Gamma-ray nucleosynthesis

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Predictions

- Gamma-ray nuclei
- Production sites

Observations

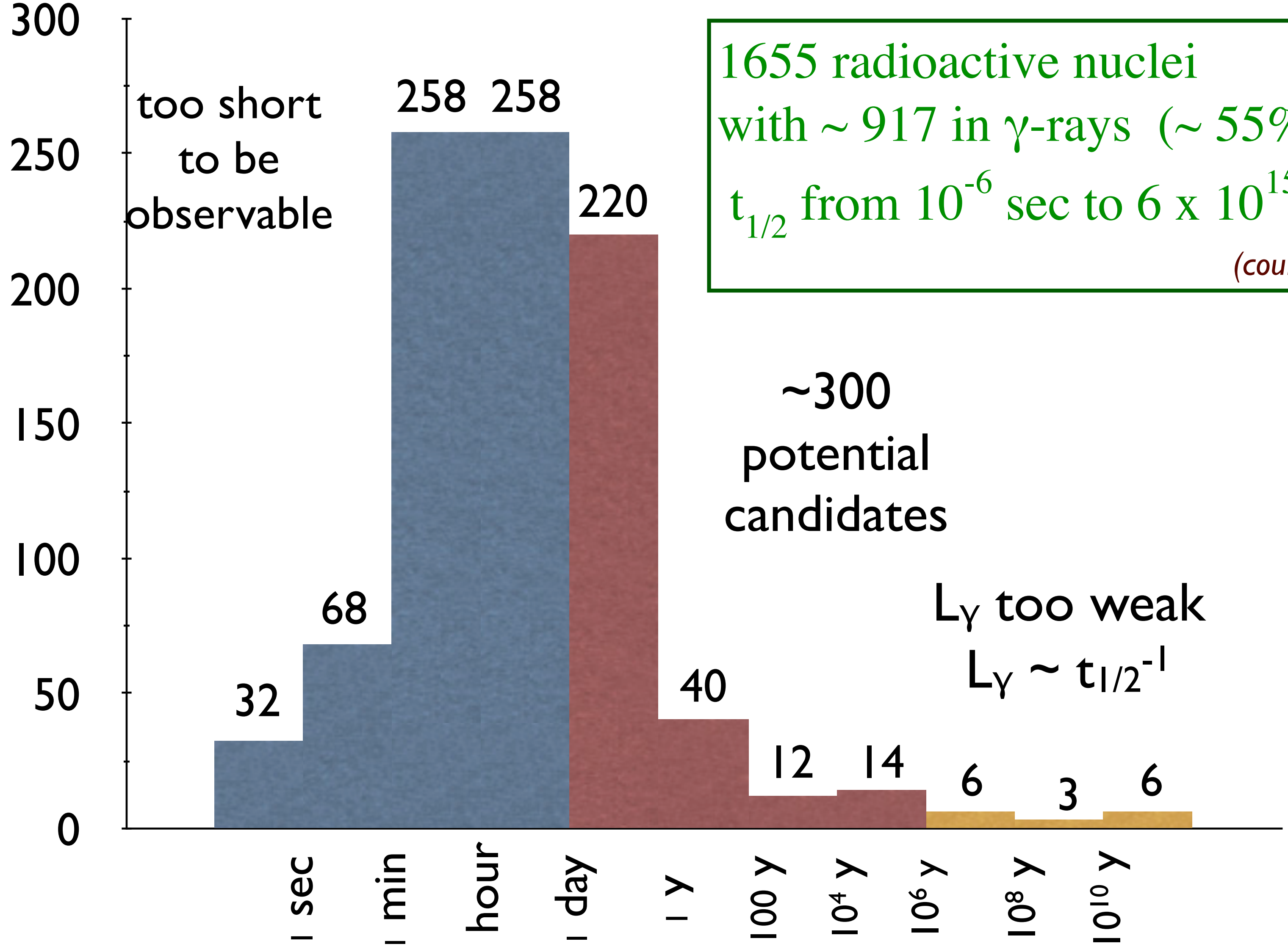
- Point sources
- Diffuse emission

I. Predictions

Gamma-ray nuclei in astrophysics

