WR} is the limiting mass for the formation of WR stars. Theses stars suffer enormous mass losses that strip them of their H-He envelopes.

Massive stars

- Stars with masses $M_{WR} \leq m_*/ M_{\odot} \leq 100$ go through the WR phase and can end their lives as Type Ib SNe (no H lines in their spectra).
  - If the proto NS exceeds the NS limiting mass (1.4-2.2 $M_{\odot}$), the star collapses directly to a BH without SN explosion.
  - Accretion onto the BH can generate γ ray bursts$\longrightarrow$ hyper nova (*Mc Fayden & Woosley, 1999: ApJ 524, 262*).
- The value of M_{WR} depends on the mass loss suffered by the WR that, in turn, depends on the stellar metallicity. For solar metallicity $M_{WR} \geq 40\ M_{\odot}$ (*Maeder 1992: A & A, 264, 105*).

Massive stars

- Stars with $m_* > 100\ M_\odot$, after exhaustion of He in their central regions, contract and proceed directly to O burning. During this phase suffer pair creation (e^-,e^+). They can end their lives as different types of SN or collapse directly to a BH.

Contribution from stars of different masses to the gas chemical enrichment

- $m_* \leq 0.08\, M_\odot$ → Never burn H. They do not contribute to chemical enrichment. Their mean lifetime is several times longer than the age of the universe.
- $0.08 \leq m_*/M_\odot \leq 0.5$ → They burn H but not He. They end their lives as He WDs. They do not contribute to the chemical enrichment. Their mean lifetime is much longer than 15 x 10^{10} yr.
- $0.5 \leq m_*/M_\odot \leq M_{HeF}$ → They experiment the He flash. They end up their lives as C-O WDs. Their mean lifetime is from $\approx 10^9$ to much longer than 15 x 10^{10} yr . The stars with $m_* > 1\, M_\odot$ contribute to the chemical enrichment in ^{4}He, ^{14}N and elements "s" (e.g. Ba y Sr).

Contribution from stars of different masses to the gas chemical enrichment

- *$M_{HeF} \leq m_{*}/M_{\odot} \leq M_{C\text{-}O}$* → They develop a C-O electron degenerate core. They end up their lives as C-O WDs. They contribute to the chemical enrichment in ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{17}o and "s" elements, produced during shell He burning phase. In models with E "overshooting" and mass loss $M_{C\text{-}O}$ is between 4 y 6.6 $M_{\odot}$ (*Maeder & Maynet 1989, A&A, 210, 155; Marigo et al. 1996, A&A, 313, 545*).
- The mean live time of these stars is between several times 10^{7} and 10^{9} yr. They eject the processed material to the ISM during the AGB and PN phases. Dredge up episodes transport H and He burning products to the stellar surface. Envelope burning transforms this material (e.g. ^{12}C into ^{13}C and ^{14}N primarios).

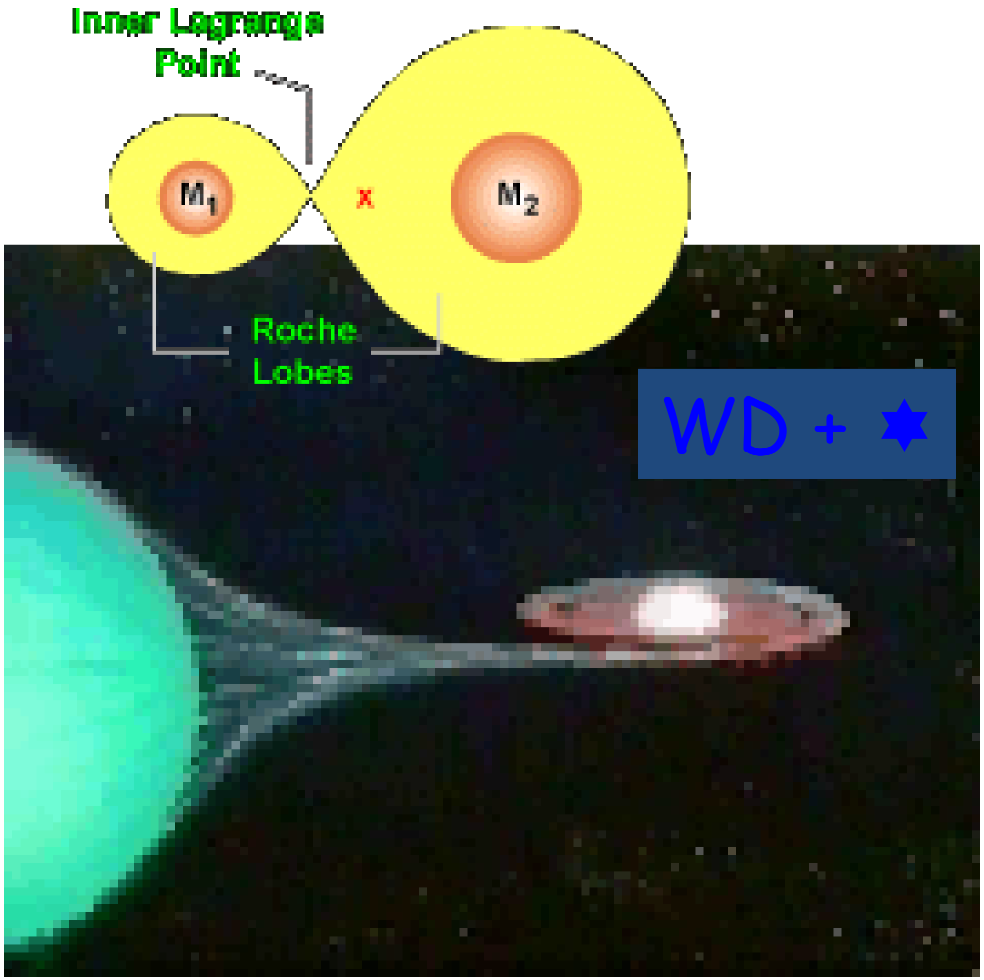
Contribution from stars of different masses to the gas chemical enrichment

