

Blocking Metal Accretion onto Population III Stars by Stellar Wind

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Introduction

Low-mass Population III Stars

- Study the initial mass function (IMF) of PopIII stars.
- Top-heavy PopIII IMF has been predicted, while some might have $< 1 M_{\odot}$.
- Low-mass PopIII stars $< 0.8 M_{\odot}$ are still in Main-sequence phase.

Machida+13

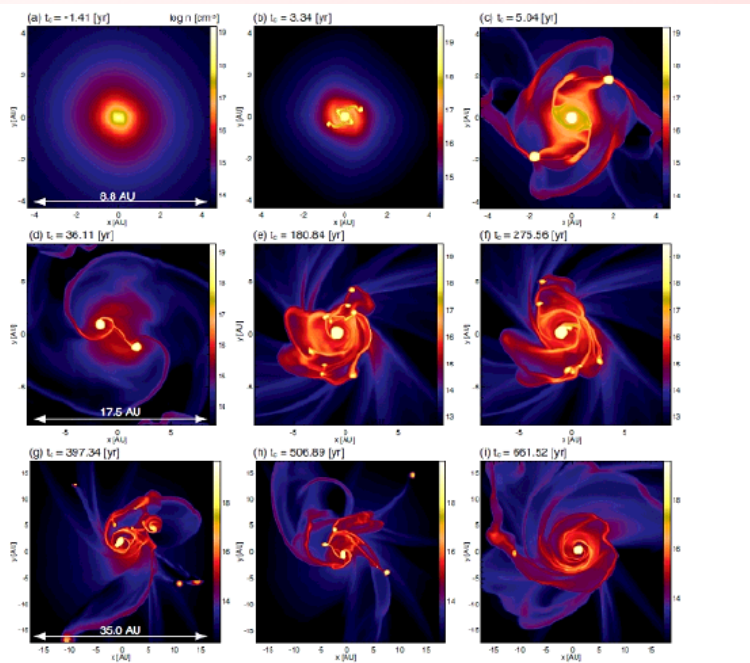
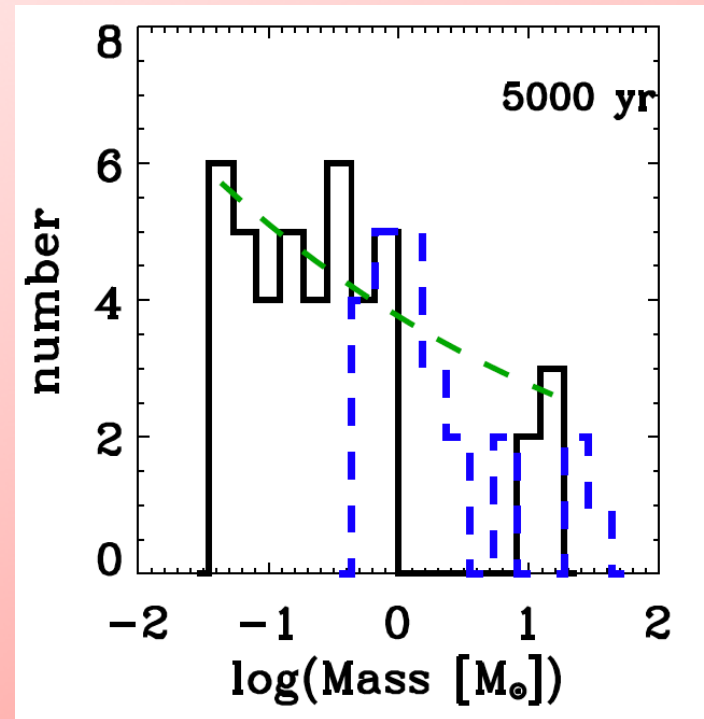


Figure 6. Time sequence images around the centre of the cloud for model 2. In each panel, the density (colour) distribution on the $x-z$ plane is plotted. The box size is different in each row. Elapsed time after protostar formation is given in each panel.

