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Abstract

The deep potential wells of galactic nuclei are capable of retaining the metal-rich gas that is returned to the interstellar medium from multiple generations of stars. Repeated fragmentation of the gas into stars is facilitated by cooling which becomes more efficient as the metallicity increases. While cooling-driven fragmentation might seem to be a runaway process, its ability to produce stable stars is ultimately inhibited by the metal enrichment process. Both the maximum mass for a stable star (that is capable of producing metals through nuclear fusion) and the stellar lifetimes decrease as the abundance of metals increases. We show that the metallicty of gas in a closed box reaches an asymptotic value $\sim$ 10-20$Z_{\odot}$, at which fragmentation into stars is suppressed. This process naturally explains the universally high metallicity inferred for the broad emission line spectra of quasars at all redshifts. We suggest that galactic nuclei feed quasar black holes with metal-rich gas because their short dynamical time and deep potential well allow them to go through many cycles of star formation and approach the asymptotic state of enrichment.

1. Introduction

The central regions of massive galaxies show evidence for high metallicities. For example, old stars in the bulge of the Milky-Way galaxy have a metallicity of 2 to 10 times solar (McWilliam & Rich 1994). High-luminosity quasars which reside in galactic nuclei, appear to be surrounded by metal-rich gas out to redshifts as high as 6, based on the spectrum of their broad emission lines (Simon & Hamann 2010, and references therein). These spectra imply metal abundances in the range of $\sim$ 5–10 $Z_\odot$. High metallicity is inferred for all quasars irrespective of their redshift or luminosity, implying that star formation generically precedes the quasar activity.

Cold gas in galactic nuclei is expected to fragment into stars long before it accretes onto the central black hole. First, a starburst phase is promptly trigerred when a large reservoir of cold gas is assembled in mergers of gas-rich galaxies Toomre & Toomre(1972), Barnes & Hernquist(1992), Cox et al.(2008), Colpi & Dotti(2009). But even the residual gas that loses angular momentum through its interaction with non-axisymmetric structures (Hopkins & Quataert 2010) faces a fragmentation catastrophe that could choke its accretion onto the central supermassive black hole. This is because a standard thin accretion disk around a massive black hole becomes unstable to fragmentation due to its self-gravity when the so-called Toomre parameter, $Q = (c_s\Omega/\pi G\Sigma)$, drops below unity (Goodman & Tan 2002). Here, c_s is the sound speed, Ω is the orbital frequency, and Σ is the surface mass density of the disk. This occurs outside a radius (Haiman et al. 2009),

$$r_1 \approx 2 \times 10^4 \alpha_{-1}^{28/45} \left(\dot{m}_{-1}/\epsilon_{-1}\right)^{-22/45} M_8^{52/45}, \tag{1}$$

where α is the viscosity parameter of the disk, $\dot{m}_{-1}$ is the mass accretion rate in units of 10% of the Eddington limit $\dot{M}_{\rm Edd}$, ϵ_{-1} is the radiative efficiency in units of 10%, and M_8 is the black hole mass in units of $10^8 M_\odot$. Here, the radius r_1 at which $Q = 1$ is expressed in units of 10 Schwarzschild radii ($= 3 \times 10^{14} M_8$ cm) and $\dot{M}_{\rm Edd} \equiv (L_{\rm Edd}/\epsilon c^2)$.

Outside the $Q = 1$ radius, a standard accretion disk gas would fragment efficiently into stars before being able to channel its gas towards the central black hole. The energy output from stellar winds and supernovae would supplement the viscous heating of the disk and might regulate the disk to have $Q \sim 1$ outside the above radius. The mass enclosed within r_1 is only a small fraction of the black hole mass (Goodman & Tan 2002; Haiman et al. 2009), and in order to allow growth of quasar black holes, ample gas must be able to flow across the fragmentation region and into the inner region of the disk. Coincidentally, the broad line region of quasars is located just inside the fragmentation boundary of the accretion disk based on the velocity width of the broad lines (Peterson).

We therefore conclude that star formation will inevitably occur on large scales, before the gas is driven into the inner accretion disk that feeds the central black hole. Indeed, the broad emission lines of quasars display very high abundance of heavy elements out to arbitrarily high redshifts. The lack of evolution in the metallicity of the broad line gas as a function of redshift suggests that stars enrich the gas up to our metallicity limit before the quasar turns on (Simon & Hamann 2010). An intriguing possibility is that stars form as long as they can, and once star formation saturates (because the gas reaches some metallicity limit), the gas has no choice but to feed the central black hole instead of fragmenting into more stars.

