# The $^{187}$Re - $^{187}$Os Cosmochronometry and Chemical Evolution in the Solar Neighborhood

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With the use of the solar abundances of $^{187}$Re and its $\beta^-$ decay daughter $^{187}$Os, the $^{187}$Re - $^{187}$Os chronometry aims at setting a stringent lower bound, $T_{\rm G}$, for the age of the Universe ([1, 2]; see [3] for a recent review). One may loosely classify the various requirements it sets out into three categories:

- It requires the *"laboratory" input data,* namely the meteoritic abundances of Re and Os isotopes (see T. Faestermann, this volume), the $\beta^-$ decay half-lives not only of neutral but also highly-ionized $^{187}$Re (P. Kienle, this volume), and the neutron capture cross sections for nuclides in the $A = 184 \sim 187$ mass region (e.g. [4]). Much experimental progress has recently put the chronometry on a safer footing with more reliable input data;

- It requires a *modelling of evolution of various stars,* which is due in the first instance in order to evaluate the effects of "astration" in the stellar interiors – transmutations of $^{187}$Re and $^{187}$Os by enhanced $\beta^-$ decays and $e^-$ captures as well as destructions by neutrons of the concerned nuclides. Additionally it provide us with input data that are necessary for a quantitative modelling of chemical evolution (e.g. the stellar lifetimes, remnant masses and possibly the yields of various elements). As far as the $^{187}$Re - $^{187}$Os chronometry is concerned, the currently available models of stellar evolution may be said to be satisfactorily accurate;

- It requires a *modelling of chemical evolution* of matter from which the solar system was formed. This is the hardest part of all even without referring to the dynamical aspects of the formation of the Galactic disk as we see presently. Being pragmatic and at least for chronometric purposes, however, one may construct simple (largely analytic) models but by imperatively imposing as many observational constraints as possible, a point stressed by Tinsley [5] and concurred by others [2, 3]. [Many attempts to describe the abundances of light elements in the Galactic disk have been made in a similar fashion (most recently: [6]).]

In designing a model of chemical evolution specifically for the chronometry, we adopt here a simple one-zone model with the allowance for "infall." As usual, the star formation is assumed to be separable in time (the star formation rate: SFR) and stellar masses (the initial mass function: IMF). Our working assumptions, which may easily be removed or modified in due course, are that: stellar evolution is independent of (Galactic) time, namely, of metallicity; the instantaneous recycling approximation holds but for astration; and that the infall rate is proportional to SFR ($\Psi$) being given externally (rather than related to the gas mass), and is metal-free. Under these assumptions, the relevant equations of chemical evolution can easily be solved. The net consumption by star formation of gas mass in the interstellar medium is $(1-R)\Psi$, where $R$ is the "returning" mass fraction of the unit mass enclosed by stars. For $\beta$-stable elements such as $^{186}$Os or the sum of $^{187}$Re+ $^{187}$Os, $R$ is to be replaced by $R_{\rm n}$ in consideration of destruction by neutrons in the stellar interiors. As for $^{187}$Re, its destruction by $^{187}$Re $\beta^-$ decays has to be taken into account in addition as well as its production by $e^-$ captures of the embedded $^{187}$Os. We have first calculated these returning fractions with the use of models of solar metallicty stars ([7] for $M \leq 10$ M$_\odot$ and [8] for $M \geq 10$ M$_\odot$). The weak interaction rates are obtained by the method developed in [9]. The results are shown in Fig. 1, which are then folded by IMF that is obtained from the present-day mass function [10] for each adopted $\Psi$ with the help of the main-sequence lifetimes given by the models.