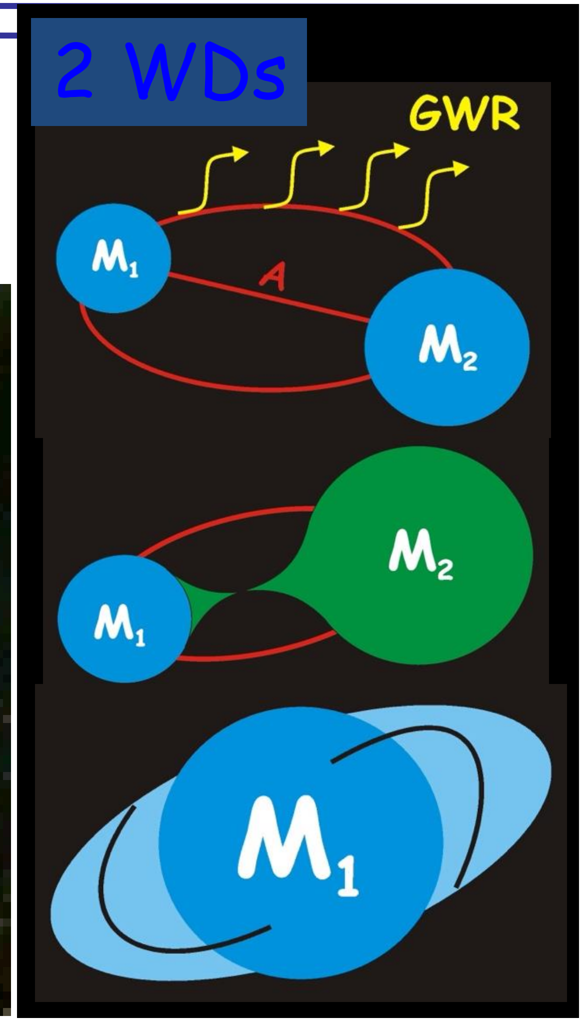
- $M_{C\text{-}O} \leq m_*/M_\odot \leq 10\text{-}12 \rightarrow$ They contribute to the chemical enrichment in ^{12}C and ^{14}N and maybe some ^{16}O. Their mean life times are of the order of several times 10^7 yr. They explode as type II SNa and leave a Ne-O-Mg as remnant.
- $10\text{-}12 \leq m_*/M_\odot \leq M_{SNII} \rightarrow$ They are responsible for the production of most heavy elements like: ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca and "r" elements. They end their lives as type II SNe.
- $M_{SNII} \leq m_*/M_\odot \leq 100 \rightarrow$ These stars becomo WR and end their lives as type Ib SNe. They contribute to the chemical enrichment in ^4He, ^{12}C, ^{22}Ne, ^{14}N and maybe ^{18}O through stellar winds, during the WR phase, and in heavy elements through SN explosions. Their mean life tiems are around 10^6 yr.
- $m_* > 100\ M_\odot \rightarrow$ contribute mainly to the chemical enrichment in ^{16}O.

