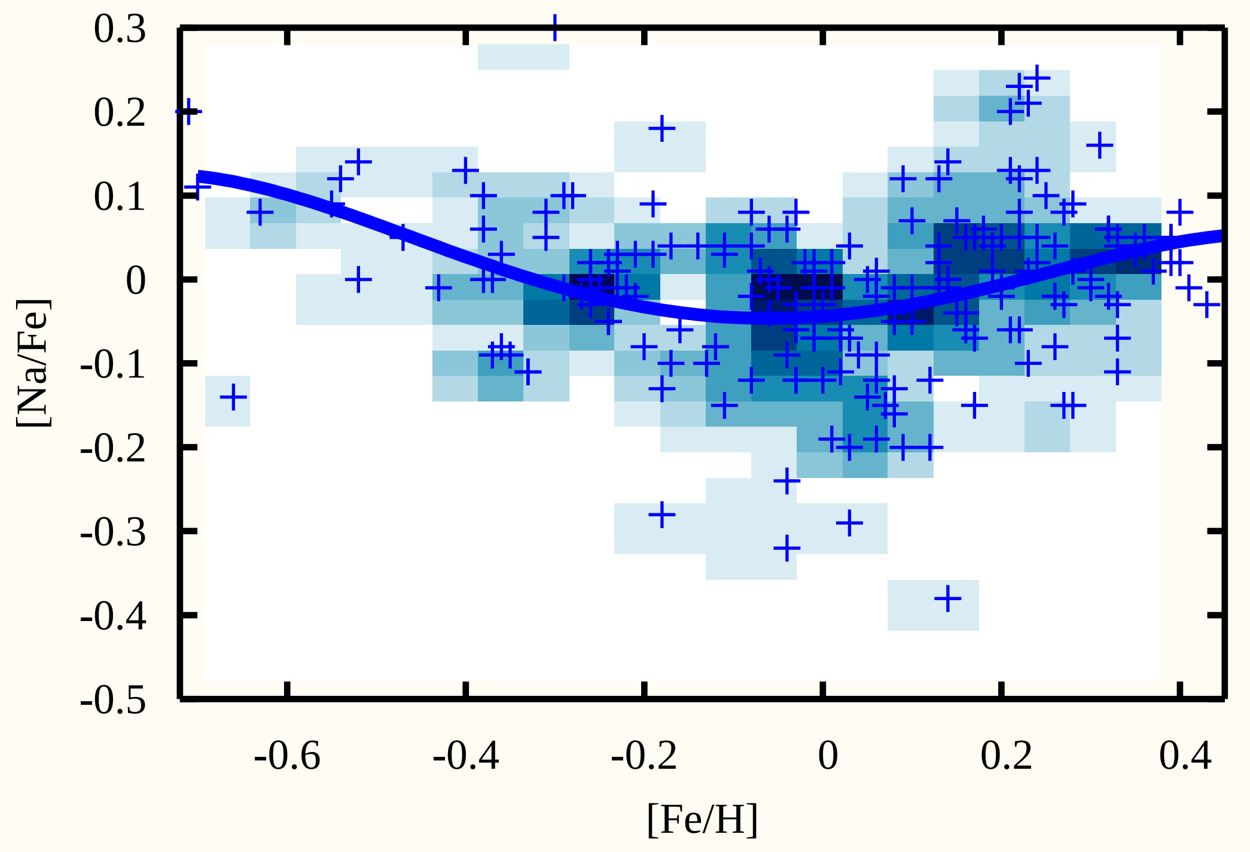
# Galactic Sodium from AGB Stars

## Introduction

Galactic chemical evolution models which include sodium from type II supernovae alone underestimate the abundance of sodium in the interstellar medium. Recent stellar observations of stars with [Fe/H] up to about 0.4 suggest that [Na/Fe] increases at high metallicity.

We have combined stellar evolution models of AGB stars, WR stars and the latest supernova yields in an attempt to resolve these problems . . . and have created many more.

## 1. Observations



Recent observations of sodium in stars with metallicities up to [Fe/H] $= 0.4$ (with $\mathrm{Fe}_\odot = 1.12 \times 10^{-3}$ from Anders & Grevesse 1989) suggest a secondary component (proportional to the metallicity) in the sodium abundance at high $Z$ (Gilli 2006, see the above figure).

