The GHZ of the Milky Way and M31 from chemical evolution models with gas radial flows

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The galactic habitable zone

The chemical evolution models for the MW and M31

Our galactic habitable zone model

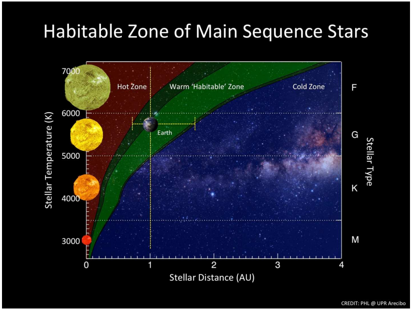
The GHZ results for models without radial gas flows

The GHZ results for models with radial flows of gas

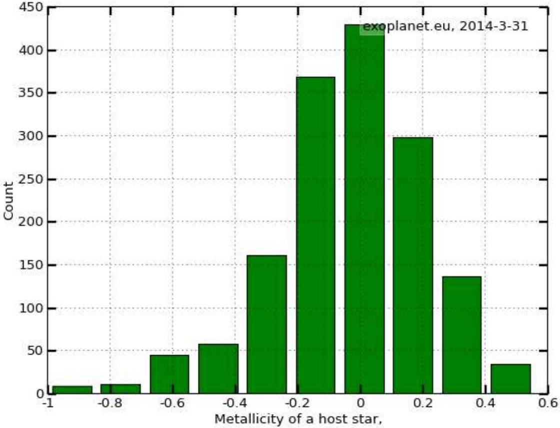
Summary

The Circumstellar Habitable zone

- The Circumstellar Habitable Zone (CHZ) has generally been defined to be that region around a star where liquid water can exist on the surface of a terrestrial (i.e., Earth-like) planet for an extended period of time (Huang 1959, Shklovsky & Sagan 1966, Hart 1979).



THE METALLICITY OF THE HOST STARS



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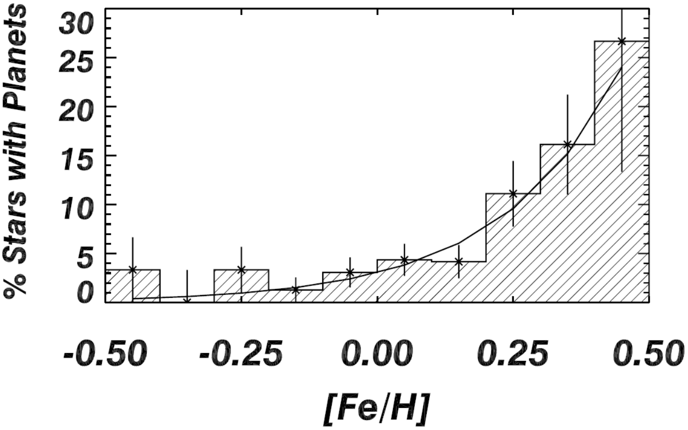
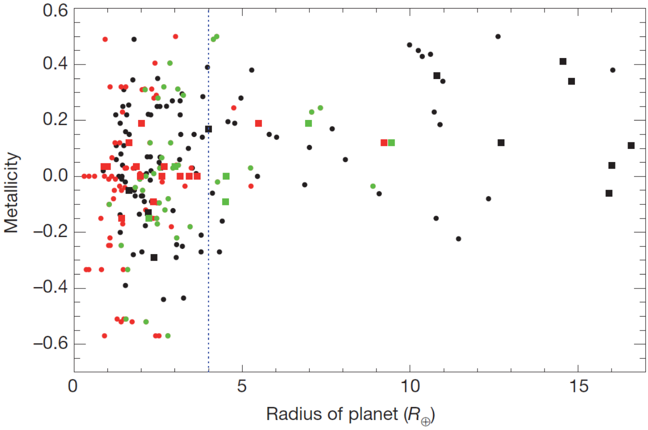
THE METALLICITY OF THE HOST STARS FOR GIANT PLANETS



FISCHER & VALENTI (2005)

P_{FE}

THE METALLICITY OF THE HOST STARS FOR EARTH-SIZE PLANETS



BUCHHAVE ET AL. (2012)

Fig. P_{FE} P_{FE}

Galactic chemical evolution can substantially influence the formation of habitable planets

A minimum metallicity is needed for planetary formation, which would include the formation of a planet with Earth-like characteristics.

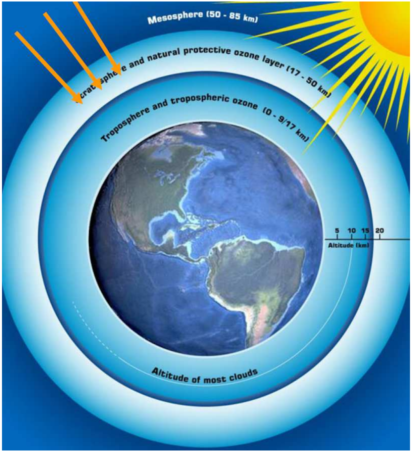
- The model of Johnson & Li (2012) showed that the first Earth-like planets likely formed from circumstellar disks with metallicities $Z \geq 0.1Z_{\odot}$.

THE GHZ DEFINITION

- THE GALACTIC HABITABLE ZONE is defined as the region with sufficiently high metallicity to form planetary systems in which Earth-like planets could be born and might be capable of sustaining life, after surviving to close supernova explosion events.