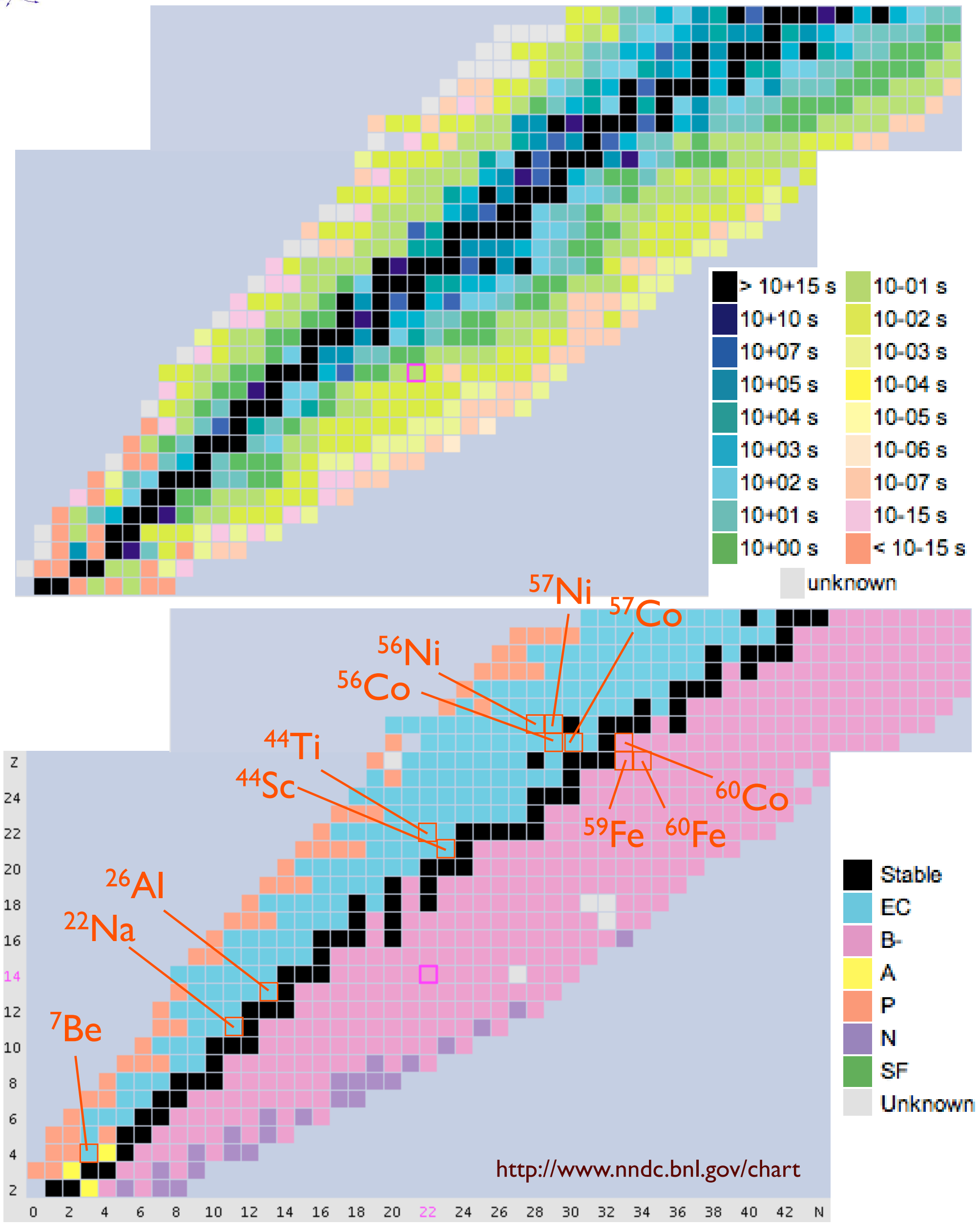
1655 radioactive nuclei
with ~ 917 in γ-rays (~ 55%)
$t_{1/2}$ from 10^{-6} sec to 6 x 10^{15} years

(courtesy G. Meynet)



Point like sources ⟵ ⟶ Diffuse sources

Nucleo chart



http://www.nndc.bnl.gov/chart

* Must be abundant

* Must be observable:

- from explosion
- or at surface

→ Most around Fe peak

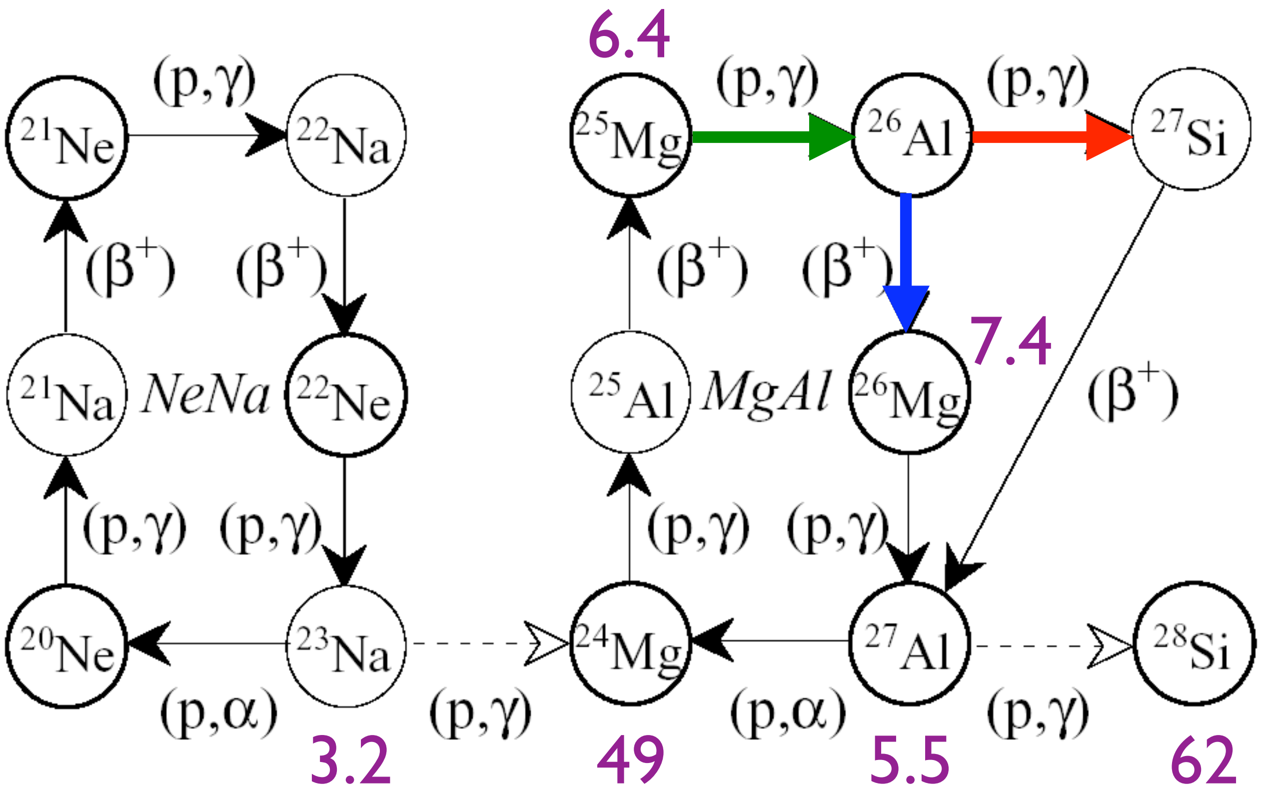
Astrophysical γ-ray lines

Decay chain	**½ life**	**Line energies keV (branching ratios)**	**Sites**
$^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li}$	53.3 d	477.6 (10.5%) EC	Novae
$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne}$	2.6 y	1274.5 (99.9%) B+	Novae
$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}$	7.4 My	1129.7 (2.4%), **1808.6** (99.7%) EC	WR, SNII, AGB, Novae
$^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc}$ $^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$	60 y 3.9 h	**67.9** (94.4%), **78.3** (96.2%) EC **1157.0** (99.9%) EC	SN
$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co}$ $^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$	6.1 d 77.3 d	158.4 (98.8%), 750.0 (49.5%), 811.9 (86.0%) B+ **846.8** (99.9%), **1238.3** (66.1%), 2598.5 (17.0%) EC	SN
$^{57}\mathrm{Ni} \rightarrow {}^{57}\mathrm{Co}$ $^{57}\mathrm{Co} \rightarrow {}^{57}\mathrm{Fe}$	35.6 h 272.8 d	127.2 (16.7%), 1377.6 (81.7%), 1919.5 (12.3%) B+ 14.4 (9.2%), **122.1** (85.6%), **136.5** (10.7%) EC	SN
$^{59}\mathrm{Fe} \rightarrow {}^{59}\mathrm{Co}$	44.5 d	192.4 (3.1%), 1099.3 (56.5%), 1291.6 (43.2%) B-	SN
$^{60}\mathrm{Fe} \rightarrow {}^{60}\mathrm{Co}$ $^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}$	1.5 My 5.3 y	58.6 B- **1173.2** (100%), **1332.5** (100%) B-	SN
$e^{+} + e^{-}$	0.1 My	**511**	