Element production in binary systems

- It is believed that binary systems can originate SN explosions that produce a relevant amount of heavy elements.
- Binary systems can originate SN of types Ia, Ib, Ic and nova bursts than can produce appreciable quantities of ^{7}Li and maybe ^{13}C y ^{15}N and some Ne, Na, Mg., Al y Si.
- The thermonuclear explosion of the system would be preceded by accretion of matter from one of the stras onto its WD companion, thus surpassing the mass of Chandrasekhar.
- This type Ia SN model produces the right amount of ^{56}Ni $\longrightarrow$ ^{56}Co $\longrightarrow$ ^{56}Fe, reproduce their light curves and allows the formation of elements of intermediate mass (from C to Si) that are observed in their spectra.

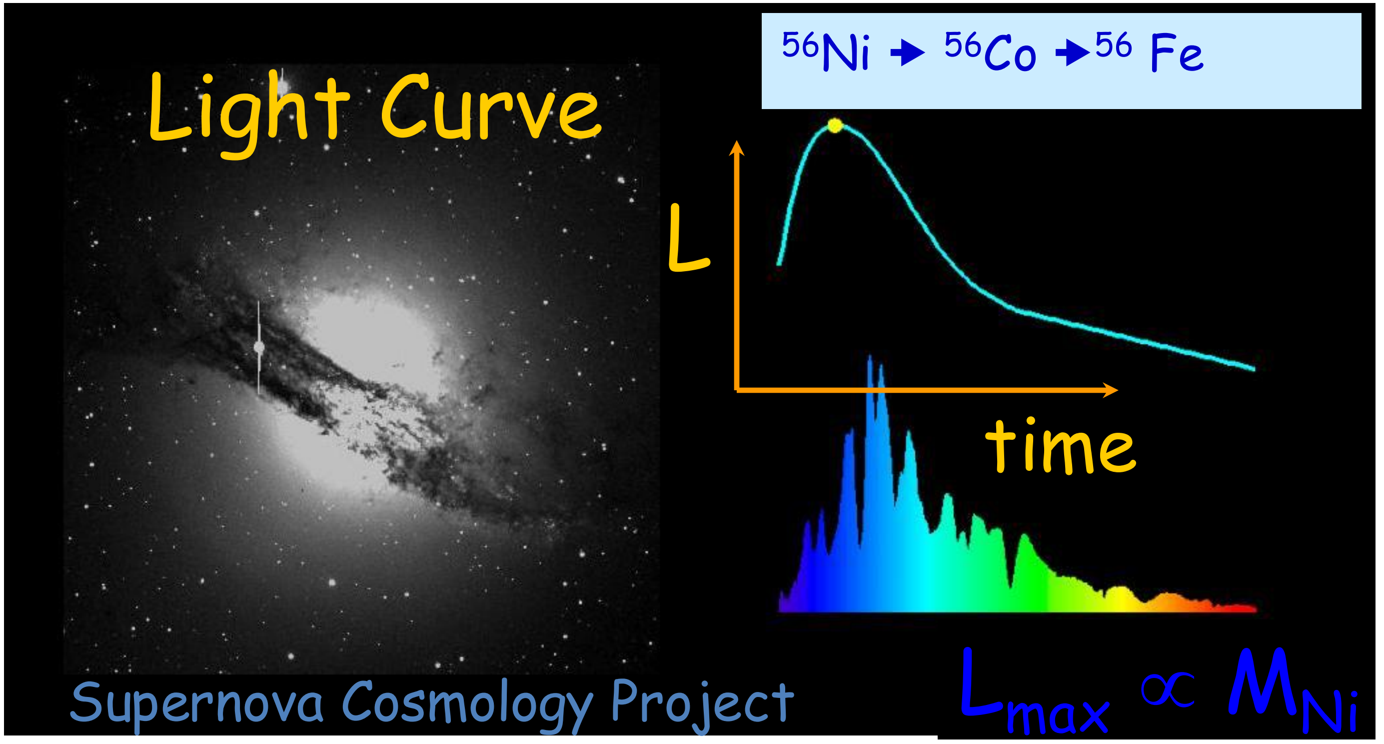
A WD in a binary system : towards a thermonuclear explosion