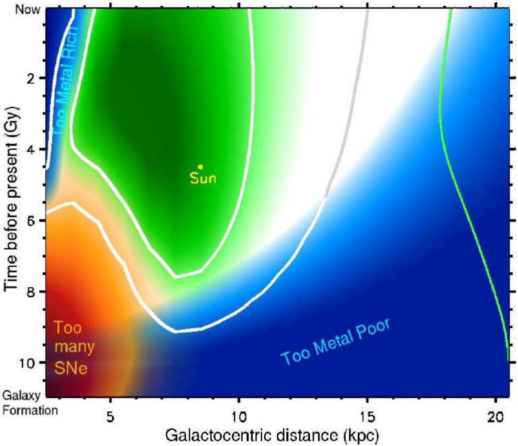
(GONZALEZ ET AL. 2001, LINEWEAVER ET AL. 2004, PRANTZOS 2008).

- When a SN explodes, it emits STRONG RADIATION that may ionize the planets atmosphere, causing stratospheric ozone depletion. Then ULTRAVIOLET FLUX from the planets host star reaches the surface and oceans, originating damage to genetic material DNA, which could induce mutation or cell death, and consequently the planet sterilization (Gehrels et al. 2003).

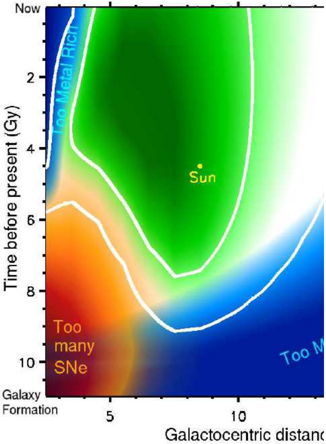


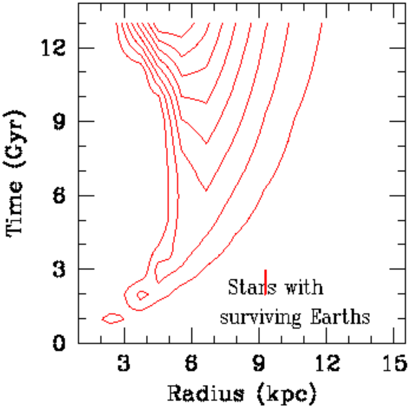
PREVIOUS GHZ MODELS: LINEWEAVER ET AL. (2004), PRANTZOS (2008), CARIGI ET AL. (2013)

Fig. M31

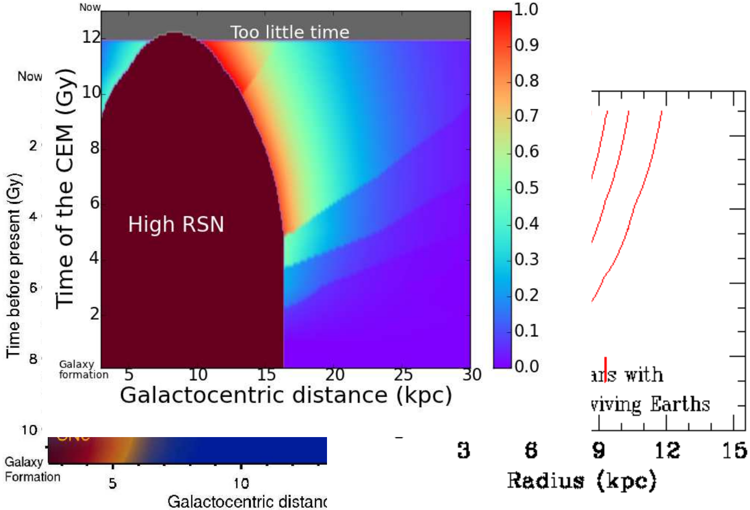


PREVIOUS GHZ MODELS: LINEWEAVER ET AL. (2004), PRANTZOS (2008), CARIGI ET AL. (2013) Fig. M31





Previous GHZ models: Lineweaver et al. (2004), Prantzos (2008), Carigi et al. (2013) Fig. M31



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THE CHEMICAL EVOLUTION EQUATIONS

Defining $G_i(r,t)$ as the normalized surface gas density in the form of element i:

$$G_i(r,t) = [\sigma_g(r,t)X_i(r,t)]/\sigma(r,t_G),$$

we have that the time evolution of $G_i(r,t)$ is followed with this equation:

$$\dot{G}_i(r,t) = -\psi(r,t)X_i(r,t) + \int_M \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm + X_{iA}A(r,t)$$

$$\dot{G}_i(r,t) = -\psi(r,t)X_i(r,t) + \int_M \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm + X_{iA}A(r,t)$$

LOCKED IN STARS: the rate at which the chemical elements are subtracted from the ISM to be included in stars

$$\dot{G}_i(r,t) = -\psi(r,t)X_i(r,t) + \int_M \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm + X_{iA}A(r,t$$

$$+ \int_{M_L}^{M_{Bm}} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

$$+A_{Ia}\int_{M_{Bm}}^{M_{BM}} \phi(M_B)\cdot\left[\int_{\mu_m}^{0.5} f(\mu)\psi(r,t-\tau_{m2})Q_{mi}^{SNIa}(t-\tau_{m2})d\mu\right]dM_B$$

$$+(1-A_{Ia})\int_{M_{Bm}}^{M_{BM}} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

$$+ \int_{M_{BM}}^{M_U} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

PRODUCED BY STARS: the rate of restitution of matter from the stars into the ISM and it is included the contribution from Type Ia SNe following the single degenerate scenario: C-O WD + red giant (Matteucci & Recchi 2001).

$$\dot{G}_i(r,t) = -\psi(r,t)X_i(r,t) + \int_M \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm + X_{iA}A(r,t)$$

INFALLING IN THE SYSTEM: this is the rate at which the element i is accreted through infall.