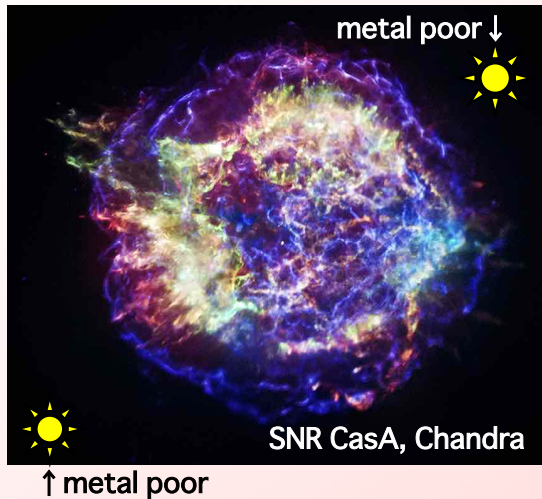
Stacy+16



Can we find **low-mass PopIII stars as metal free star** in our Galaxy? 3

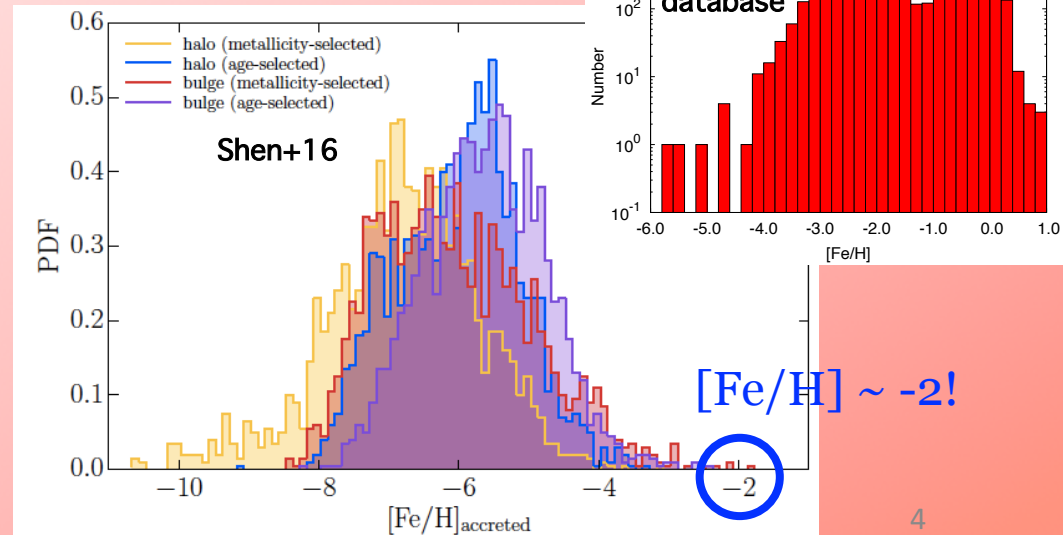
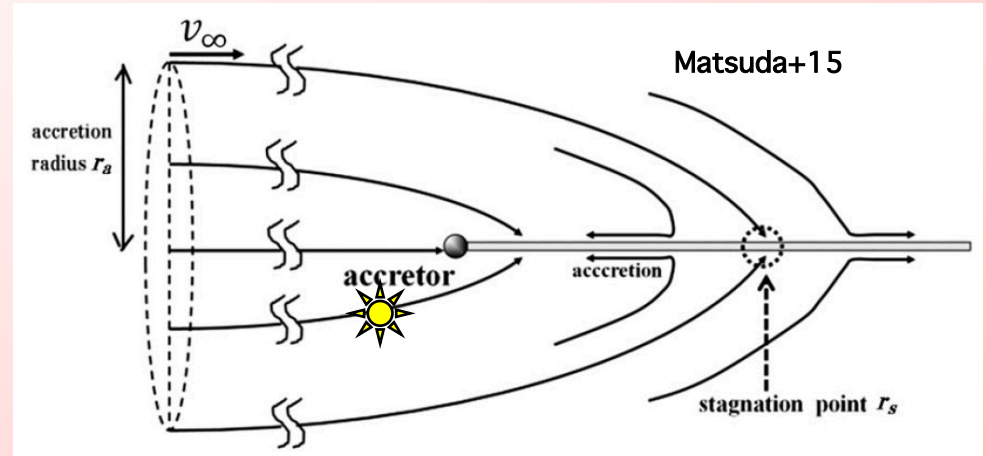
Origin of Metal Poor Stars

1. Second generation stars?



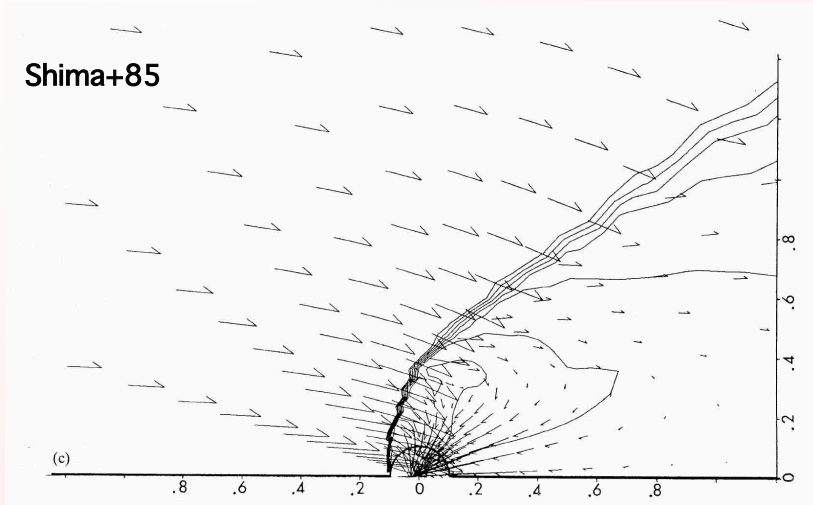
- Forget about scenario 1 (second generation hypothesis) in this study.
- Study of scenario 2 predicts $[\text{Fe}/\text{H}] \sim -2$ in an extreme case.