- Is it a chemical evolution effect?
- If so, what is the source of the sodium?
- Canonical GCE models (e.g. Timmes 1995) underproduce sodium by $\sim 0.2\,\mathrm{dex}$, but only include massive star yields.
- How can we make interstellar gas with [Fe/H] $\sim 0.4$?
- There is considerable scatter, up to half a dex, much larger than the errors on the [Na/Fe] measurements ($< 0.1\,\mathrm{dex}$).

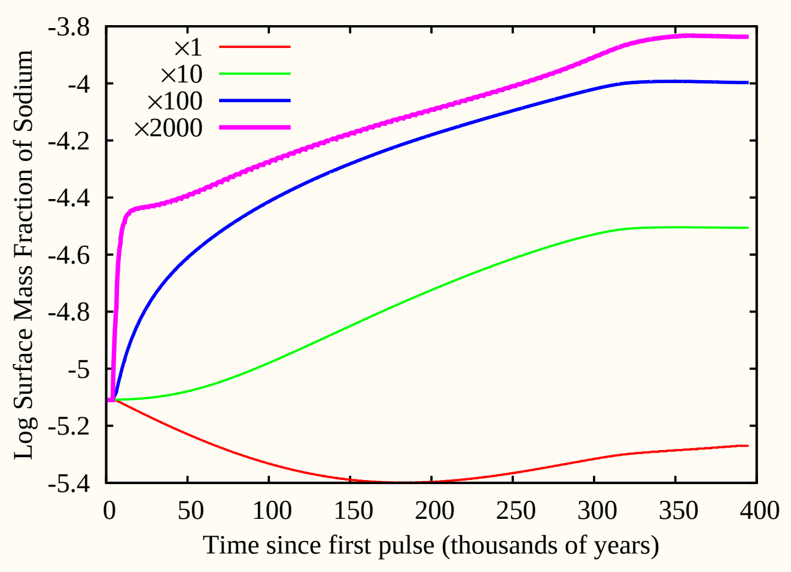
## 2. Stellar Models

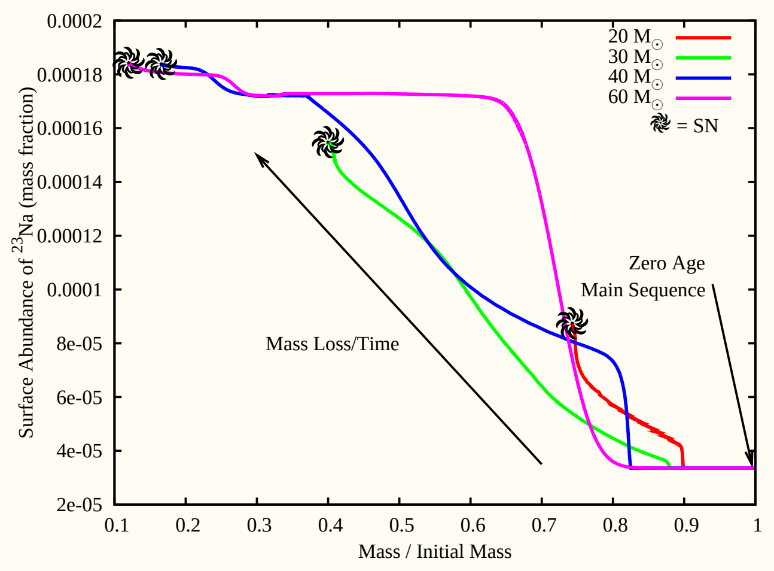
### Synthetic AGB

Our models include 1st, 2nd and 3rd dredge-ups, hot-bottom burning (HBB) and mass-loss, $1 \leq \mathrm{M}_\odot \leq 6.5$, $10^{-4} \leq Z \leq 0.02$.

AGB stars with $4 \lesssim M/\mathrm{M}_\odot \lesssim 8$ make sodium by HBB via the $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$ reaction. The rate is uncertain so we vary it within experimental limits (up to $\times 2000$).