The radial inflow as a consequence of the infall

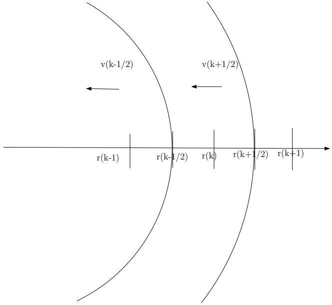
- The majority of chemical evolution models assumes that the Galactic disk forms by means of infall of gas and divides the disk into several independent rings without exchange of matter between them.
- However, if gas infall is important, to maintain consistency, radial gas flows have to be taken into account as a dynamical consequence of infall. Lacey & Fall (1985) estimated that the gas inflow velocity is up to a few km s^{-1}:

$$v_r \simeq -\frac{A(R,t)}{\sigma_g}\frac{(h_c - h_f)}{dh_c/dr}$$

THE IMPLEMENTATION OF RADIAL INFLOWS

- Radial inflows with a flux $F(r)$, contribute to altering the gas surface density in the k-th shell in according to (ES & Matteucci 2011)

$$\left[\frac{d\sigma_{gk}}{dt}\right]_{rf} = -\frac{1}{\pi\left(r^2_{k+\frac{1}{2}} - r^2_{k-\frac{1}{2}}\right)}\left[F(r_{k+\frac{1}{2}}) - F(r_{k-\frac{1}{2}})\right]$$



where the gas flows can be written as:

$$F(r_{k+\frac{1}{2}}) = 2\pi r_{k+\frac{1}{2}}\, v_{k+\frac{1}{2}}\left[\sigma_{g(k+1)}\right],$$

$$F(r_{k-\frac{1}{2}}) = 2\pi r_{k-\frac{1}{2}}\, v_{k-\frac{1}{2}}\left[\sigma_{g(k)}\right].$$

The radial flow term to be added into the chemical evolution equation is:

$$\left[\frac{d}{dt} G_i(r_k, t)\right]_{rf} = -\beta_k\, G_i(r_k, t) + \gamma_k\, G_i(r_{k+1}, t)$$

The chemical evolution equation + radial flows

$$\dot{G}_i(r,t) = -\psi(r,t)X_i(r,t) + \int_M \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm + X_{iA}A(r,t)$$

$$+\left[\frac{d}{dt}G_i(r,t)\right]_{rf}$$

THE MILKY WAY CHEMICAL EVOLUTION MODELS:

- The "classical" model without radial flow (ES & Matteucci 2011)
- Our best model with radial inflows of gas (Mott, ES, Matteucci 2013)

THE MW MODEL WITHOUT RADIAL FLOWS: AN UPDATED VERSION OF THE TWO INFALL MODEL OF CHIAPPINI ET AL. (2001)

- The infall rate is defined as

$$A(r,t) = a(r)e^{-t/\tau_H} + b(r)e^{-(t-t_{max})/\tau_D(r)}.$$

- Inside-out formation on the disk:

$$\tau_D = 1.033r(\mathrm{kpc}) - 1.27\ \mathrm{Gyr},$$

- The SFR is proportional to a Schmidt (1959) law;

$$\psi(r,t) \propto \nu\sigma_g^k(r,t),$$

  where ν is the SF process efficiency and is fixed to the value of $\nu = 1\ \mathrm{Gyr}^{-1}$ and the exponent k is equal to 1.4 (see Kennicutt 1998);

- Threshold in the gas density for the SF: 4 $M_\odot pc^{-2}$ in the halo-thick disk phase, 7 $M_\odot pc^{-2}$ in the thin disk phase.
- IMF of Scalo (1986);
- Constant total surface mass density for the halo: σ_H=17 $M_\odot pc^{-2}$

Our best model for the MW with the radial flows of gas

- No Threshold in the gas density;
- Different prescription for the total surface mass density of the halo: σ_H=17 $M_{\odot}pc^{-2}$ if $R \leq 8$ kpc otherwise σ_H= 0.01 $M_{\odot}pc^{-2}$
- Inflow velocity pattern in agreement with the models of Lacey & Fall (1985), Schoenrich & Binney (2009), and Bilitewski & Schoenrich (2012).