In this paper we suggest that the gas in galactic nuclei might have reached an asymptotic state of enrichment due to vigorous star formation, beyond which its fragmention into stable metal-producing stars is inhibited and the formation of a massive black hole is inevitable. To explain our motivation we consider the following thought experiment. We imagine filling a closed box with gas and letting the gas fragment into stars indefinitely. The question then arises: *will the metallicity of the gas increase without limit as a function of time?*

It is well known that the requirement for stability limits the maximum mass of stars. Above a certain mass, Schwarzschild & Härm (1959) showed that a nuclear-energized instability in the fundamental radial mode could disrupt a chemically homogeneous star. For a stellar model based on e^--scattering opacity the critical mass was found to be $\sim 60 M_\odot$ for a solar composition. More recent calculations with total opacity which includes atomic absorption raise the upper mass to around $\sim 100 M_\odot$ (Stothers 1992; Glatzel & Kiriakidis 1993). The instability is made possible by the dominance of radiation pressure over gas pressure inside massive stars, and it will depend upon the mean molecular weight, μ, because the pressure ratio is a function of μ^{-2}. Therefore the maximum stellar mass will decrease with increasing metallicity. We therefore anticipate that at some value of the metallicity, the upper mass cut-off for stable stars would approach a solar mass. At this point, newly-formed stars will not be able to produce metals out of their nuclear fuel in less than the Hubble time and so the metallicity of the gas will saturate at some asymptotic value. It is the purpose of this paper to estimate this asymptotic metallicity value and to compare it to that found in galactic nuclei.

Galactic nuclei possess deep potential wells that can retain the metal-enriched gas produced during their stellar evolution. Their short dynamical time $[(\sim \text{ kpc}/100 \text{ km s}^{-1}) \sim 10^7 \text{ yr}]$ and short cooling time (due to their high density) allow them to go through many cycles of star formation and possibly reach the asymptotic state of enrichment postulated above. We propose that once the gas reaches this asymptotic state its fragmentation process is suppressed. On the longer viscous timescale the gas loses its angular momentum and finally collects at the center to the most stable end-state of a massive black hole.

To quantify the above model for the formation of quasar black holes we approximate a galactic nucleus as a closed box and formulate the metallicity evolution of the gas in it in §2. We then calculate the maximum mass (§3) and lifetime (§4) of stable stars as a functions of their metallicity. We incorporate the most recent opacity tables and corresponding equations of state (EOSs) for stellar interior calculations (Rogers & Iglesias 1997; Seaton et al. 1996) in this calculation. Finally, §5 summarizes the main conclusions of this work.

2. Closed Box Model for a Galactic Nucleus

We consider a galactic nucleus as a closed box system, with negligible mass transfer due to inflows or outflows. We further assume that the metals in the system are well mixed because of its short dynamical time.

Our model is then described by the basic equations of galactic chemical evolution (see, e.g. Pagel 1998),

$$\frac{d\rho_{\rm gas}}{dt} = E(t) - S(t) \tag{2}$$

where the mass of gas is governed by the star formation rate, $S(t)$, and the mass loss rate from stars (including all modes of ejection),

$$E(t) = \int_{m_{\tau=t}}^{m_{\rm max}} (m - m_{\rm rem}) S[t - \tau(m)] \phi(m) dm, \tag{3}$$

where $m_{\rm rem}$ is the mass of the remaining stellar remnant at the end of the evolution of a star of mass m, and $\phi(m)$ is the initial mass function (IMF) for the stars. The limits of integration are from the minimum stellar mass, $m_{\tau=t}$, for which the stellar lifetime τ equals the age of the system, t (which we equate to the age of the Universe, 10^{10} yr), and up to the maximum mass, $m_{\rm max}$.