e^{+} emitter

H-burning: ^{26}Al production

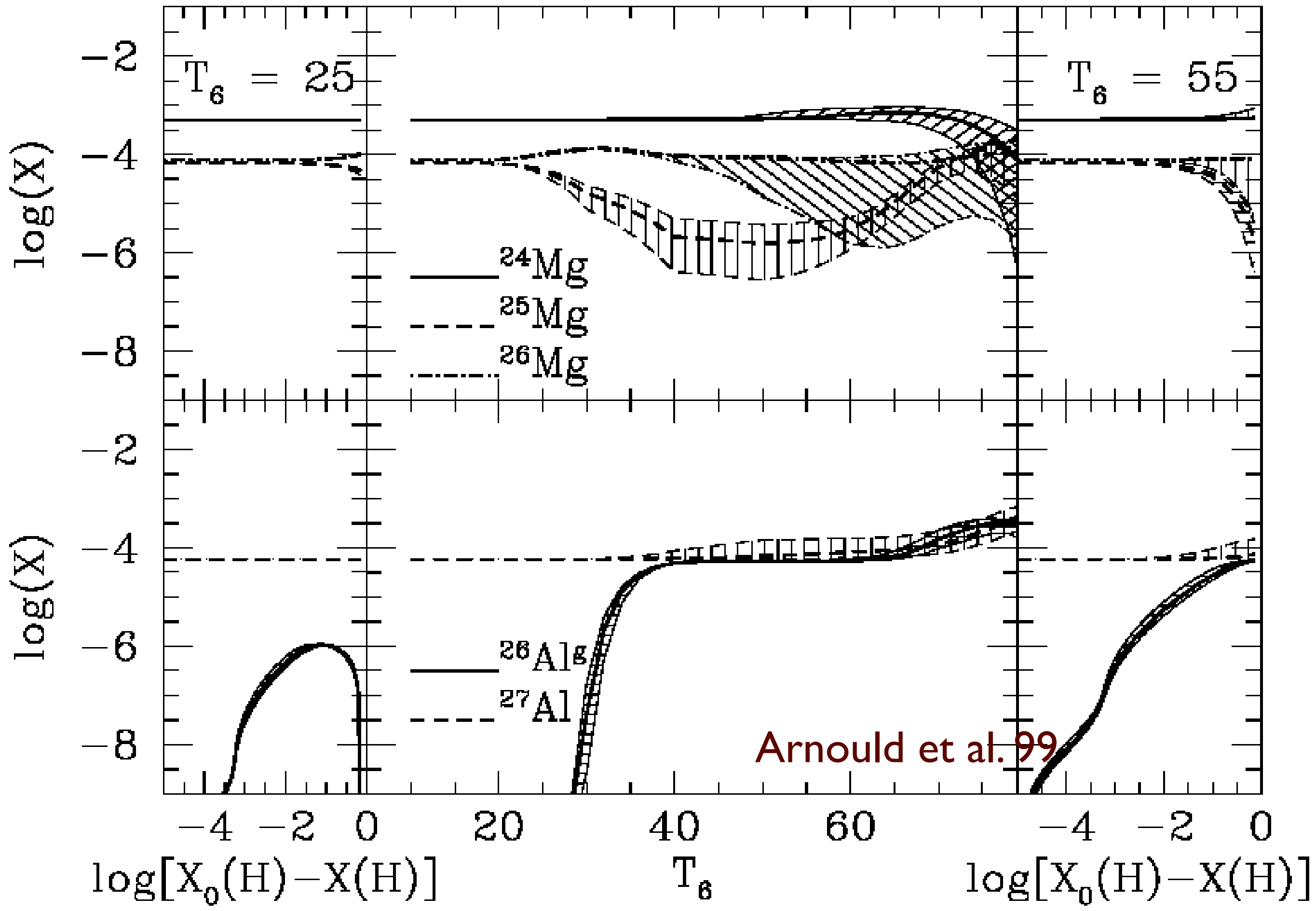
Ne-Na chain *Mg-Al chain*



$t_{1/2} = 7\text{x}10^5$ y

Solar mass fractions (x10^{-5})

H-burning: ^{26}Al production

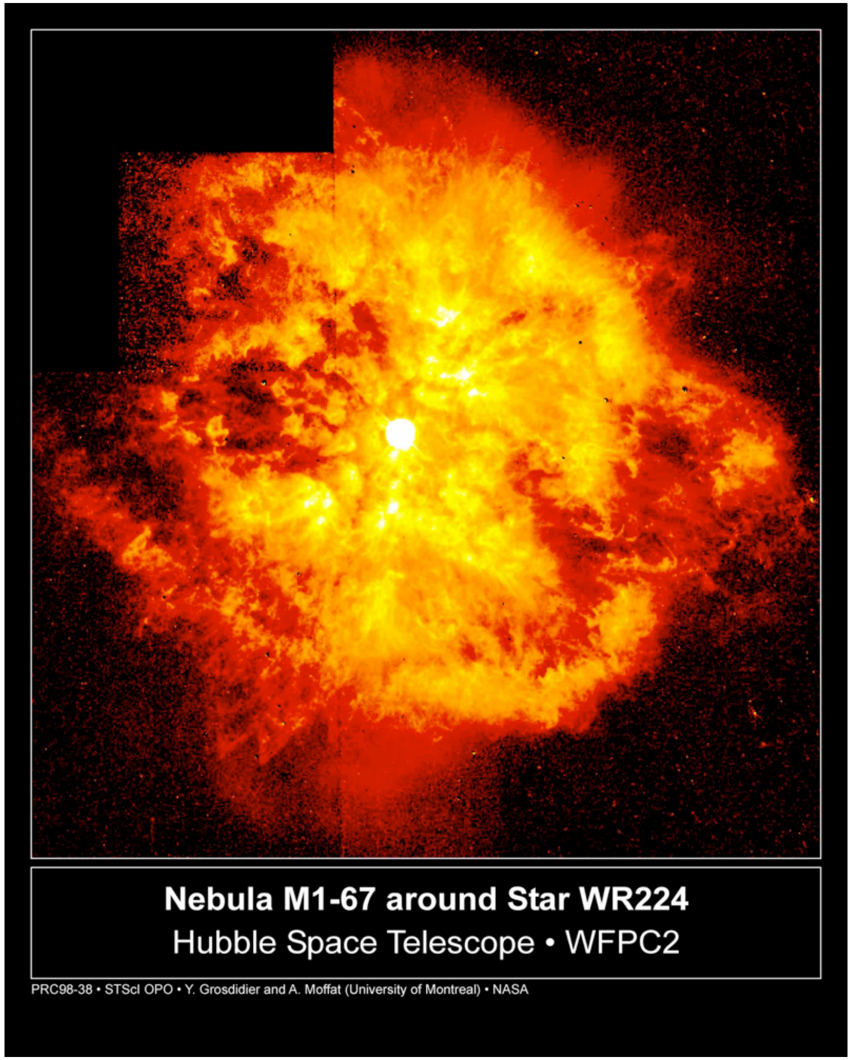


Arnould et al. 99

^{26}Al production requires T > 35-40 x 10^6 K

- in cores of *massive stars*
- in burning shells of *low- and intermediate-mass stars*

Wolf-Rayet stars


Nebula M1-67 around Star WR224
Hubble Space Telescope • WFPC2
PRC98-38 • STScI OPO • Y. Grosdidier and A. Moffat (University of Montreal) • NASA

WR stars are seldom
(227 WR known in our Galaxy,
a few thousands estimated)

However:

- Contribute through their winds to the **interstellar chemical enrichment**
- **Identifiable in remote galaxies** through their very broad emission lines
  -> study of star formation and evolution in different environments