The inflow velocity pattern for our best model with radial gas flows

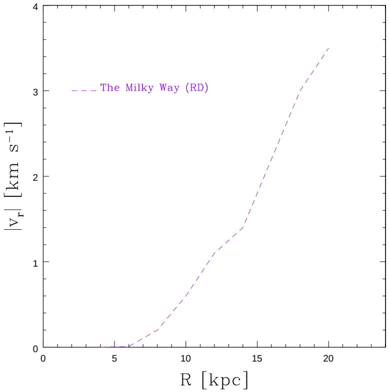
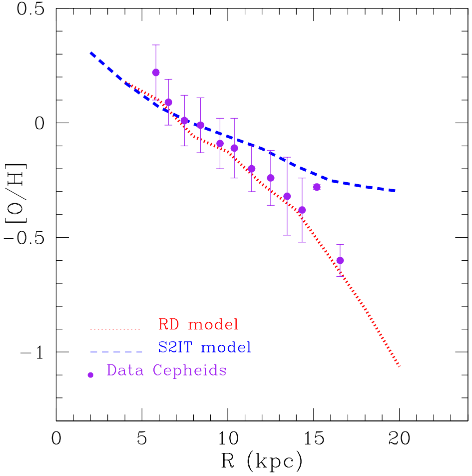


Table : Chemical evolution models for the Milky Way

Models	Infall type	τ_d [Gyr]	τ_H [Gyr]	ν [Gyr^{-1}]	Threshold [$M_\odot pc^{-2}$]	$\sigma_H(R)$ [$M_\odot pc^{-2}$]
S2IT no radial flows	2 infall	1.033 R[kpc]-1.27	0.8	1	7 (thin disc) 4 (halo-thick disk)	17
RD Radial flows	2 infall	1.033 R[kpc]-1.27	0.8	1	/	17 if $R \leq 8$ kpc 0.01 if $R \geq 10$ kpc

MW: THE ABUNDANCE GRADIENT (DATA BY LUCK & LAMBERT 2011)



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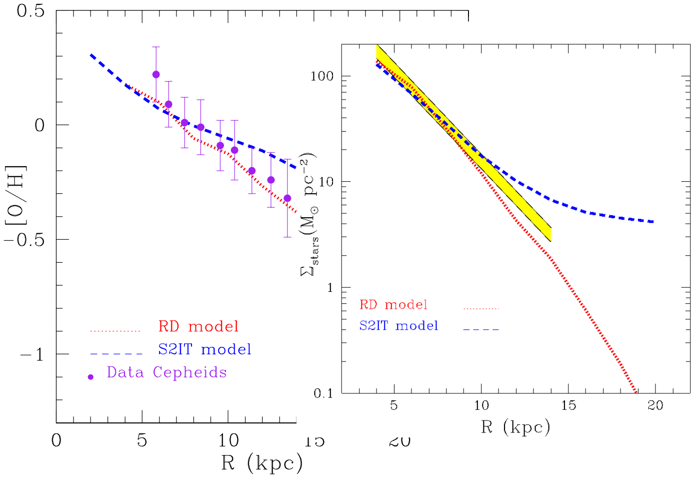
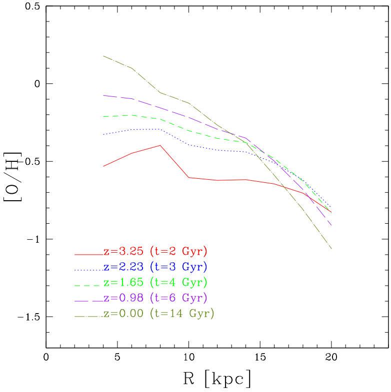


THE HIGH-REDSHIFT INVERSION OF THE ABUNDANCE GRADIENT

- Cresci et al. (2010) observed abundance gradient inversion of oxygen at z=3
- Curir et al. + ES (2012) imposed the high redshift inversion in the abundance gradients to explain the thick disk rotation-metallicity correlation for the MW.

Our best model with radial gas flows



Our explanation for the gradient inversion in the Milky Way is based on the inside-out disc formation:

- At early epoch the efficiency of chemical enrichment (i.e. of the SFR) in the inner regions is high but the rate of infalling primordial gas is dominating, thus diluting the gas more in the inner regions than in the outer ones;
- As time passes by, the infall of pristine gas in the inner parts decreases and the chemical enrichment takes over;
- Then, at later epochs, the SFR in the inner regions is still much higher than in the outer parts of the disc where the gas density is very low, but the infall is lower and the abundance gradients assume the shape seen in the observational data.

THE M31 CHEMICAL EVOLUTION MODELS:

- The best "classical" model without any radial gas flows (Marcon-Uchida et al. 2011)
- Our best model with radial inflows of gas (ES, Matteucci, Marcon-Uchida 2013)

The best "classical" model for M31 without any radial gas flows

- The infall rate is defined as

$$A(r,t) = b(r)e^{-(t)/\tau_D(r)}.$$

$\tau_D(r)$ is the timescale for the formation of the disk.

- Inside-out formation on the disk:

$$\tau_D = 0.62r(\text{kpc}) - 1.62 \text{ Gyr},$$

- The SFR is proportional to a Schmidt (1959) law;

$$\psi(r,t) \propto \nu \Sigma^k_{gas}(r,t),$$

where ν is the SF process efficiency and is fixed to the value of

$$\nu = \frac{24}{R} - 1.5 \text{ [Gyr}^{-1}]$$

- Threshold in the gas density for the SF: 5 $M_\odot pc^{-2}$.

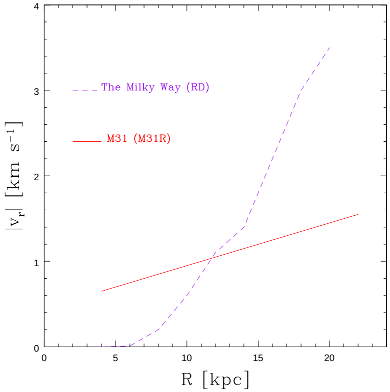
The best model for M31 with radial flows of gas

- No Threshold in the gas density;
- Constant star formation efficiency ν fixed at the value of 2 Gyr^{-1}
- Inflow velocity pattern in agreement with the models of Lacey & Fall (1985), Schoenrich & Binney (2009), and Bilitewski & Schoenrich (2012).