2. Chemically enriched PopIII stars?

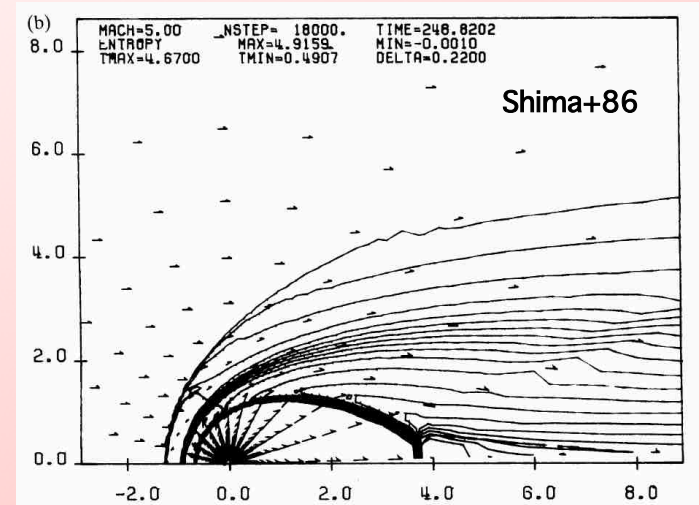


Accretion or Wind?

Bondi-Hoyle-Lyttleton accretion

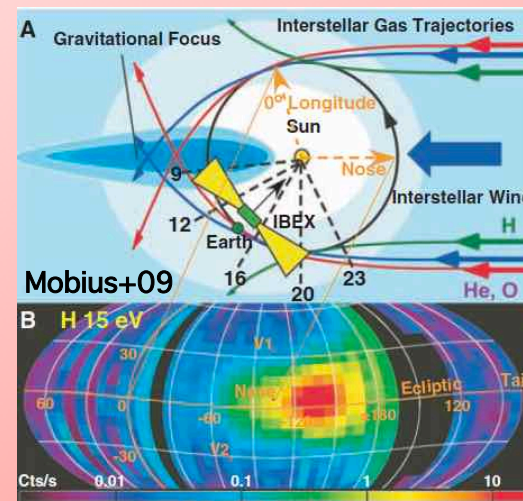
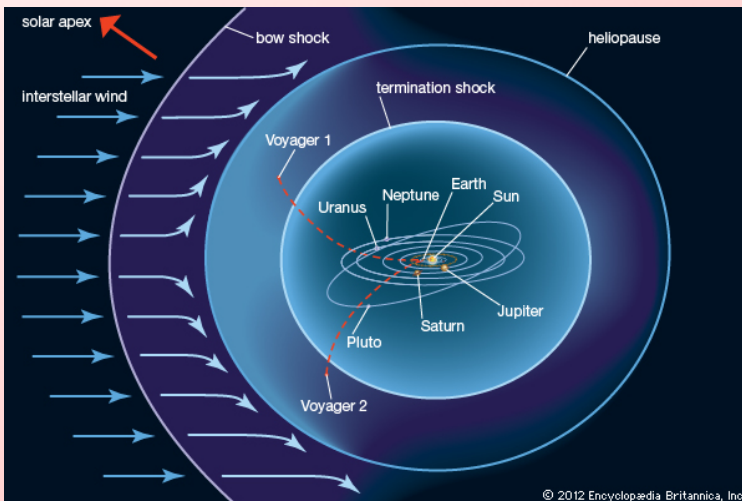


Formation of astrosphere



VS.

Case of our Sun: interstellar particles are picked up by the solar wind!!