The figure on the right shows surface abundance during the TPAGB phase in a $6\mathrm{M}_\odot$, $Z = 0.004$ model, with a varying $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$ rate: the surface abundance is uncertain by up to a factor of 40.





### Wolf-Rayet

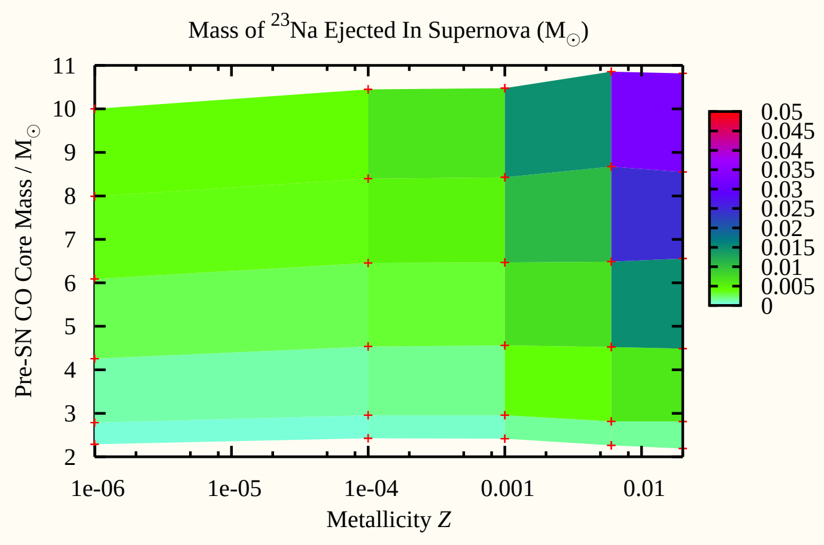
We made models with the STARS code, using a full nucleosynthetic network with NACRE nuclear reaction rates and mass loss; $10 \leq M/\mathrm{M}_\odot \leq 80$, $10^{-4} \leq Z \leq 0.03$.

Mass loss during the WR phase of massive star evolution exposes layers which have converted $^{22}\mathrm{Ne}$ to $^{23}\mathrm{Na}$ by hydrogen burning, as shown in the left diagram.

The steepness of the stellar initial mass function means that the WR contribution to sodium yields is only a few per cent.

### Supernovae

$^{23}\mathrm{Na}$ is made during carbon burning in massive stars and is ejected in the SN explosion at the end of the star's life. We use the $^{23}\mathrm{Na}$ yields of Chieffi and Limongi (2004), which, as the figure to the right shows, are a strong function of mass and metallicity.