Table : Chemical evolution models for M31

Models	Infall type	τ [Gyr]	ν [Gyr^{-1}]	Threshold [$M_\odot pc^{-2}$]
M31B No radial flow	1 infall	0.62 R[kpc] +1.62	24/(R[kpc])-1.5	5
M31N No Radial flow	1 infall	0.62 R[kpc] +1.62	2	/
M31R Radial flow	1 infall	0.62 R[kpc] +1.62	2	/

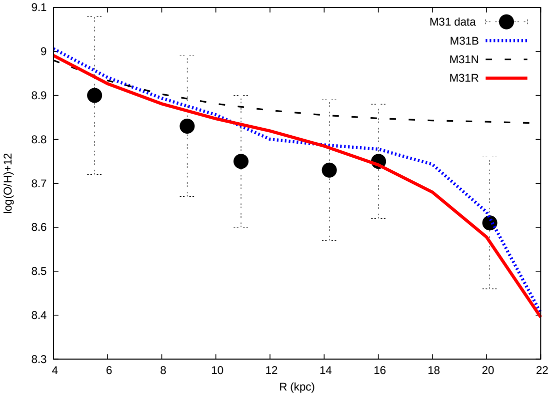
THE INFLOW VELOCITY PATTERN FOR THE MW AND M31 MODELS



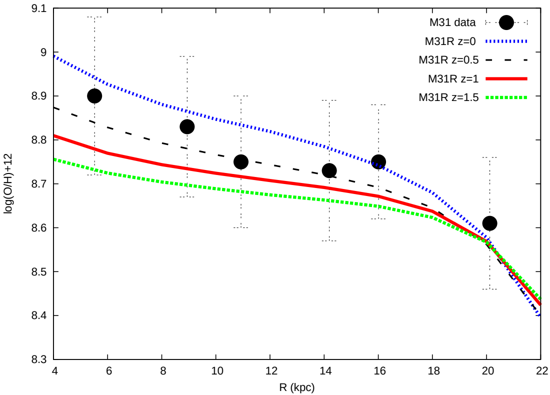
$$v_r(M31) = 0.05R[kpc] + 0.45$$

at 20 kpc $\frac{v_r(MW)}{v_r(M31)} = 2.5$

THE ABUNDANCE GRADIENT OF M31 (DATA BY GALARZA ET AL. 1999, BLAIR ET AL. 1982, DENNEFELD & KUNT 1981, TRUNDLE ET AL. 2002)



M31: THE EVOLUTION IN TIME OF THE ABUNDANCE GRADIENT OF THE BEST MODEL WITH RADIAL GAS FLOWS



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The Galactic Habitable zone model of Es, Matteucci & Sozzetti (2014, accepted by MNRAS)

THE PROBABILITY OF FORMING EARTH-LIKE PLANETS

FOLLOWING PRANTZOS (2008) PRESCRIPTIONS

- P_{FE} is the probability of forming Earth-like planets which is a function of the Fe abundance: the P_{FE} value is 0.4 for [Fe/H] $\geq$ -1 dex, otherwise $P_{FE} = 0$ for smaller values of [Fe/H] (in agreement with BUCHHAVE ET AL (2012)).

  Fig. Buchhave et al (2012)

- Fischer & Valenti (2005) studied the probability of formation of a gaseous giant planet which is a function of [Fe/H].

$$P_{GGP}\left([\mathrm{Fe/H}]\right) = 0.03 \times 10^{2.0[\mathrm{Fe/H}]},$$

Fig. Fischer & Valenti (2005)

THE PROBABILITY OF FORMING EARTH-LIKE PLANETS BUT NOT GAS GIANT PLANETS (PRANTZOS 2008)

$$P_E = P_{FE} \times (1 - P_{GGP}).$$

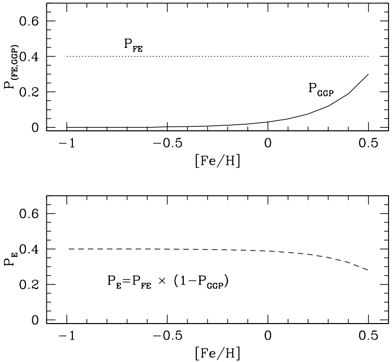


Fig. Buchhave et al (2012)

THE PROBABILITY $P_{GHZ}(R,t)$

- The fraction of all stars having Earths (but no gas giant planets) which survived supernova explosions as a function of the galactic radius and time.

$$P_{GHZ}(R,t) = \frac{\int_0^t SFR(R,t')P_E(R,t')P_{SN}(R,t')dt'}{\int_0^t SFR(R,t')dt'}$$

$$P_{GHZ}(R,t) = \frac{\int_0^t SFR(R,t')P_E(R,t')P_{SN}(R,t')dt'}{\int_0^t SFR(R,t')dt'}$$

- $SFR(R,t')$ is the star formation at the time t'
- $P_E(R,t')$ is the probability of having stars with Earth like planets but not gas giant planets which destroy them, is reported as P_E.
- $P_{SN}(R,t')$ is the probability of surviving supernova explosion.