$dM/dt = 10^{-5} – 10^{-6}\ M_{\odot}/year$

v_{eject} ~ 2500 km/sec

^{26}Al production in WR stars

WR = bare cores of initially massive stars (M > ~30 M⊙) whose original H-envelope has been removed by stellar winds or through Roche lobe overflow (Maeder and Conti 1994)

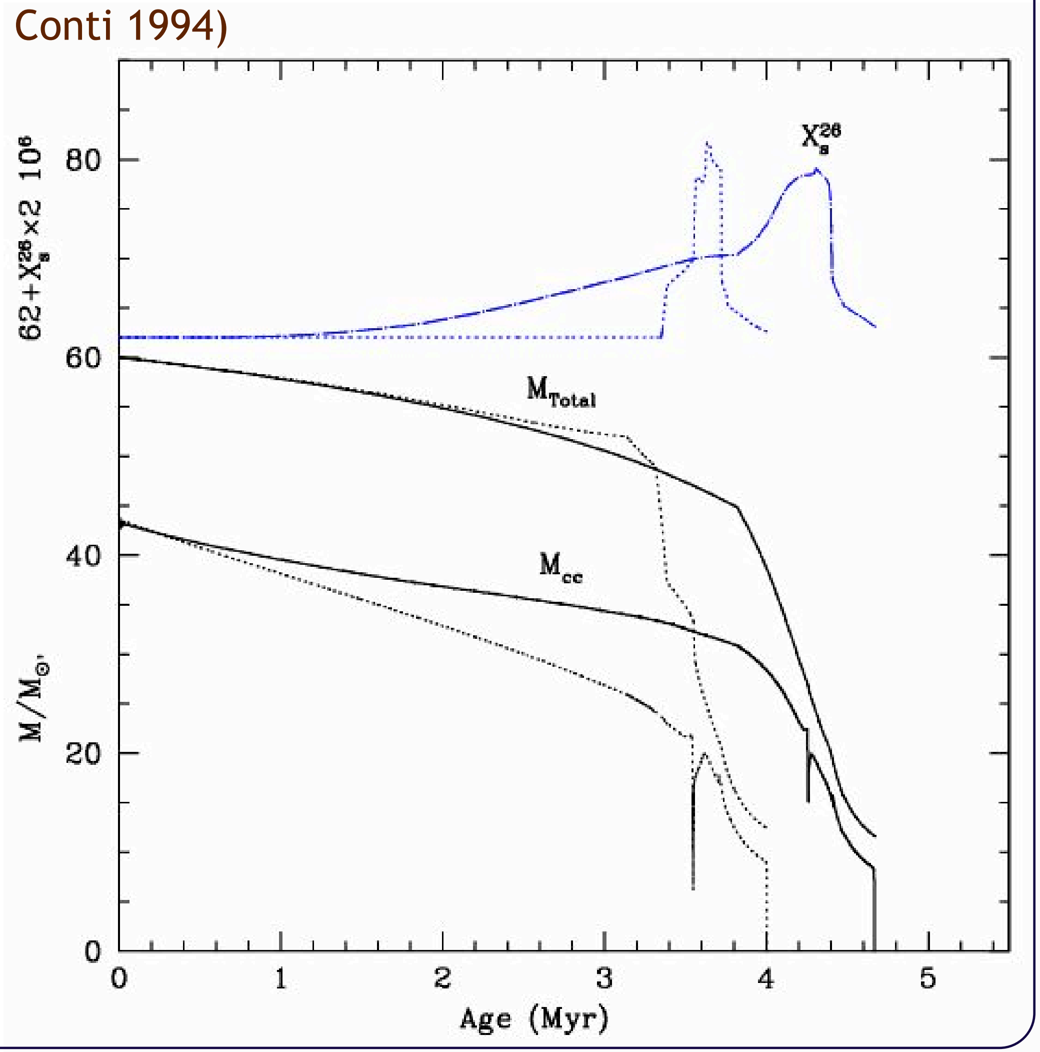
Impact of *rotation* on ^{26}Al production by WR stars:

- **Longer lifetimes**
- **More ^{26}Al ejected**
- **^{26}Al appears at surface earlier**

60 Mo

M(^{26}Al) ejected (x10^{-4} Mo)

	0 km/s	300km/s	500km/s
Z=0.02	1.3	2.2 X 1.7	2.6 X 2.0
Z=0.04	3.0	7.6 X 2.5	



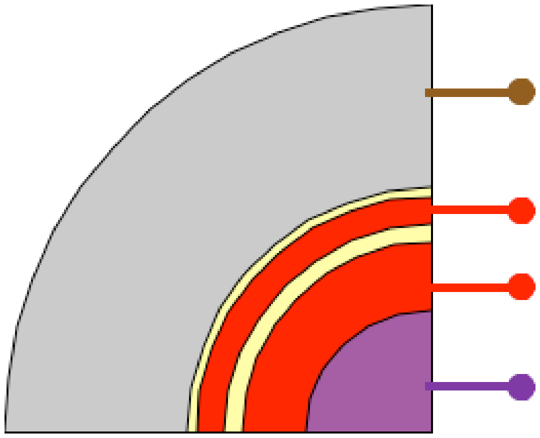
Asymptotic Giant Branch stars

* Last phase of stars with $0.8\ M_\odot \leqslant M \leqslant 7\ M_\odot$

* Fate of ~80% of stars

* Are giant (several 100 $R_\odot$)
and red ($T_{eff} < 3000$ K)