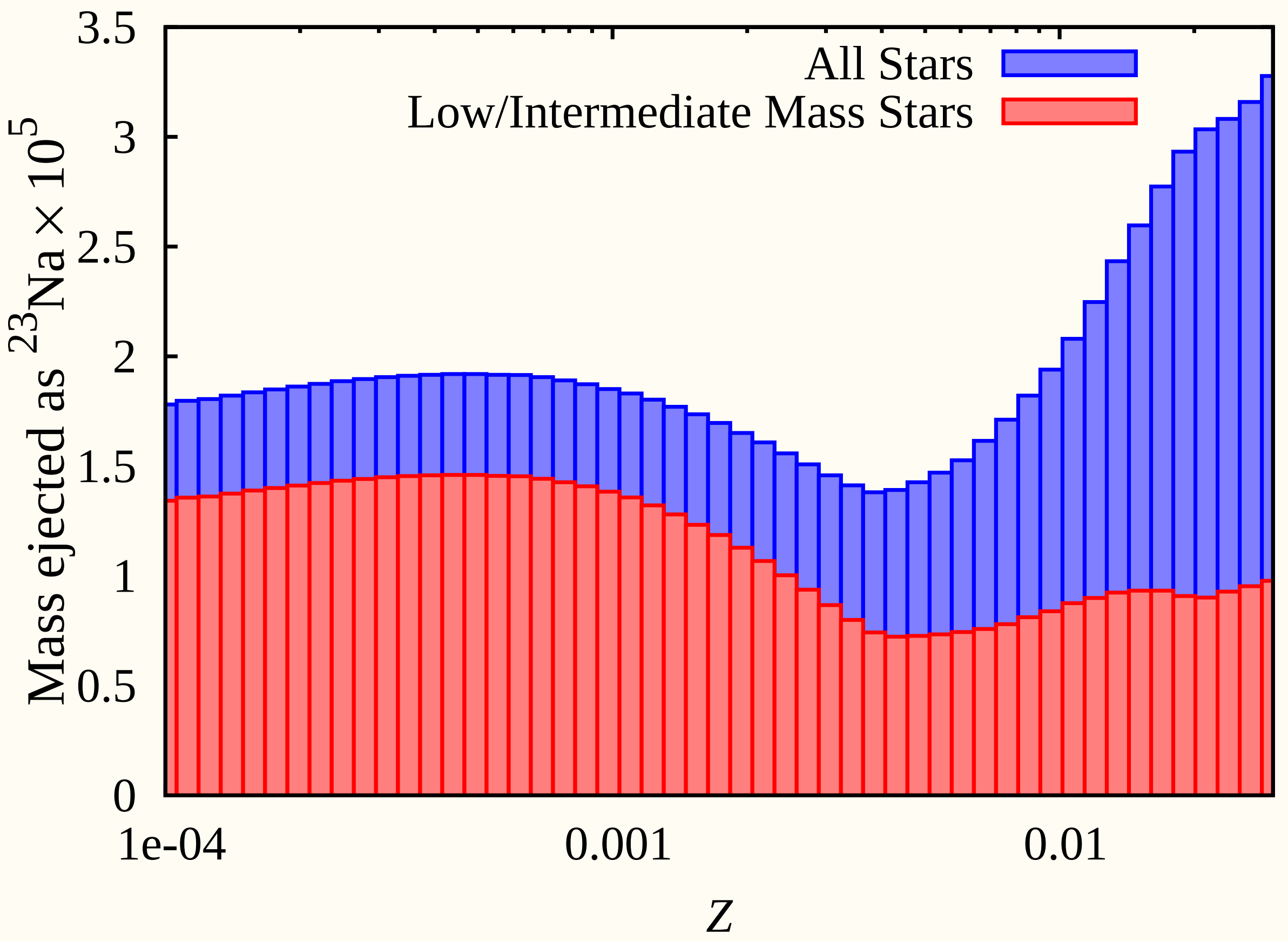


## 3. Intermediate vs High Mass

Previous studies used windless massive star and core-collapse supernova yields (e.g. Timmes 1995). We include yields of massive stars, from winds and explosions (SNeII/Ib/c), low/intermediate mass AGB stars and type Ia SNe.

The figure below shows the time- and mass-integrated yields from our stellar populations as a function of metallicity $Z$.

1. In the first $100\,\mathrm{Myr}$ since the birth of the Milky Way, halo stars formed with [Fe/H] $< -1$, and the sodium abundance was dominated by yields from short-lived WR and SN yields.
2. Later, when [Fe/H] $> -1$, intermediate mass AGB stars make sodium by HBB. Overall these contribute more than supernovae, but on a longer timescale (hundreds of Myr).
3. At high metallicity supernovae again dominate due to secondary production of sodium.