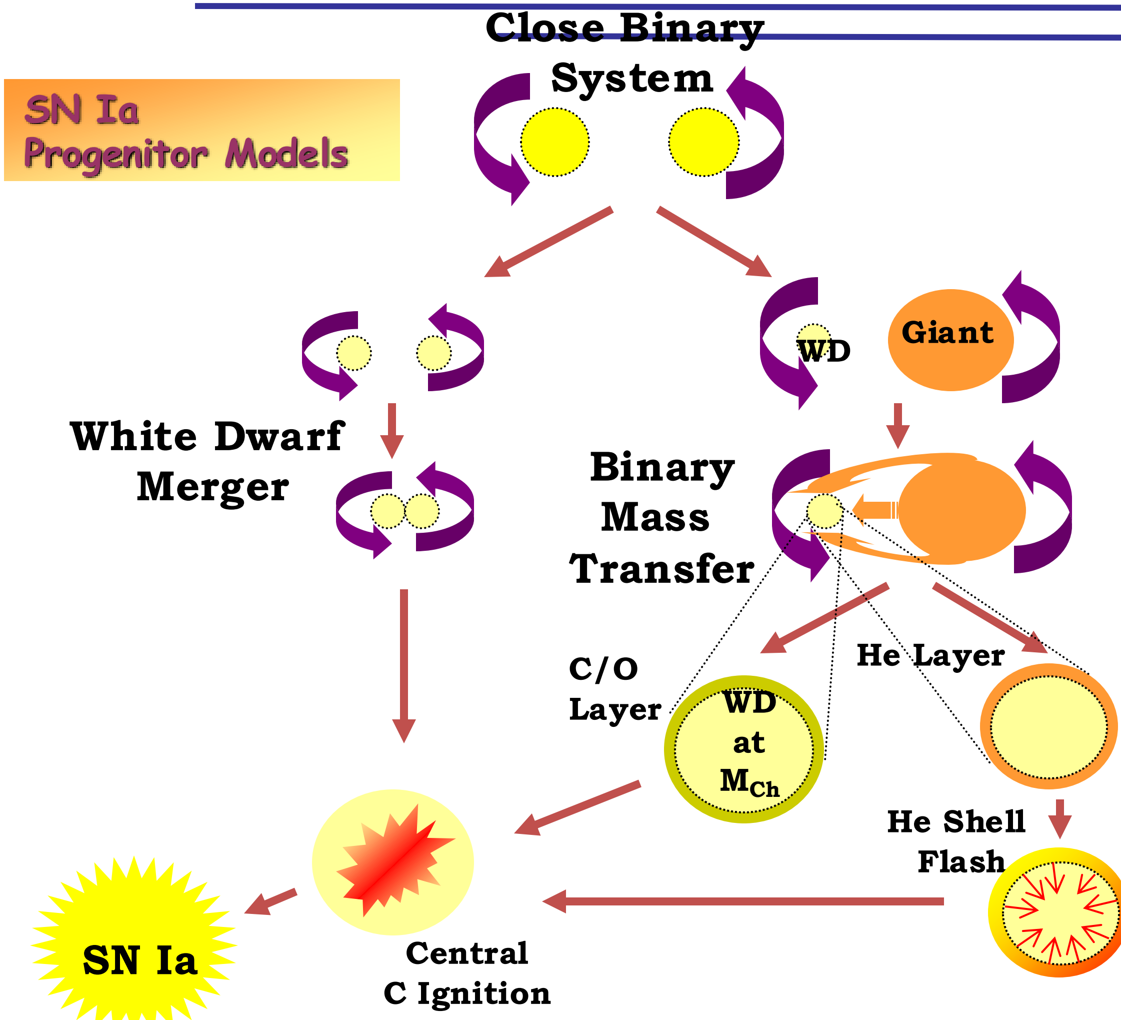


Current SNIa model

Thermonuclear explosion of a CO WD



SNIa progenitor models



Nucleosynthesis summary

Element production in SNe

SNe are prime source of both Fe-peak and r-process nuclei.

SN II

Table 7.2. *Primary element production from massive stars with modest mass loss*

$M_{\rm ini}$	$M_{\rm fin}$[a]	M_α[b]	$M_{\rm CO}$[c]	He	C	O	Z
120	81	81	59	9.8	0.88	35	42
85	62	62	38	8.1	0.72	23	27
60	47	28	25	6.0	0.70	14	17
40	38	17	14	4.2	0.55	6.8	10
25	25	9	7	3.5	0.40	2.4	4.4
20	19	7	5	2.1	0.30	1.3	2.9
15	15	5	3	1.6	0.20	0.46	1.5
12	12	4	2	1.4	0.10	0.15	0.8
9	9	3	2	1.0	0.06	0.004	0.3
5	5	1	1	0.45			
3	3			0.09			

[a] Final mass at end of carbon burning (or helium burning for lower masses).
[b] Mass of He core at end of carbon or helium burning.
[c] Mass of CO core at end of carbon or helium burning.
Source: Maeder (1992) for the case $Z = 0.001$, $Y = 0.24$.