The abundance of metals in the gas is then governed by the relation,

$$\frac{d(\rho_{\rm gas} Z)}{dt} = E_Z(t) - S(t)Z, \tag{4}$$

where $Z \equiv \sum_i X_i = \sum_i \frac{N_i A_i}{\rho N_{\rm A}}$, is the mass fraction of all heavy elements (metals) or a specific element, X_i, with density $\rho_i = X_i \rho_{\rm gas}$. The mass loss rate, $E_Z(t)$, is given by

$$E_Z(t) = \int_{m_{\tau=t}}^{m_{\rm max}} \{(m - m_{\rm rem}) Z[t - \tau(m)] + m q_Z(m)\} S[t - \tau(m)] \phi(m) dm, \tag{5}$$

where $q_Z(m)$ is the fraction of the initial mass of a star which is ejected in the form of freshly synthesized metals, Z. It is often convenient to use the definition of a return fraction, $R(m)$, as the mass fraction of a generation of stars which is returned to the interstellar medium (see Fig. 3). This fraction increases with time as progressively lower mass stars complete their evolution.

Our addition to the standard set of equations summarized above is contained in the metallicity dependence of the upper mass cutoff,

$$m_{\rm max} = m_{\rm max}[Z(t)], \tag{6}$$

and the stellar lifetimes

$$\tau = \tau[Z(t)]. \tag{7}$$

Before discussing the full numerical solution of the above equations, we first quantify these metallicity dependences.

3. Metallicity Dependence of the Maximum Stellar Mass

The stability of the most massive stars has fascinated astronomers for a long time (Eddington 1926; Ledoux 1941). A modern study of the issue was done by Schwarzschild & Härm (1959), using detailed stellar structure models. Since then improvements have been contributed by many authors (Stothers & Simon 1970; Appenzeller 1970; Ziebarth 1970; Maeder 1985; Glatzel & Kiriakidis 1993).

The physics involved in determining a critical stable mass is as follows. The problem is defined for a zero-age main sequence (ZAMS) star, i.e. a chemically homogeneous model at the onset of core hydrogen burning. The central role is played by the balance of the radiation and the gas pressures inside the star. The increasing dominance of the radiation pressure in a low central condensation leads to an upper mass limit. Traditionally, the nuclear energy generation mechanism (the ϵ-mechanism) has been considered as the one driving the instability. The relevant dynamical mode, leading to the disruption of the star, is then the fundamental radial mode. Envelope instability mechanisms (e.g. the κ-mechanism) could be equally efficient in destabilizing the star in higher order modes. However, whatever the driving in the inner region, it should be able to overcome the damping of the outer region. Then the star can attain a large enough growth in pulsation amplitude to suffer a significant loss of mass. The growth in pulsation amplitude competes with the nuclear timescale, because core nuclear burning affects the level of central condensation, which in turn reduces the instability.

Nearly all of the pulsational damping occurs in the outermost layers of the star and can be very sensitive to the radiative opacity there, thus making the critical stellar mass a strong function of metallicity.

3.1. The linearized analysis

A brief review of the linear solution is instructive to the detailed study later in this paper. In the most simple analysis we require the central pressure, $P_c = P_{\rm rad} + P_{\rm gas}$, to support the star of mass M_* in hydrostatic equilibrium,

$$P_c = \left[\frac{3(1-\beta)}{a\beta^4}\right]^{1/3} \left[\frac{k\rho_c}{\mu m_{\rm p}}\right]^{1/4} = \left[\frac{\pi}{36}\right]^{1/3} G M_*^{2/3} \rho_c^{4/3}, \tag{8}$$

where $P_{\rm gas} = \beta P_c$ and the mean molecular weight, μ, is a function of composition (Y and Z, in particular). Equation (8) encapsulates in simplest terms the problem. The first term describes the pressure due to photons, electrons, and ions at the center of the star in thermal equilibrium. The second term approximates hydrostatic equilibrium of a chemically homogeneous star with pressure at the center which greatly exceeds the average pressure (e.g. Clayton 1986). We note from (8) that the stellar mass determines the fractional contributions of the gas, β, and the radiation, 1-β, to P_c, and that the fractional contribution of radiation increases with M_* increasing. Recall the virial theorem for the support of a self-gravitating system $-$ its binding energy becomes small when $P_{\rm rad}$ comes to dominate P_c, and destabilizes the star. Then solving the expression (8) for M_*, we get the expression for the critical mass as a function of metallicity:

$$M_{\rm crit} = 40.2 M_\odot \mu^{-2} \approx 116 M_\odot (1 - 2.4Z)^2. \tag{9}$$

This is the simplest dependence for $M_{\rm crit}$ (see Schwarzschild & Härm 1959; Adams & Laughlin 1997), which already sets the sign $-$ increasing abundance of Z reduces the critical mass. The origin of this metallicity dependence is directly traced to (8), where the product which determines β is $M_* \mu^{-2}$.