THE $P_{SN}(R, t')$ PROBABILITY

We define $< RSN_{SV} >$ as the average SN rate in the solar neighborhood during the last 4.5 Gyr of the Milky Way's life (Carigi et al. 2013).

$$< RSN_{SV} > = 0.013 \ \mathrm{Gyr}^{-1} \ \mathrm{pc}^{-2}$$ (ES & Matteucci 2011)

- Case 1): if the SNR is larger than $< RSN_{SV} >$ then $P_{SN}(R, t)$ = 0 else $P_{SN}(R, t)$ = 1;
- Case 2): if the SNR is larger than $2\times < RSN_{SV} >$ then $P_{SN}(R, t)$ = 0 else $P_{SN}(R, t)$ = 1.

We consider also the case where the effects of SN explosions are not taken into account, $P_{GHZ}(R,t)$ becomes:

$$P_{GHZ}(R,t) = \frac{\int_0^t SFR(R,t')P_E(R,t')dt'}{\int_0^t SFR(R,t')dt'}$$

Fig. MW

THE TOTAL NUMBER OF STARS HOSTING EARTH-LIKE PLANET

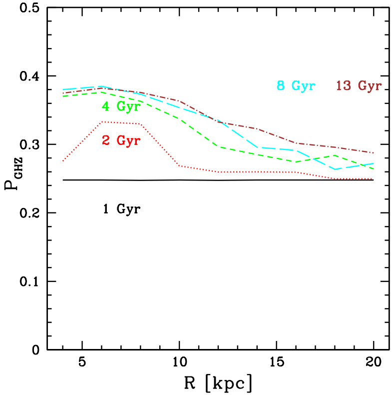
$$N_{\star\, life}(R,t) = P_{GHZ}(R,t) \times N_{\star tot}(R,t),$$

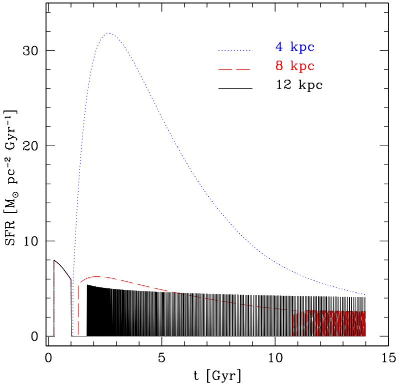
- here $N_{\star tot}(R,t)$ is the total number of stars created up to time t at the galactocentric distance R.

Fig. S2IT case2 life

The Milky Way results for the "classical" model without radial gas flows

THE MW: P_{GHZ} WITHOUT SN DESTRUCTION EFFECTS

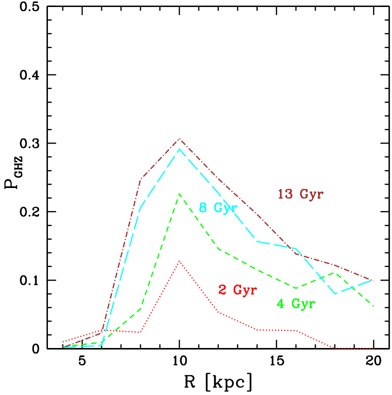


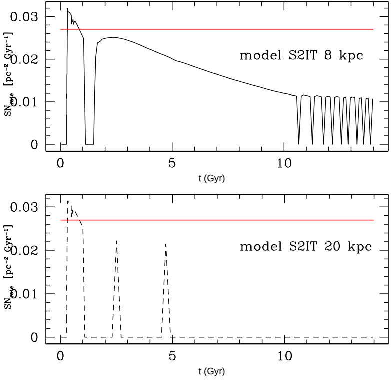


eq. No SN M31B No SN

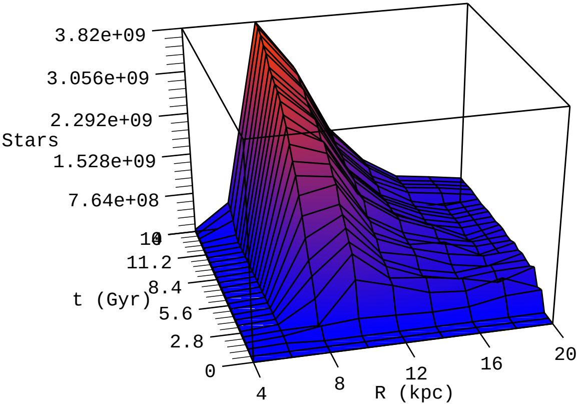
MW: P_{GHZ} WITH CASE 2) SN DESTRUCTION EFFECTS

case 2): if $SNR > (2 < RSN_{SV} >) \Rightarrow P_{SN} = 0$





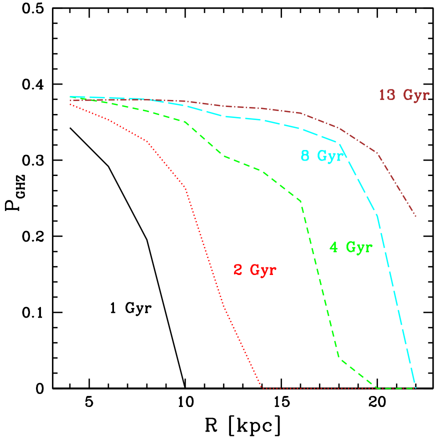
THE MW: THE N_{*life} VALUES eq. N_{*life} WITH THE CASE 2) FOR THE SN EFFECTS Fig. RD case 2