* **Structure**:



Convective enveloppe (< □ $M_\odot$)

H-burning shell (~ 0.002 $M_\odot$)

He-burning shell (~ 0.02 $M_\odot$)

e^- degenerate core (0.5 - 1.1 $M_\odot$)

* **Observations** reveal that AGB stars have:

- *Peculiar surface abundances (Li, C, O, s-process,...)*
- *High mass loss rates (up to $10^{-4}\ M_\odot\ y^{-1}$)*

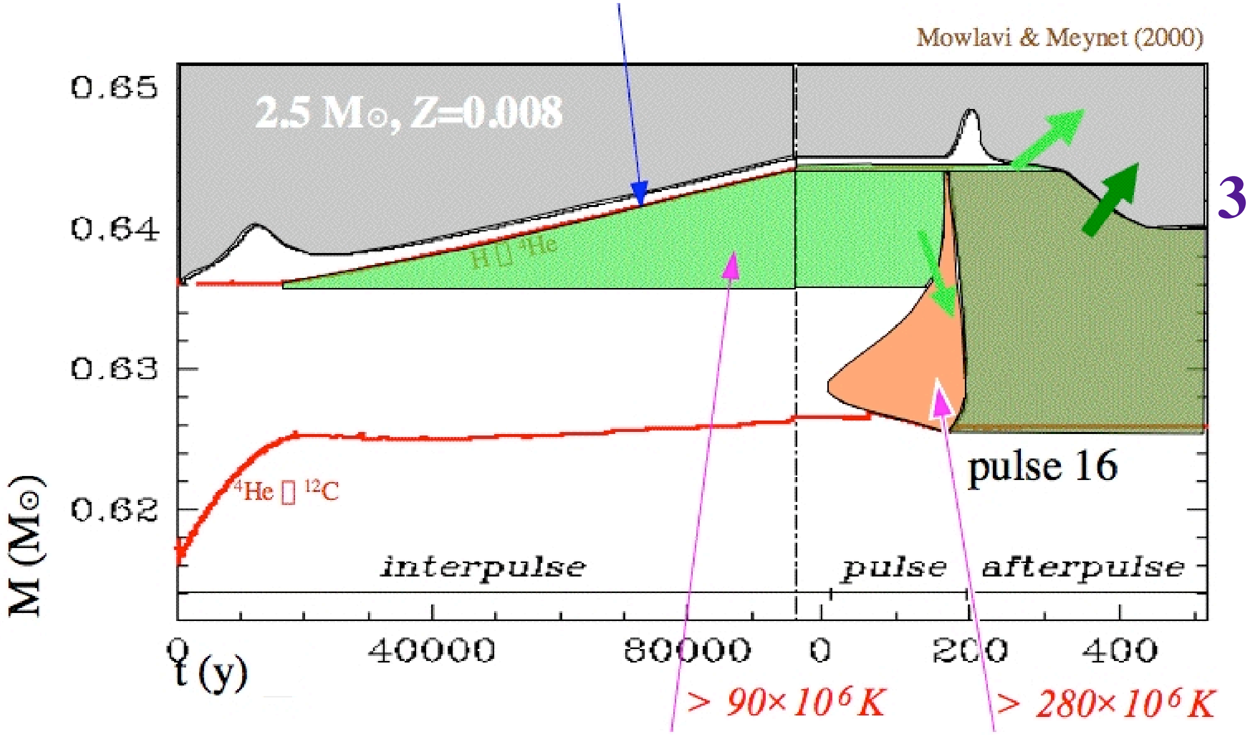
^{26}Al production in AGB stars

1. ^{26}Al production in H-burning shell:

$^{24}\mathrm{Mg} + p \rightarrow {}^{25}\mathrm{Al} + \gamma$ $(T > 55\times10^{6}\,K)$

$\downarrow \beta^{+}$

$^{25}\mathrm{Mg} + p \rightarrow {}^{26}\mathrm{Al} + \gamma$ $(T > 35\times10^{6}\,K)$



Mowlavi & Meynet (2000)

3. ^{26}Al transport to surface

2. ^{26}Al destruction in He-burning shell:

$^{13}\mathrm{C}\,(\alpha,n)\,{}^{16}\mathrm{O}$ $^{22}\mathrm{Ne}\,(\alpha,n)\,{}^{25}\mathrm{Mg}$

$^{26}\mathrm{Al} + n \rightarrow {}^{26}\mathrm{Mg} + p$

^{26}Al production in AGB stars

* Standard model predictions

at last computed pulse number n_p (for different dredge-up scenarios min, nom, max):

		Surface mass fraction (10^{-7})			Mass in the wind of the AGB star ($10^{-7}\,M_\odot$)			Mass ejected by the PN ($10^{-7}\,M_\odot$)		
	n_p	Min	Nom	Max	Min	Nom	Max	Min	Nom	Max
Solar metallicity stars (Z = 0.02)										
$M = 6\,M_\odot$	*34*		< 7.5 >			< 0.3 >			< 35 >	
$4\,M_\odot$	*25*	0,24	**0,34**	0,59	0,1	**0,1**	0,2	0,7	**1,0**	1,8
$3\,M_\odot$	*23*	0,64	**0,99**	3,48	0,1	**0,3**	1,2	1,3	**2,1**	7,4
$2.5\,M_\odot$	*29*	0,69	**1,04**	4,03	0,2	**0,5**	2,1	0,9	**1,5**	5,9
$1.5\,M_\odot$	*16*		1,75	12,0		0,3	1,7		1,0	7,2
Low metallicity stars (M = 2.5 Mo)										
$Z = 0.008$	*26*	0,25	0,29	0,65	0,1	0,2	0,4	0,3	0,4	0,9
0,004	*23*	0,10	0,12	0,21	0,0	0,0	0,1	0,1	0,2	0,3