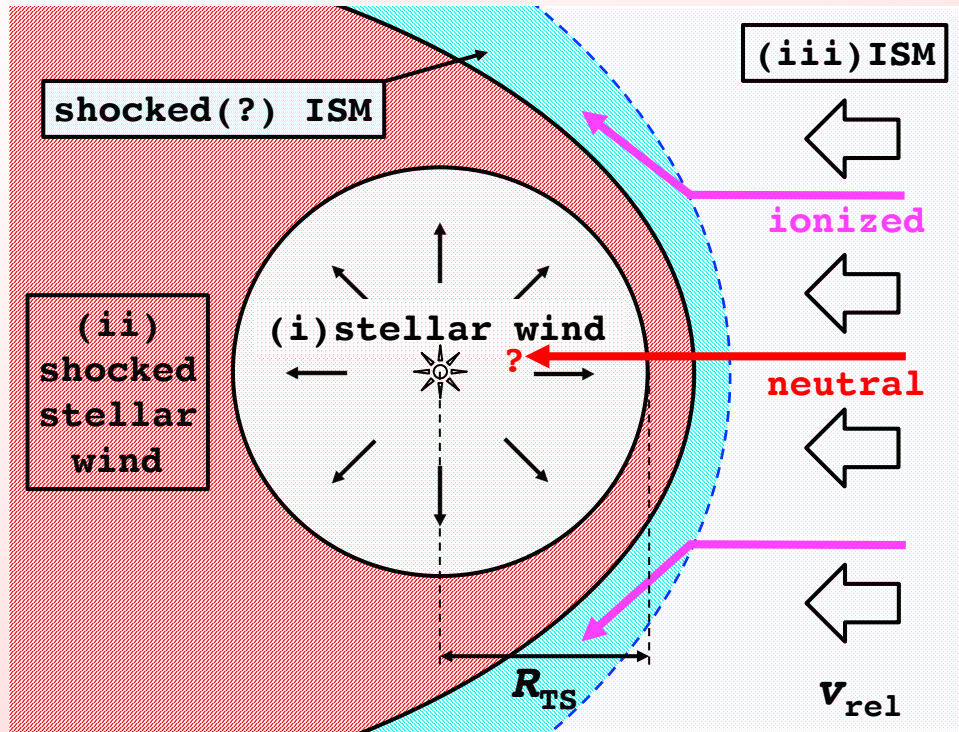


Can interstellar heavy elements accrete onto low-mass PopIII stars against their wind?

Model

Stellar Wind & ISM

The parameters of stellar wind are set to the Solar values.



(i) Thermal driven supersonic flow

$$n_{sw}(r) = n_{sw\star} \left(\frac{r}{R_{\star}} \right)^{-2}$$

$$v_{sw}(r) = v_{sw\star},$$

(iii) Bondi-Hoyle-Lyttleton accretion flow

$$n_{HL}(r, \theta, \xi) = \frac{n_{ISM} \xi^2}{r \sin \theta (2\xi - r \sin \theta)},$$

$$v_{HL,r}(r, \theta, \xi) = -\sqrt{v_{rel}^2 + \frac{2GM_{\star}}{r} - \frac{\xi^2 v_{rel}^2}{r^2}},$$

Neutrals in the ISM behave different from ionized ones!!

Stellar Radiation

Photoionization by stellar radiation.

Absorbed black body + EUV emission.

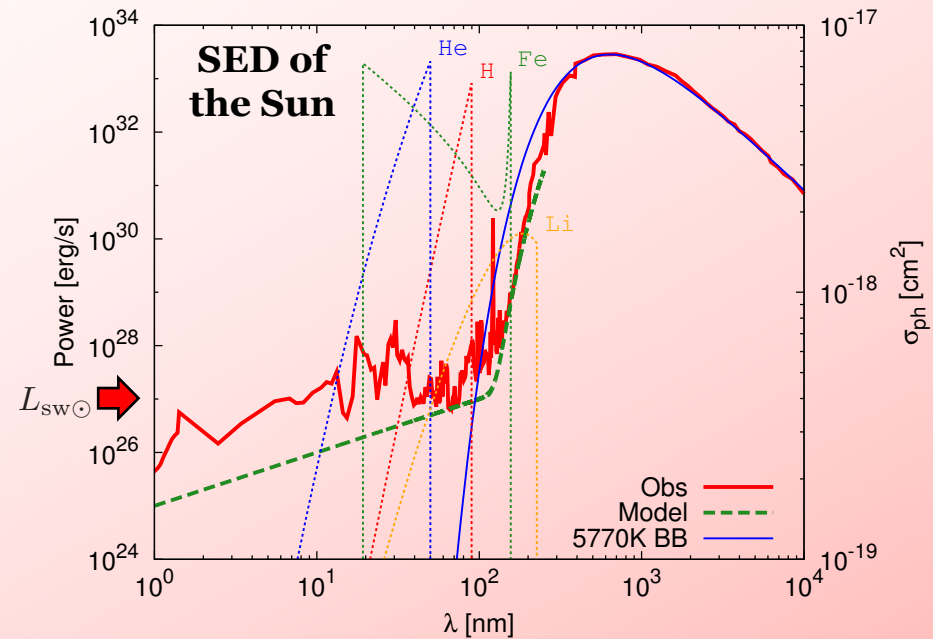
Lines from heavy elements

Related with the wind (?)