There are at least two major simplifications entering into the above result $-$ the pressure terms in (8) and the lack of description for the dynamical instability. Hence, the next step is to study the pulsational stability of a stellar system described by (8) or by a detailed model. Since Ledoux (1941), the pulsational instability has been ascribed to the fundamental radial mode, because it is the only one providing a large amplitude at both the core and the surface, i.e. disrupting the whole star (Schwarzschild & Härm 1959; Ziebarth 1970; Maeder 1985). All these studies confirmed fairly closely the critical mass dependence of equation (9). Most recently Stothers (1992) computed detailed models, using the modern opacity tables by Rogers & Iglesias (1992). He obtained a result that reverses the sign in equation (9). The explanation seems to be related to the stronger surface damping introduced by the new opacities, plus the increased central concentration of the stellar models, also due to the new opacities. However, Stothers analysis was limited to the ϵ-mechanism and did not include consideration of pulsation modes, other than the fundamental, e.g. like the first radial overtone mode. A complete pulsation stability analysis, including the κ-mechanism, was done by Glatzel & Kiriakidis (1993) and Kiriakidis, Fricke, & Glatzel (1993), who reaffirm the sign of the metallicity dependence in equation (9). We also find that the fundamental mode is often irrelevant in describing the stability of metal-rich massive stars – the new detailed opacities help describe conditions for the excitation of higher order radial modes, which can disrupt the star over a series of mass loss events.

However, as with the stability analysis of the fundamental mode, we need to answer the same questions about the rate of growth of the pulsation amplitude of the higher order modes as compared to the nuclear timescale. This is of added importance now, since the star is disrupted over a series of mass loss events. Schwarzschild & Härm (1959) did that in terms of a stability coefficient, after Eddington (1926), $K = 0.5(L_{\rm P}/E_{\rm P})$ – the reciprocal of the time in which the pulsation amplitude changes by a factor of e (a positive K indicates instability). The net rate of gain of pulsation energy, $L_{\rm P}$, is the rate of gain of pulsation energy due to the nuclear sources ϵ-mechanism reduced by the rate of loss due to envelope damping (heat leakage) and loss at the surface from progressive waves. Schwarzschild & Härm determined a critical time, τ, over which the growth of pulsation instability will outperform the evolution off the ZAMS, $\tau = 0.05(M_*/M_\odot - 60)$; then the exponential change in pulsation amplitude – number of e-folding times, is:

$$N(\tau) = \int_0^\tau K d\tau. \tag{10}$$

They found the correction to increase the critical mass by 8% or less. We will determine τ by computing a grid of evolving models.

3.2. A non-linear analysis with detailed opacity tables and EOS

The main difference between the older set of opacities, LAOL (Huebner et al 1977), and the new OPAL opacities (Rogers & Iglesias 1992), is in the contribution of heavy elements. The detailed treatment of the heavy elements opacity in the OPAL calculations leads to a significant opacity enhancement around $T = 200,000\ K$. This enhancement is only barely