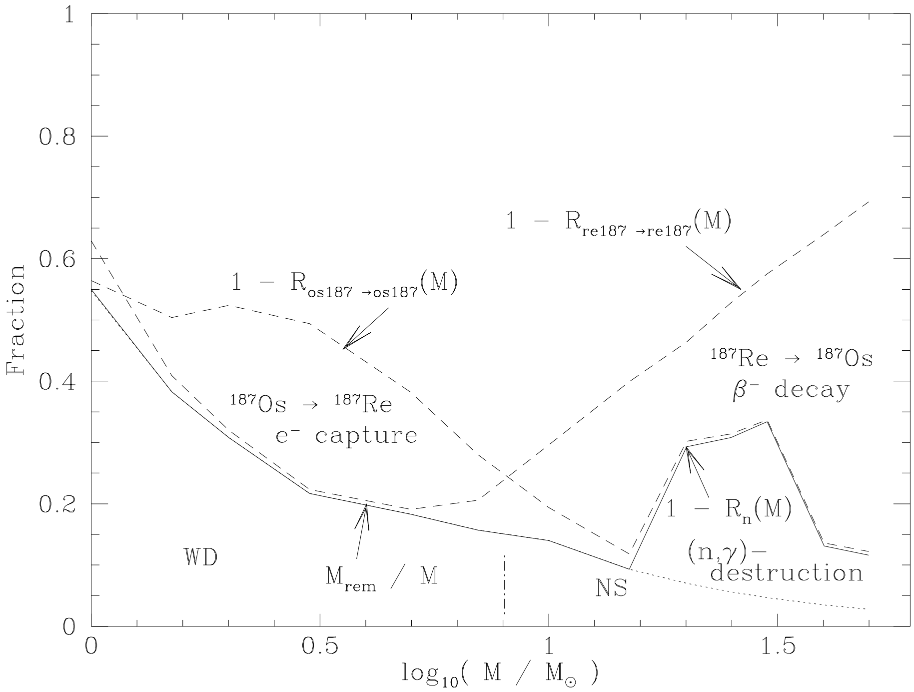


Figure 1: The fates of Re and Os isotopes embedded in stars of the initial mass $M = 1 \sim 50$ M$_\odot$. The dotted line separates the ejecta from the remnants: The "returning" fraction $R(M) = 1-\ M_{\rm rem}/M$. The area between the solid and dotted lines represents a fraction that has been destroyed by neutron captures: $R_{\rm n}$ is the returning fraction having survived neutron captures. The area between the dashed and solid lines represents a fraction of $^{187}$Re or $^{187}$Os that has undergone $\beta^-$ decays or $e^-$ captures, respectively: Of the unit amount of $^{187}$Re ($^{187}$Os) embedded, $R_{\rm re187\to re187}$ ($R_{\rm os187\to os187}$) is in the ejecta after having survived astration, $R_{\rm n} - R_{\rm re187\to re187}$ ($R_{\rm n} - R_{\rm os187\to os187}$) is found as $^{187}$Os ($^{187}$Re), whereas $1-R_{\rm n}$ never returns

The $\beta$ transmutation between $^{187}$Re and $^{187}$Os occurs most importantly during the main-sequence phase: portions of these elements that encounter higher temperatures in later evolutionary phases are either destroyed by neutrons or eventually absorbed by remnants anyway. At H-burning temperatures, the densities are relatively high in low mass stars such that $^{187}$Os $e^-$ captures dominate, whereas in massive stars the effect of $^{187}$Re $\beta^-$ decays becomes appreciable. Neutron captures destroy much of Re and Os isotopes during the core He burning in massive stars. In low mass stars, such destructions occur during the thermal pulse phase but are negligible because only a tiny amount of matter is dredged up. [We are concerned with elements initially existed, and not those freshly produced (and tremendously enhanced) s-process elements.]

We are now left with typically three to four adjustable parameters (one or two for a functional of $\Psi$, then one for the infall rate, and the other being the initial gas mass. In order to constrain the ranges of parameter values, we adopt the following observational data:

the current total mass of 40 - 60 $M_\odot/pc^2$;
the current gas mass of 5.7 - 7.0 $M_\odot/pc^2$;
the current infall rate of 0.3 - 1.5 $M_\odot/pc^2/Gyr$; and
the current star formation rate of 0.5 - 1.5, relative to its average in the past.

[See the references in [6] for these limits observed in the solar neighborhood. We presume that the solar system had been formed out of material that ended up in the solar neighborhood. If the solar system is atypical, as some assert, then we may have to refer to different numbers.] Some typical results concerning the metallicity distribution and the age-metallicity relation are compared with observations in Figs. 2 and 3. For a given $T_G = m$ Gyr, the class of models "S$n$–$m$" assumes a step function for $\Psi$: a constant up to time $m - n$ Gyr and another one at later times, and the model "E-$m$" an exponential function.