Mowlavi & Meynet (2000)

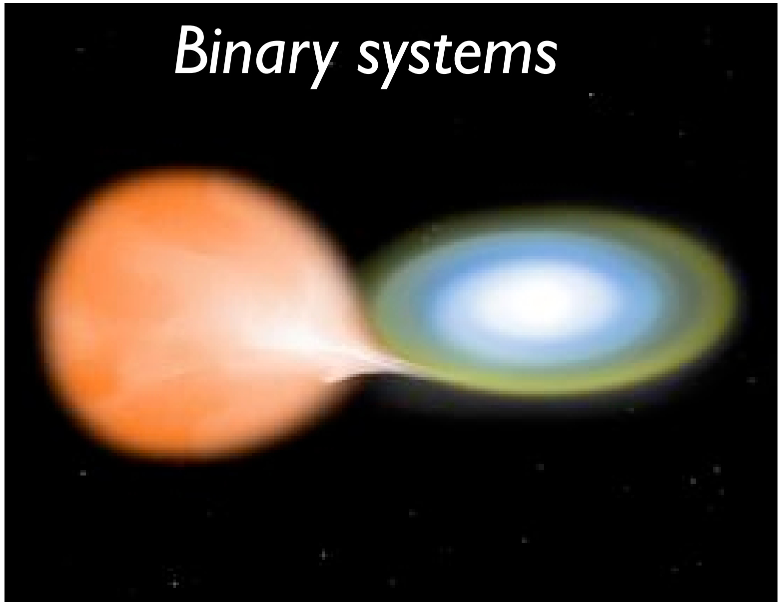
*** Uncertainties:**
- Dredge-up efficiency (as a function of M, Z, np)
- AGB lifetime (mass loss history)
- Extra mixing mechanisms? (diffusion, shears, rotation)

-> amount of intersehlll ^{26}Al destruction

-> amount of ^{26}Al dredged-up

Novae

Red Giant
filling
its Roche lobe



White Dwarf
accreating
matter

~35/y in Galaxy, but only ~4 observed

Thermonuclear runaways

Convection → β^+ nuclei to outer layers where they decay:

^{14}O (102 s), ^{15}O (176 s), ^{17}F (93 s) — Expansion and L increase

^{13}N (10 min), ^{18}F (158 min) — gamma-ray emission

+ e^+ emission

Novae: ^{7}Be, ^{22}Na, ^{26}Al

Novae

CO novae : ^{7}Be (77d) through ^{3}He(a,g)^{7}Be

ONeMg novae :
- less ^{7}Be (^{3}He burns)
- ^{22}Na (3.75y)
- ^{26}Al (1.04 My)

Nova type	$M_{WD}(M_{€})$	$M^{TOT}_{ejected}$ ($M_{€}$)	<KE> (erg·g^{-1})	^{13}N ($M_{€}$)* (τ =862 s)	^{18}F ($M_{€}$)* (τ =158 min)	^{7}Be ($M_{€}$) (τ =77 days)	^{22}Na ($M_{€}$) (τ =3.75 yr)
CO	0.8	6.2 x 10^{-5}	8 x 10^{15}	1.5 (-7)	1.8 (-9)	6.0 (-11)	7.4 (-11)
CO	1.15	1.3 x 10^{-5}	4 x 10^{16}	2.3 (-8)	2.6 (-9)	1.1 (-10)	1.1 (-11)
ONe	1.15	2.6 x 10^{-5}	3 x 10^{16}	2.9 (-8)	5.9 (-9)	1.6 (-11)	6.4 (-9)
ONe	1.25	1.8 x 10^{-5}	4 x 10^{16}	3.8 (-8)	4.5 (-9)	1.2 (-11)	5.9 (-9)

22Na ejected in ONe

WD mass	Minimum	Best	Maximum*
1.15	$3.1\cdot10^{-9}$	$7.0\cdot10^{-9}$	$1.4\cdot10^{-8}$
1.25	$3.4\cdot10^{-9}$	$6.3\cdot10^{-9}$	$1.2\cdot10^{-8}$
1.35	$3.4\cdot10^{-9}$	$4.4\cdot10^{-9}$	$6.2\cdot10^{-9}$

26Al ejected in ONe

WD mass	Minimum	Best	Maximum
1.15	$8.6\cdot10^{-9}$	$2.1\cdot10^{-8}$	$3.1\cdot10^{-8}$
1.25	$3.6\cdot10^{-9}$	$1.2\cdot10^{-8}$	$1.6\cdot10^{-8}$
1.35	$6.6\cdot10^{-10}$	$3.2\cdot10^{-9}$	$4.8\cdot10^{-9}$

José, Coc and Hernanz 1999

SuperNovae

* ~3 core collapse SN /century in the Galaxy

* Important contributors for the interstellar enrichment

* Ashes from all nucleosynthesis phases ejected.