Assumption:

PopIII stars have unabsorbed blackbody spectrum & also have the EUV component of the similar power to the Sun.

$$\pi J_{\lambda\star} = \pi B_{\lambda}(T_{\text{eff}}) + \frac{L_{\text{EUV}}}{4\pi R_{\star}^2}$$

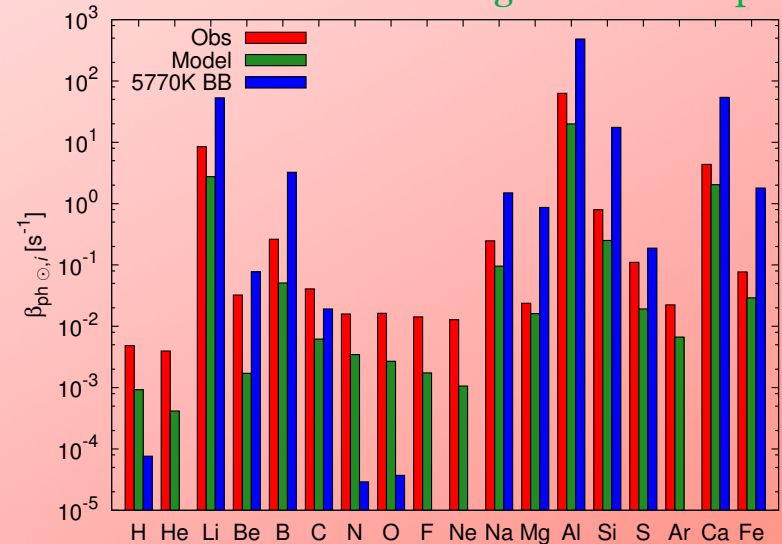


Photoionization rate

$$\beta_{\text{ph},i}(r) = \int d\lambda \dot{N}_{\lambda}(r) \sigma_{\text{ph},i}(\lambda)$$

Case for the Sun

red: observed spectrum
green: model spectrum



Rate Equation

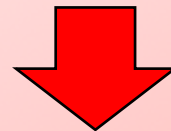
Ionization of interstellar neutrals

$$v(r) \frac{dn_i(r)}{dr} = -\beta_{\text{ph},i}(r)n_i(r) + \cancel{\alpha_{\text{rec},i}n_e n_i(r)}$$

Recombination processes
can be neglected.

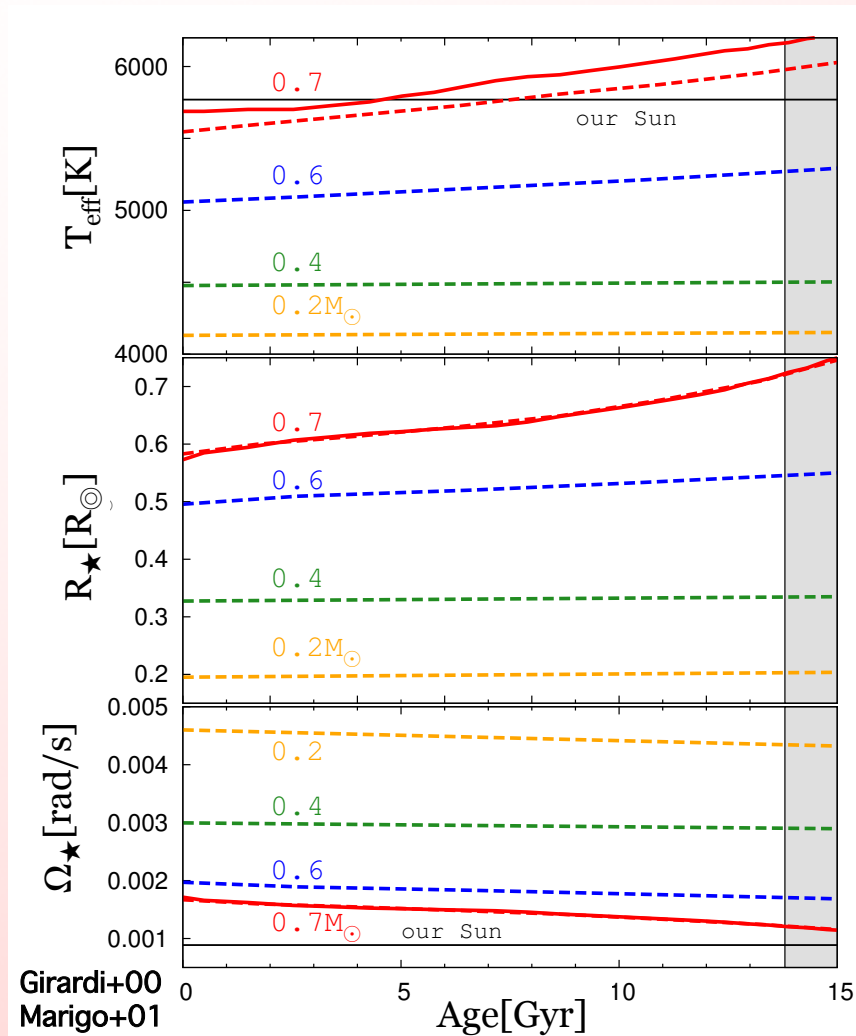
$$v(r) = -\sqrt{v_{\text{rel}}^2 + \frac{2GM_{\star}}{r}}$$