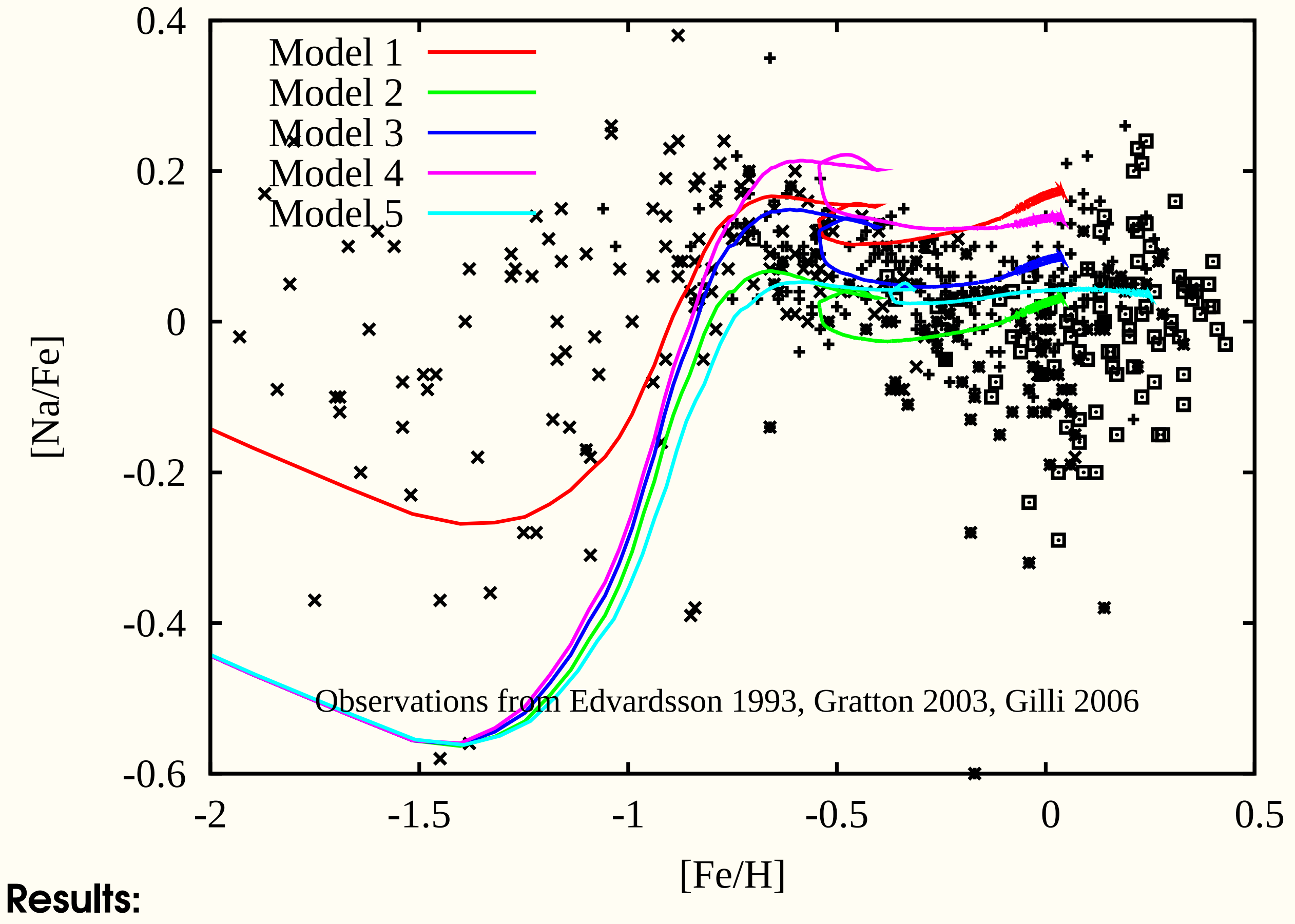
Enhancing the $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$ rate by a factor of 2000 boosts the integrated AGB yields by up to a factor of 2, with most effect at low metallicity.

## 4. Galactic Chemical Evolution

**Models:**

We have implemented our stellar models into the Chiappini 1997 dual-infall one-zone Milky Way model with various assumptions:

1. Our standard models
2. SN yields of sodium $\times \frac{1}{2}$
3. As 2 with $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$ rate $\times 10$
4. As 2 with $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$ rate $\times 2000$
5. As 2 with infall from a polluted instead of primordial IGM



**Results:**

1. Reducing the SN yield is necessary at solar metallicity, but is not good for [Fe/H] $< -1$.
2. A $2000\times$ increase in the $^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$ rate gives too much $^{23}\mathrm{Na}$, but $\times 10$ is compatible with the observations.
3. It is hard to make gas with [Fe/H] $> 0$ unless we include IGM feedback or some thaumaturgy.
4. With a one-zone model we cannot reproduce the scatter seen even at high-[Fe/H]. Is it real?

## Conclusions

- Galactic chemical evolution models of sodium should include the contribution from AGB stars undergoing hot-bottom burning.
- Our twin-infall GCE models fail to reproduce both the scatter in [Na/Fe] and the high-[Fe/H] stars.
- The hint of an increase in [Na/Fe] at high [Fe/H] may be due to secondary Na from type II supernovae, not AGB stars.

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