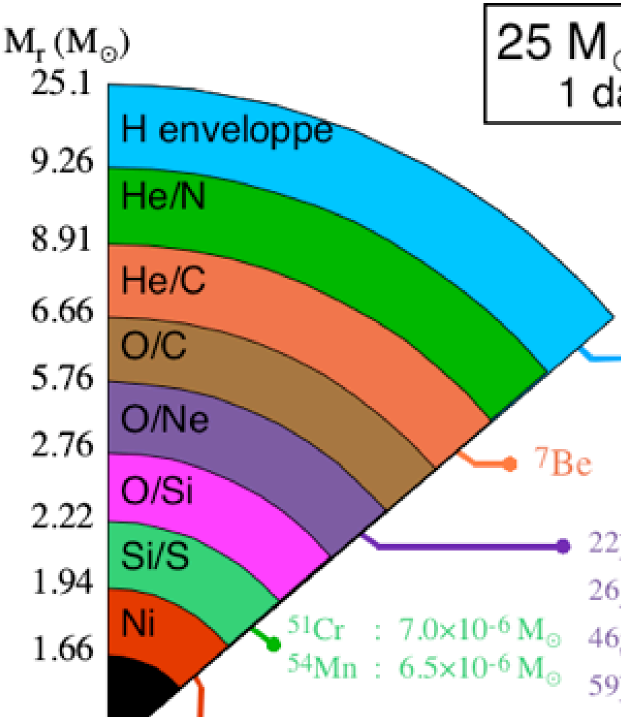
- Collapse → Bounce on dense core (in which $e^+ + p \rightarrow n + \nu$)
  → Shock wave (to surface in few hours)
- ~10^{53} erg released in neutrinos
  → ν emitted over 1-10 sec
  → most ν escape within first sec

~10^{51} erg in visible light

TYPE II SUPERNOVAE

25 $M_\odot$ SN composition 1 day after explosion

(Meyer, Weaver, Woosley 1995)



some H-burning

H-burning

H + some He-burning

He-burning

C-burning

Ne + some O-burning

hydr. + expl. O-burn.

hydr. + expl. Si-burn.

^{26}Al : 4×10^{-5} $M_\odot$

^{7}Be : 2.5×10^{-7} $M_\odot$

^{22}Na : 3.3×10^{-6} $M_\odot$
^{26}Al : 6.0×10^{-5} $M_\odot$
^{46}Sc : 2.0×10^{-7} $M_\odot$
^{59}Fe : 1.8×10^{-5} $M_\odot$
^{60}Fe : 8.0×10^{-6} $M_\odot$
^{60}Co : 2.0×10^{-5} $M_\odot$

^{51}Cr : 7.0×10^{-6} $M_\odot$
^{54}Mn : 6.5×10^{-6} $M_\odot$

^{44}Ti : 1.4×10^{-4} $M_\odot$
^{56}Co : 2.3×10^{-2} $M_\odot$
^{57}Co : 3.2×10^{-3} $M_\odot$
^{58}Co : 1.5×10^{-5} $M_\odot$
^{56}Ni : 2.0×10^{-1} $M_\odot$
^{57}Ni : 5.3×10^{-3} $M_\odot$

$$\begin{cases} {}^{56}\mathrm{Ni} \xrightarrow{8.5\,d} {}^{56}\mathrm{Co} \xrightarrow{112\,d} {}^{56}\mathrm{Fe} \\ {}^{57}\mathrm{Ni} \xrightarrow{2.1\,d} {}^{57}\mathrm{Co} \xrightarrow{392\,d} {}^{57}\mathrm{Fe} \end{cases}$$

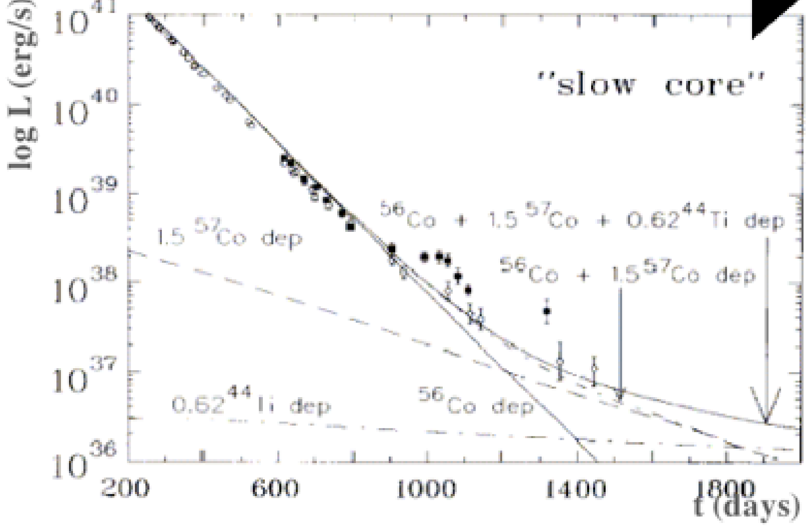


FIG. 1.—Model "slow core" light curve. Suntzeff et al. (1992) photometry is open circles. With 57/56 = 1.5 × solar (the meaning of coefficients in this figure), this model suffices for late time power from radioactivity alone because its larger optical depth deposits a larger fraction of the ^{57}Co power.