THE M31 RESULTS FOR THE "CLASSICAL" MODEL WITHOUT RADIAL GAS FLOWS

M31: P_{GHZ} WITHOUT SN DESTRUCTION EFFECTS

Fig. S2IT No SN Fig. M31R

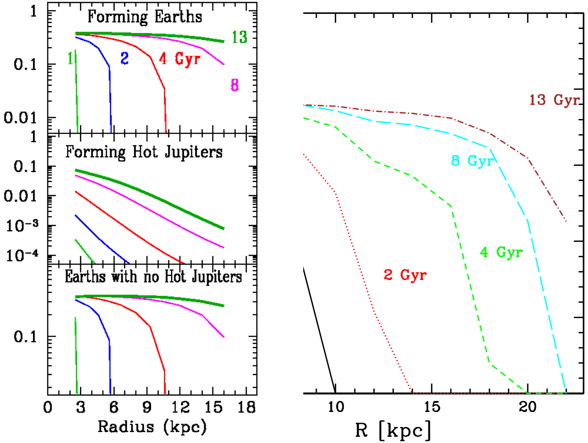


- The shape and evolution in time is similar to the one found by Prantzos (2008) for the MW.
- Similar law for the SFR, ν is a function of the galactocentric distance.

The MW: Prantzos (private comunication)

M31: P_{GHZ} WITHOUT SN DESTRUCTION EFFECTS

Fig. S2IT No SN Fig. M31R



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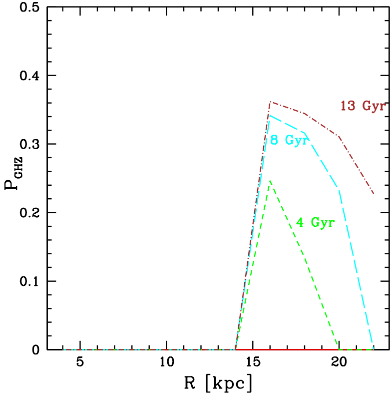
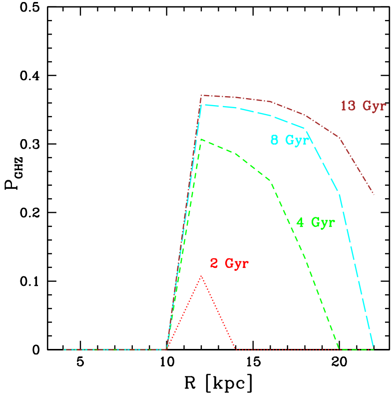
The MW: Prantzos (private comunication)

P_{GHZ} with SN destruction effects



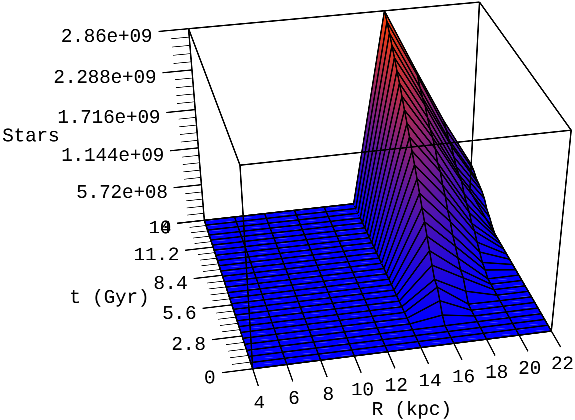
Case 1) if $SNR > (< RSN_{SV} >) \Rightarrow P_{SN} = 0$



Case 2) if $SNR > (2 < RSN_{SV} >) \Rightarrow P_{SN} = 0$

M31: THE TOTAL NUMBER N_{*life}) WITH THE CASE 1) SN EFFECT

Fig. Carigi et al. (2013) N_{*life} M31R



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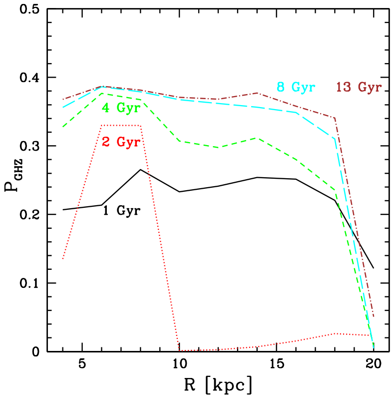
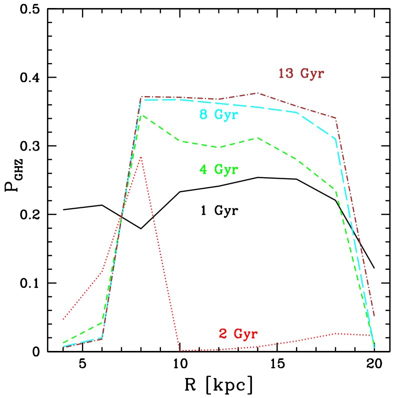
The Milky Way results for the best model with radial flows of gas