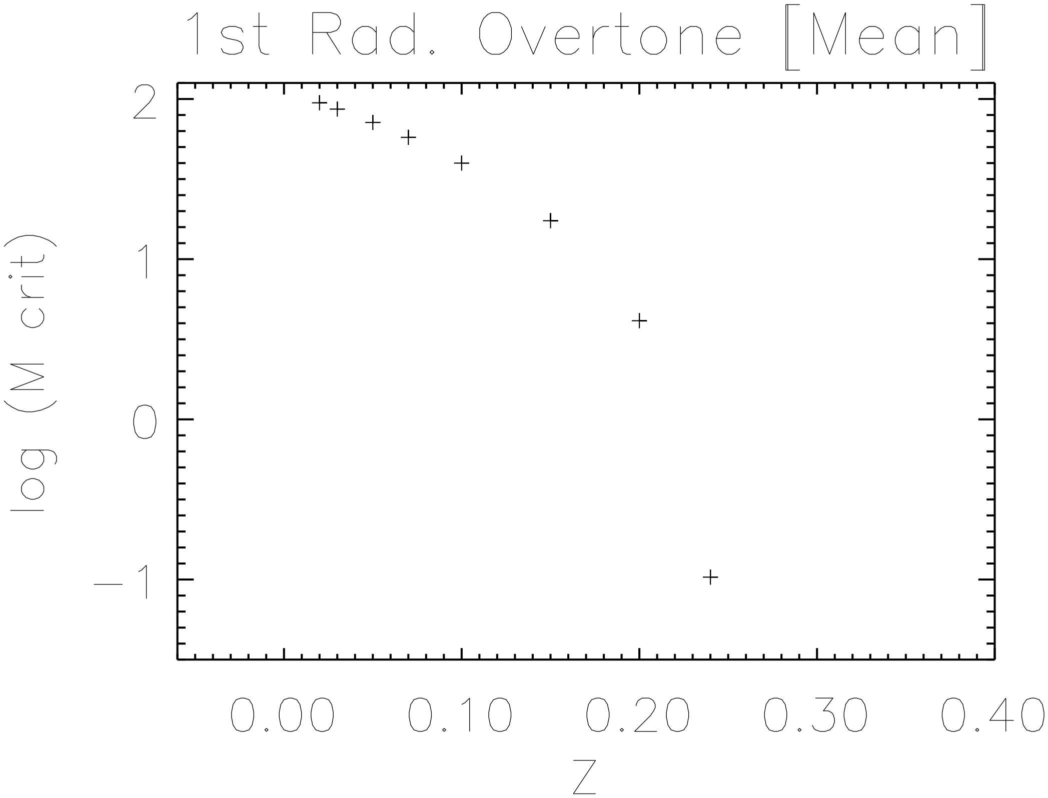

Fig. 1.— The metallicity dependence of the critical stellar mass for a shallow helium enrichment ratio of 2 and primordial helium mass fraction of 0.24.

present in the LAOL opacities, and introduces a strong sensitivity to Z in the LAOL-OPAL comparison. The differences are small at small metallicities, and increase progressively with Z.

We calculated grids of main sequence models (ZAMS to end of H-burning). The stellar code is our updated version of the stellar evolution package prepared by Sienkiewicz (1996) and based on an original code by Paczynski (1983). The most recent OPAL opacities and corresponding EOS are used (Iglesias & Rogers 1995). For the very high metallicities required by our work, Iglesias & Rogers (1998) kindly computed accurate extensions of their OPAL opacities for Z $\geq$ 0.10 and standard mixtures. The nuclear reaction rates are from Bahcall & Pinsonneault (1995). We use standard mass loss rates and overshooting as defined by the Geneva group models (e.g. Mowlavi et al. 1998).