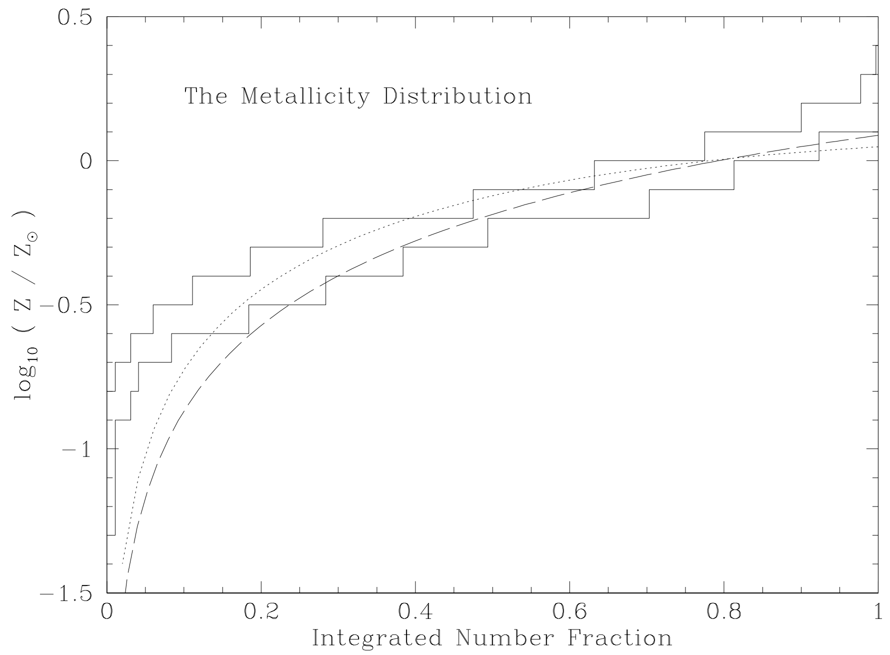


Figure 2: Accumulative metallicity distribution for models S6-13 (dot) and S6-17 (dash). The horizontal axis is the number of stars integrated up to time at which metallicity $Z$ in the ordinate is reached (normalized at the present time). The solid lines define the boundaries set by observed [Fe/H] distribution in G-dwarf stars ([11]). See text for the naming of the models

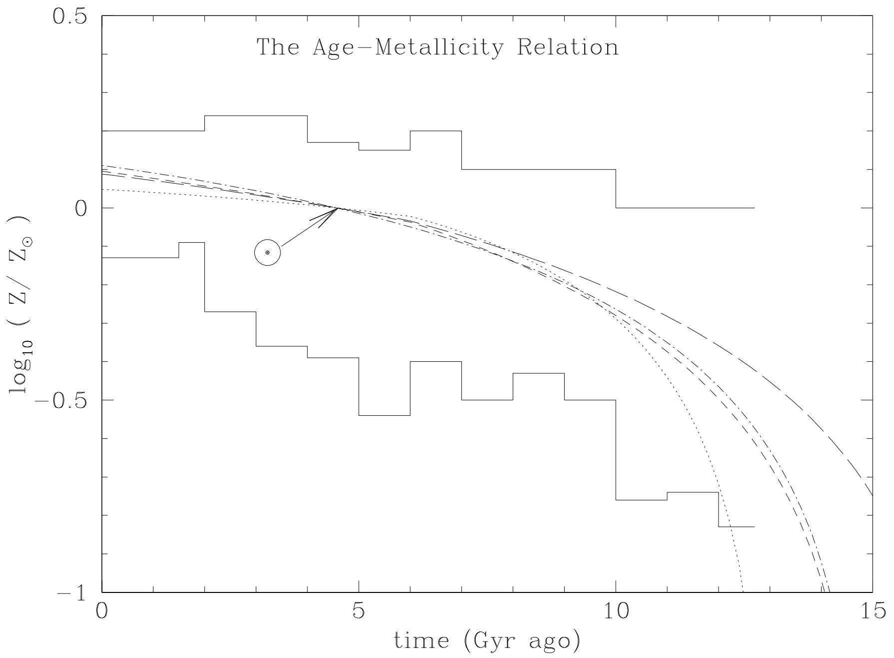


Figure 3: Evolutions of metallicity backward in time for models S6-13 (dot), S6-15 (short dash), S6-17 (long dash) and E-15 (dot-dash). The solid lines define the boundaries set by various observational analyses of [Fe/H] ([12]). See text for the naming of the models