THE MW: P_{GHZ} WITH RADIAL FLOWS OF GAS

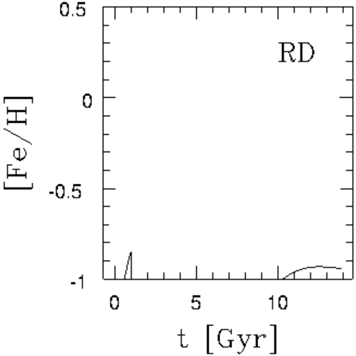


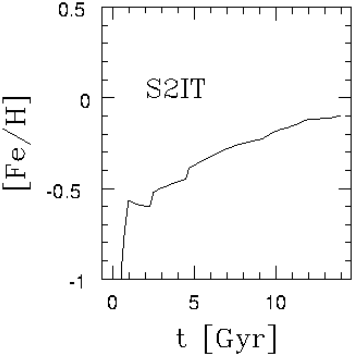
No SN destruction effects



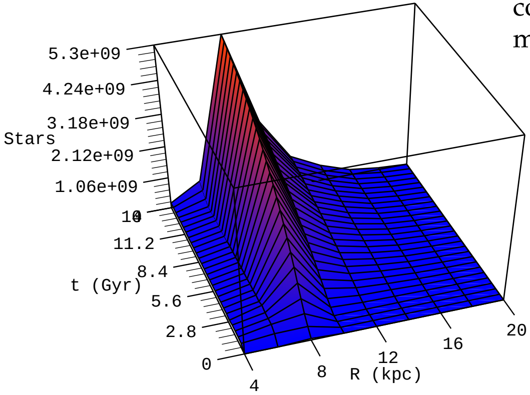
Case 2) if $SNR > (2 < RSN_{SV} >) \Rightarrow P_{SN} = 0$

WHY THE DEEP DROP IN THE P_{GHZ} AT 20 KPC?





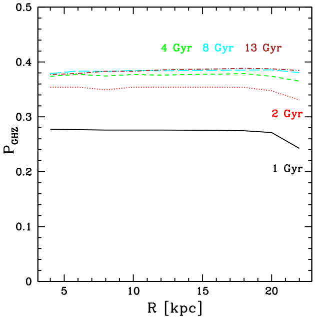
The MW: the (N_{*life}) hosting Earth-like planets. With the case 2) with radial flows

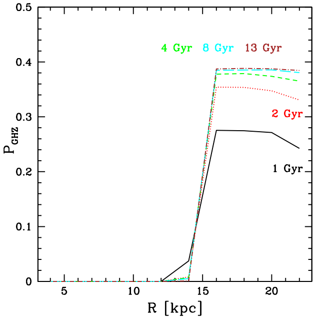


- At the present time at 8 kpc N_{*life} is increased by 38 % compared to the "classical" model Fig. S2IT case 2

M31 results for the best model with radial flows of gas

M31: P_{GHZ} WITH RADIAL FLOWS OF GAS



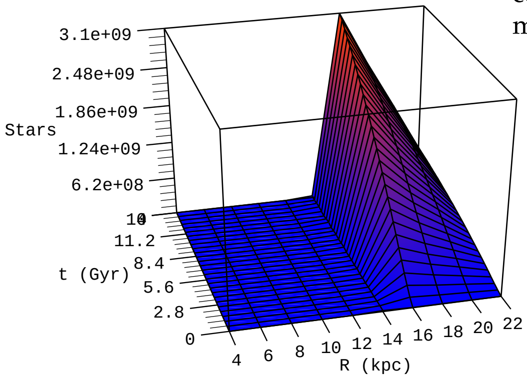


No SN destrution effects

Case 1) if $SNR > (< RSN_{SV} >) \Rightarrow P_{SN} = 0$

Fig. M31 No Radial

M31: THE (N_{*life}) HOSTING EARTH-LIKE PLANETS. WITH THE CASE 1) WITH RADIAL FLOWS



- At the present time at 8 kpc N_{*life} is increased by 10 % compared to the "classical" model N_{*life} M31B.

SUMMARY FOR MODELS WITHOUT RADIAL GAS FLOWS

- The Milky Way model which is in agreement with the work of Lineweaver et al. (2004) assumes the case 2) for the SN destruction. With this assumption, we find that the Galactic region with the highest number of host stars of an Earth-like planet is between 7 and 9 kpc with the maximum localized at 8 kpc.
- For Andromeda, comparing our results with the ones of Carigi et al. (2013), with the same prescriptions for the SN destruction effects, we find substantial differences in the inner regions ($R \leq 14$ kpc). In particular, in this region there is a high enough SN rate to annihilate life on formed planets at variance with Carigi et al. (2013). Nevertheless, we are in agreement for the external regions.

SUMMARY FOR MODELS WITH RADIAL GAS FLOWS

- Both for the Milky Way and M31 the effect of the gas radial inflows is to enhance the number of stars hosting a habitable planet with respect to the "classical" model results in the region of maximum probability for this occurrence.
- At the present time, for the Milky Way if we treat the SN destruction effect following the case 2) criteria, the maximum number of host stars is centered at 8 kpc, and the total number of host stars is increased by 38 % compared to the "classical" model results.
- In M31 the main effect of the gas radial inflow is to enhance at anytime the fraction of stars with habitable planets, described by the probability P_{GHZ}, in outer regions compared to the classical model results also for the models without SN destruction.
- The galactocentric distance with the maximum number of host stars is 16 kpc if we consider the case 1) SN destruction effects. Presently, at this distance the total number of host stars is increased by 10 % compared to the M31 "classical" model results. These values for the M31 model with radial flows are always higher than the "classical" ones.