Once calculated, the ZAMS models from the grid are used for runs with our radial

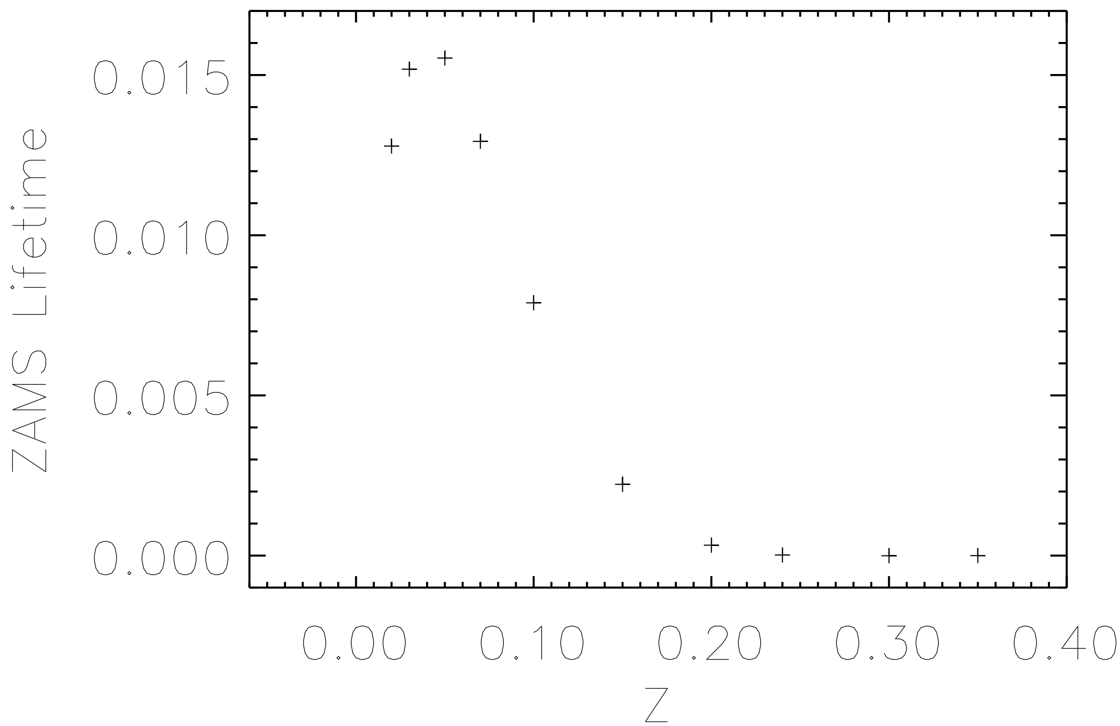

Fig. 2.— The metallicity dependence of the stellar lifetime for a shallow helium enrichment ratio of 2 and primordial helium mass fraction of 0.24.

pulsation code. The growth rates of all low-order modes are calculated and compared to the evolutionary rates of change of the stellar models. For any mode higher than fundamental (e.g. 1st overtone), exponential growth rates correspond to mass loss events (of the mass fraction above the node), which we include in the evolution calculation, until the star is completely "evaporated".

4. The Metallicity Dependence of Stellar Lifetimes

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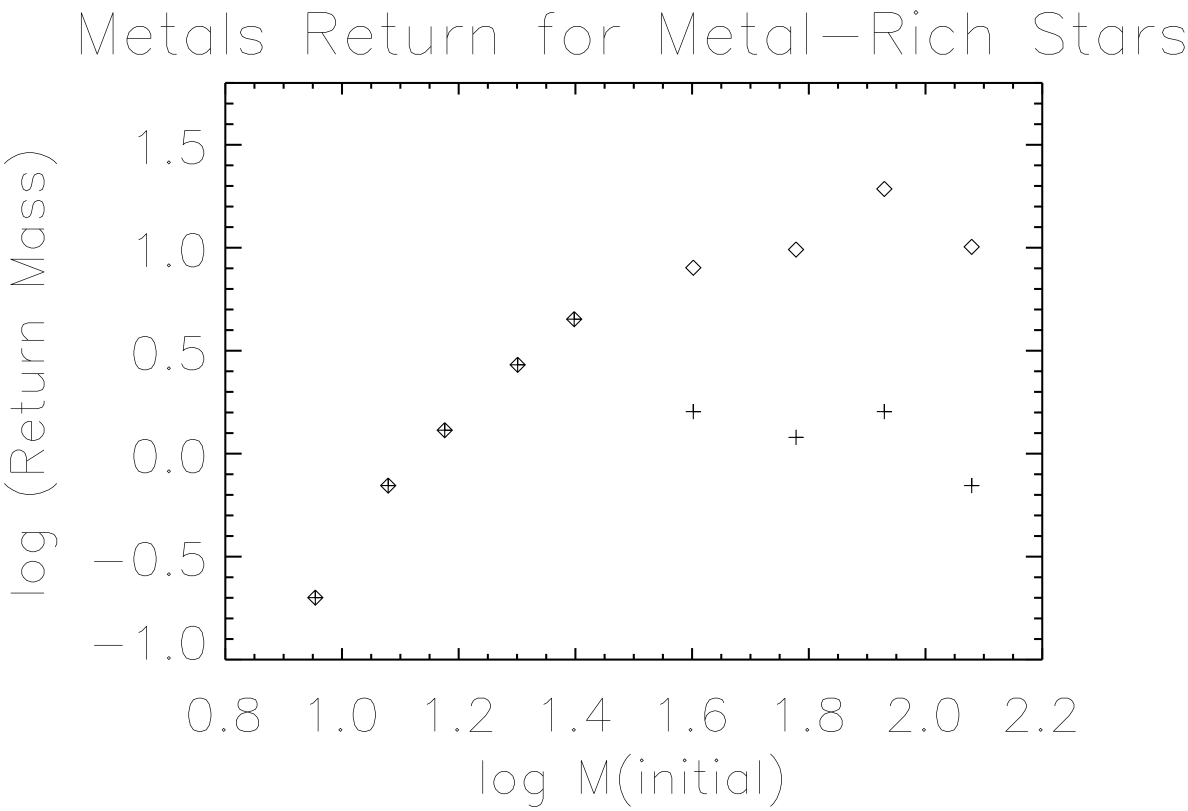

Fig. 3.— The return function in terms of nuclear production of metals, Z, for enriched stars in a multiple cycle star formation scenario. The two curves represent total return, as well as end-of-evolution return only (+).

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