Motion of neutrals in
gravitation field


$$\beta_{\text{ph},i} \propto r^{-2}$$

$$\frac{n_i(r)}{n_{\text{ISM},i}} = \exp \left[-\frac{\sqrt{2}\beta_{\text{ph}\star,i}}{\Omega_{\text{K}\star}} \left(\sqrt{\frac{v_{\text{rel}}^2}{v_{\text{esc}\star}^2} + \frac{R_{\star}}{r}} - \frac{v_{\text{rel}}}{v_{\text{esc}\star}} \right) \right]$$

Stellar Model



$$\frac{r_{\text{g,FeII}}(R_{\star})}{R_{\star}} \approx 10^{-5} \left(\frac{B_{\text{sw}\star}}{1 \text{ G}} \right)^{-1} \left(\frac{\Omega_{\text{K}\star}}{10^{-3} \text{ rad s}^{-1}} \right),$$

Important parameters of
low-mass PopIII stars

Effective temperature

- Photoionization of neutrals by blackbody

Stellar radius

- Photoionization of neutrals by EUV component

Kepler frequency @ stellar surface

- Rate equation

Magnetic field

- Trapping photoionized neutrals

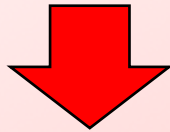
Results

Formation of Magnetosphere

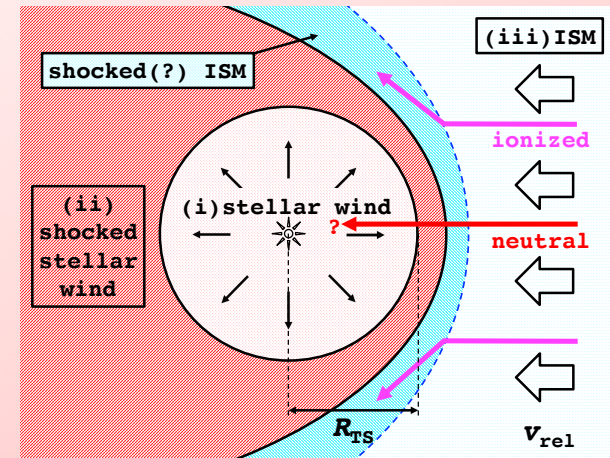
Pressure balance between accretion and wind flows.

$$n_{\text{sw}\star} v_{\text{sw}\star}^2 \left(\frac{R_\star}{R_{\text{TS}}} \right)^2 \approx n_{\text{ISM}} \left(v_{\text{rel}}^2 + v_{\text{esc}\star}^2 \frac{R_\star}{R_{\text{TS}}} \right).$$

For $(R_\star <) \xi_{\text{BHL}} < R_{\text{TS}}$
c.f., Talbot&Newman77



$$\begin{aligned} \xi_{\text{BHL}} &= \frac{2GM_\star}{v_{\text{rel}}^2} \\ &= R_\star \frac{v_{\text{esc}}^2}{v_{\text{rel}}^2} \end{aligned}$$



$$n_{\text{crit}} \equiv \frac{n_{\text{sw}\star}}{2} \frac{v_{\text{sw}\star}^2 v_{\text{rel}}^2}{v_{\text{esc}\star}^4}$$

$$\approx 10^4 \text{ cm}^{-3} \underbrace{\left(\frac{n_{\text{sw}\star}}{7.0 \times 10^5 \text{ cm}^{-3}} \right) \left(\frac{v_{\text{sw}\star}}{400 \text{ km s}^{-1}} \right)^2}_{\text{Solar wind value}} \underbrace{\left(\frac{v_{\text{rel}}}{200 \text{ km s}^{-1}} \right)^2}_{\text{Average of halo stars}} \underbrace{\left(\frac{v_{\text{esc}\star}}{680 \text{ km s}^{-1}} \right)^{-4}}_{\text{0.7 M}_\odot \text{ PopIII star}}$$