We now proceed to an age determination. For a given trial value of $T_{\rm G}$ and a set of $\Psi$s with constrained parameter values, we first use the $^{186}$Os solar abundances to get its bulk (s-process) yield, from which the s-process contribution to the solar $^{187}$Os abundance is derived ([4]). We then fit the summed solar abundance of $^{187}$Re and $^{187}$Os in order to deduce the $^{187}$Re r-process yield. Finally, a comparison of the then computed $^{187}$Re abundances with the solar value leads to a most probable $T_{\rm G}$ value for each $\Psi$ functional. The results are shown in Fig. 4. The error bars attached there are theoretical and reflect the spreads in the parameter space. It is clear that the $^{187}$Re - $^{187}$Os chronometry leads as yet to a considerable spread in the derived $T_{\rm G}$ values, particularly owing to the uncertainties in modelling of chemical evolution. On the other hand, it is comforting to find $T_{\rm G}$ in a “reasonable” range, whereas the utter neglect of astration effects would result in $T_{\rm G}$ well beyond 20 Gyr. There are much more observational data that are worth considering in constructing a model of chemical evolution. We add also that the assumptions underlying our models have been introduced just for simplicity, and have to be removed or modified in due course, particularly in relation to chemical evolution in the early, metal-poor (halo) phase.

We should like to dedicate this work to the memory of David N. Schramm with admiration for his important contributions not only to nucleo-cosmochronology but to nuclear astrophysics in general. We thank R. Bender, D. Thomas, W. Hillebrandt and H.-Th. Janka for helpful discussions on the “atypicality” of the Sun in the solar neighborhood. The work was supported by the “Sonderforschungsbereich 375-95 der Deutschen Forschungsgemeinschaft.”

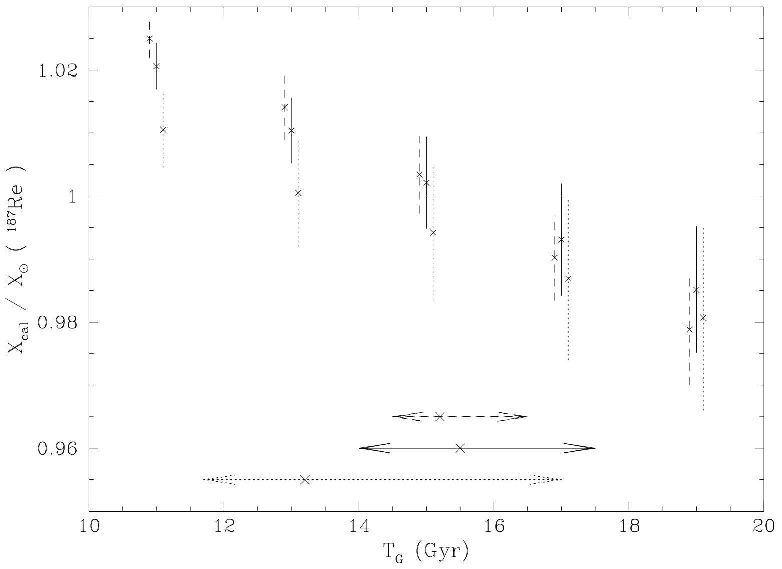


Figure 4: Computed $^{187}$Re abundances relative to the solar value and theoretical $1\sigma$ errors (vertical lines) for models S6-11 $\sim$ -19 (solid), S9-11 $\sim$ -19 (dotted), and E-11 $\sim$ -19 (dashed). The probable age intervals thus derived are displayed at bottom

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