Table 7.6. *Element production from SN Ia*

Species	Mass/$M_\odot$	$[X_i/X_{56}]$[a]
^{24}Mg	.09	−1.1
^{28}Si	.16	−0.3
^{32}S	.08	−0.4
^{36}Ar	.02	−0.3
^{40}Ca	.04	0.1
^{54}Fe	.14	0.6
^{56}Fe	.61	0.0
^{58}Ni	.06	0.4
Cr–Ni	.86	

[a] Logarithmic element:^{56}Fe ratio relative to solar.
Source: Nomoto *et al.* (1984), model W7; cf. also Thielemann *et al.* (1986).

SNe winds may play an important role in effective yield.
Maeder 1992, A&A 254, 105.

Timescale for SNIa: about 10^8yr after formation

see: Pagel IAC Winter School (1993), Matteucci ASP Conf. 20 p. 539 (1991)

UAM UNIVERSIDAD AUTONOMA DE MADRID

Grupo de Astrofísica
Universidad Autónoma de Madrid

Stellar yields

Table 5. Stellar yields for models with $Z = 0.001$ (in solar mass units)

Mass	He	C	O	Z	He	C	O	Z
	Final Ejecta (SN, PN)				Wind and Final Ejecta			
120	2.28	0.89	35.30	41.6	9.81	0.88	35.3	41.6
85	5.56	0.72	22.60	26.7	8.09	0.72	22.6	26.7
60	5.23	0.70	14.20	17.1	5.96	0.70	14.2	17.1
40	4.24	0.55	6.80	9.71	4.24	0.55	6.80	9.71
25	3.52	0.403	2.40	4.45	3.52	0.403	2.40	4.45
20	2.11	0.298	1.27	2.93	2.11	0.298	1.27	2.93
15	1.65	0.196	0.46	1.53	1.65	0.196	0.46	1.53
12	1.35	0.101	0.15	0.83	1.35	0.101	0.15	0.83
9	0.98	0.056	0.004	0.27	0.98	0.056	0.004	0.27
7	0.788				0.788			
5	0.452				0.452			
4	0.285				0.285			
3	0.091				0.091			
2.5	0.065				0.065			
2	0.059				0.059			
1.7	0.026				0.026			
1.5	0.022				0.022			
1.25	0.016				0.017			
1	0.010				0.010			

Table 6. Stellar yields for models with $Z = 0.020$ (in solar mass units)

Mass	He	C	O	Z	He	C	O	Z
	Final Ejecta (SN, PN)				Wind and Final Ejecta			
120	-0.128	0.290	0.18	0.72	42.74	8.04	0.05	10.11
85	-0.392	0.350	0.59	1.56	16.66	13.48	3.96	19.31
60	-0.263	0.333	0.40	1.16	13.52	7.22	1.43	9.85
40	-0.410	0.369	0.62	1.61	6.10	4.88	2.08	8.01
25	0.600	0.319	2.60	4.48	1.54	0.297	2.57	4.48
20	1.520	0.221	1.27	2.73	1.60	0.219	1.27	2.73
15	1.338	0.141	0.41	1.32	1.386	0.140	0.41	1.32
12	1.181	0.072	0.11	0.686	1.195	0.071	0.11	0.686
9	0.871	0.028	0.00	0.173	0.879	0.027	0.00	0.173
7	0.684				0.688			
5	0.401				0.403			
4	0.184				0.185			
3	0.072				0.074			
2.5	0.079				0.080			
2	0.066				0.067			
1.7	0.019				0.020			
1.5	0.015				0.016			
1.25	0.012				0.013			
1	0.010				0.012			
Case of lower $\dot{M}$								
120	-1.304	0.410	2.80	4.56	18.347	20.206	11.18	34.53
85	-1.654	0.393	3.65	5.60	5.243	13.638	13.56	29.92
60	-1.344	0.462	2.95	4.71	6.681	7.741	6.29	15.99
40	-1.406	0.483	3.15	4.91	3.116	3.423	5.17	10.20
25	1.330	0.266	2.55	4.50	1.666	0.259	2.54	4.50
20	1.560	0.233	1.27	2.82	1.585	0.232	1.27	2.82

<u>important:</u>
element-production
depends on initial metallicity
see: Maeder, A&A <u>264</u>, 105 (1992)

IMPRS Astrophysics Introductory Course — Fall 2007