Solar wind value

Average of halo stars
e.g., Chiba&Beers00

0.7 M_⊙
PopIII star

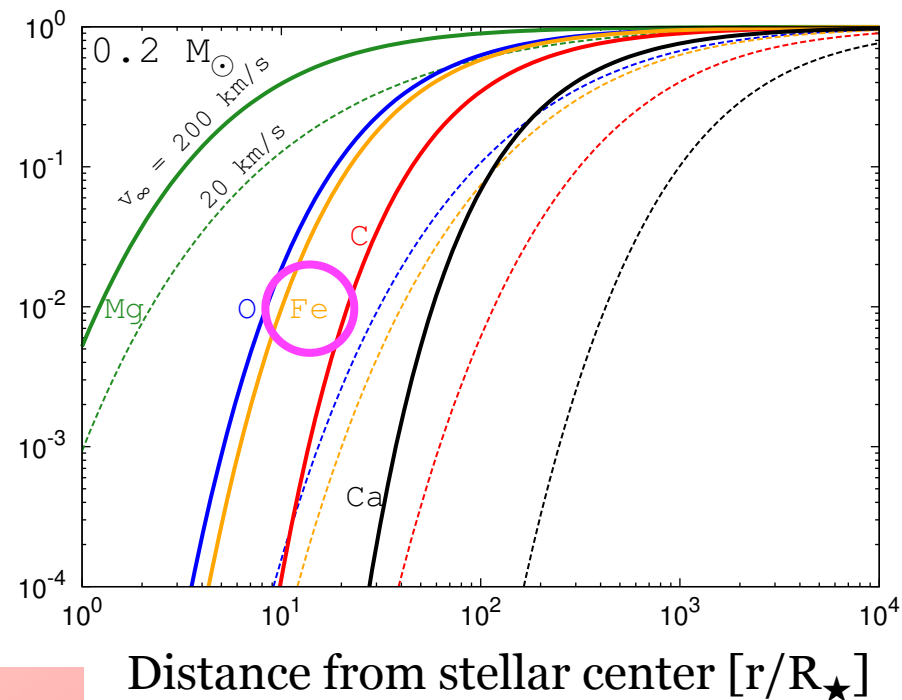
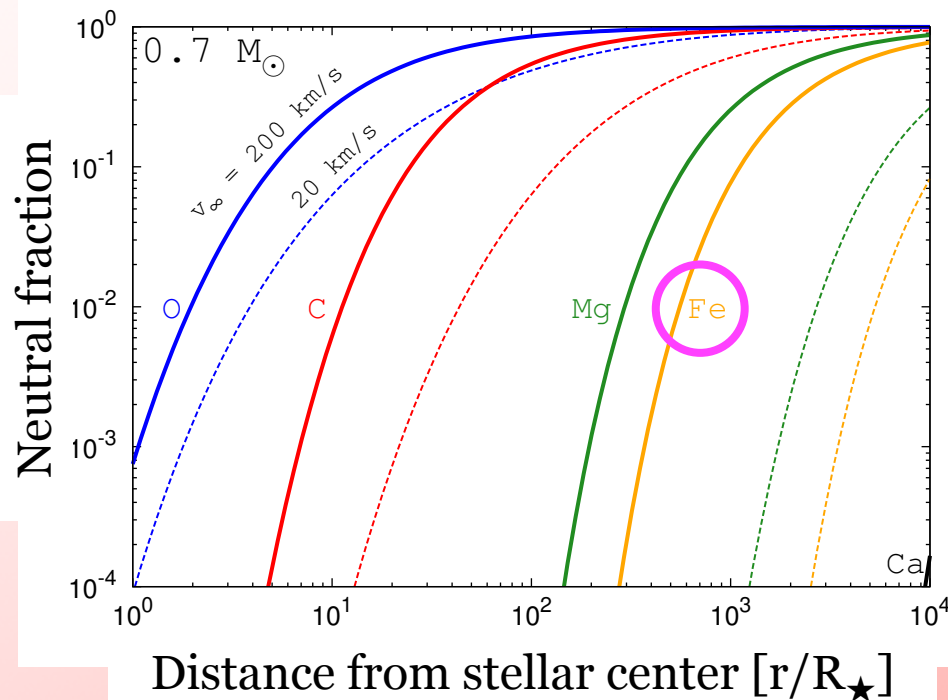
Volume fraction of $n_{\text{ISM}} > n_{\text{crit}}$ is very small even at Gal. disk.

=> **Magnetosphere is sustained!!**

Survival Probability

Neutral fraction at given radius.

$$\frac{n_i(r)}{n_{\text{ISM},i}} = \exp \left[-\frac{\sqrt{2}\beta_{\text{ph}\star,i}}{\Omega_{\text{K}\star}} \left(\sqrt{\frac{v_{\text{rel}}^2}{v_{\text{esc}\star}^2} + \frac{R_{\star}}{r}} - \frac{v_{\text{rel}}}{v_{\text{esc}\star}} \right) \right]$$



Iron hardly attains stellar surface

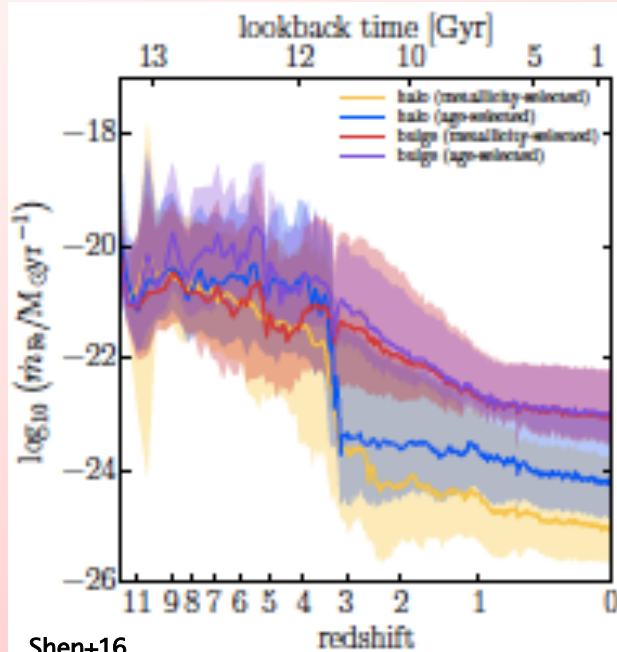
Discussion & Conclusions

Accretion from $n > n_{\text{crit}}$

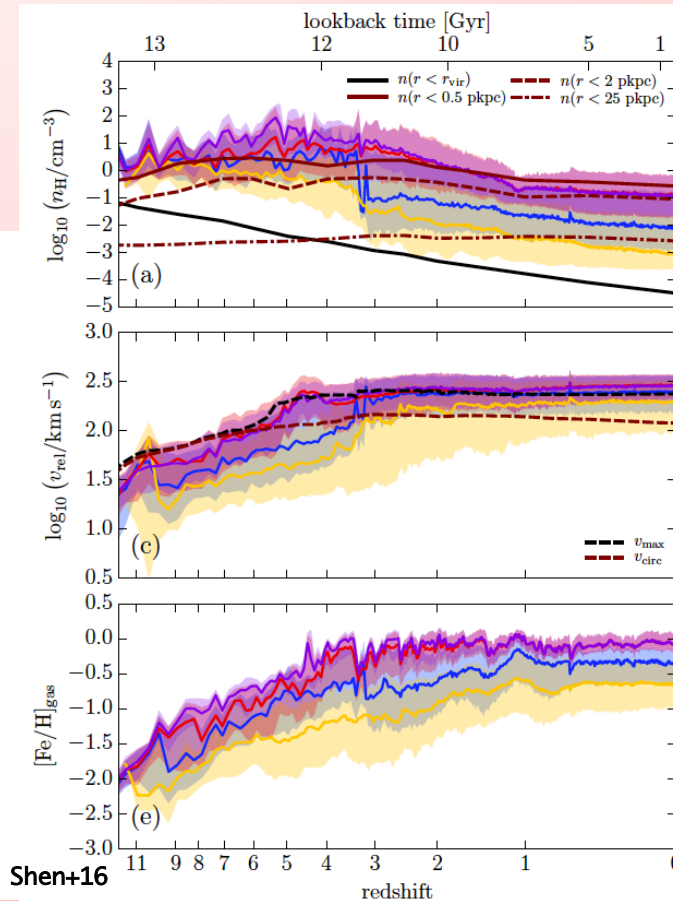
Density probability distribution $P(n, t)$ and metallicity distribution $Z(n, t)$

$$M_{Z,\text{acc}} = \int dt \int_{n_{\text{crit}}(t)}^{\infty} dn P(n, t) Z(n, t) \dot{M}_{\text{BHL}}(n, t).$$

Accretion @ high- z is dominant because $\dot{M}_{\text{BHL}} \propto (v_{\text{rel}})^{-3}$



Shen+16



Shen+16

Shen+16 set $n_{\text{crit}} = 0$, i.e., no wind and $n < 10^2 \text{ cc}^{-1}$ always! (difficult to resolve $n > 10^2 \text{ cc}^{-1}$ numerically.)

Johnson & Khochfar11 estimated that the probability of encounter of a star and a cloud at high- z is less than 0.1. $[\text{Fe}/\text{H}] \sim -6$ for one encounter.

Conclusions & Further Studies

Conclusions

- $[\text{Fe}/\text{H}]$ is reduced by photoionization ($[\text{Fe}/\text{H}] < -14$ even for extreme case).
- Currently observed metal poor stars are not low-mass PopIII stars.
- Low-mass PopIII stars will be found as metal free stars or current observations have already constrained PopIII IMF.

Further Studies

- Metal accretion in dust phase
 - Dusts may enrich low-mass PopIII stars (however, Johnson2015)
- Stellar wind from low-mass PopIII stars
 - Magnetic field and cooling function may be very different from the Sun.
- Bondi-Hoyle-Lyttleton accretion with stellar wind
 - n_{crit} given in this paper may be over-simplified because we consider 1D trajectory.