Beryllium abundances and the formation of the halo and the thick disk

Rodolfo Smiljanic[1,2]
L. Pasquini[2], P. Bonifacio[3,4,5], D. Galli[5], B. Barbuy[1],
R. Gratton[5], S. Randich[5]

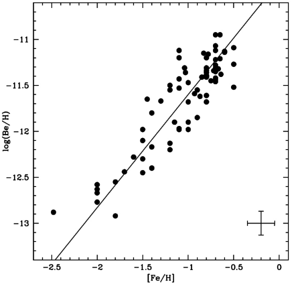
(1)University of São Paulo, (2) ESO, (3) CIFIST (4) GEPI-CNRS, (5) INAF

IAUS 268: Light Elements in the Universe, Geneva, 9 – 13 Nov. 2009

Be nucleosynthesis

- Be^9 is a pure product of cosmic-ray spallation in the ISM (Reeves et al. 1970).
- In the early-Galaxy it is a primary element.
- Collisions of accelerated CNO nuclei with protons and α of the ISM dominate (inverse process; Duncan et al. 1992).

- A linear relation between Be and Z with slope ~ 1.0 (Gilmore et al. 1992, Molaro et al. 1997, Boesgaard et al. 1999, Smiljanic et al. 2009).



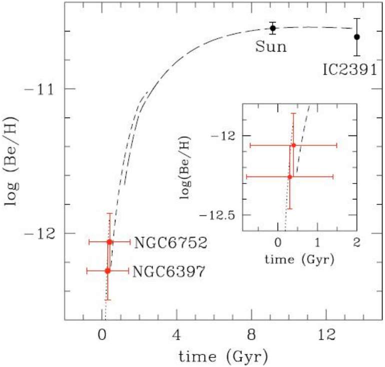
Be in the Galaxy

In the early Galaxy:

- If cosmic-rays are globally transported across the Galaxy, the production of Be should be a widespread process.
- Star formation is disperse and inhomogeneous, there is no efficient mixing of the gas.
- Be abundances should be more homogeneous than the abundances of nucleosynthetic products of SNe (like Fe and O).
- Be should be a good tracer of time (Suzuki & Yoshii 2001, Beers et al. 2000).

Be in globular clusters

- Be abundances derived in turn-off stars of NGC 6397 and NGC 6752 (Pasquini et al. 2004,2007).
- Chemical evolution models of Valle et al. (2002).
- Ages in excellent agreement with ages derived using isochrones.



Be and stellar population

Pasquini et al. 2005

- *[O/Fe] as star formation rate and Be as time.*
- *20 stars analyzed by Boesgaard et al. 1999.*
- *Accretion and dissipative components (Gratton et al. 2003) seem to separate.*

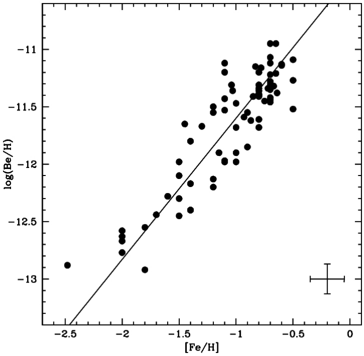
Smiljanic et al. 2009

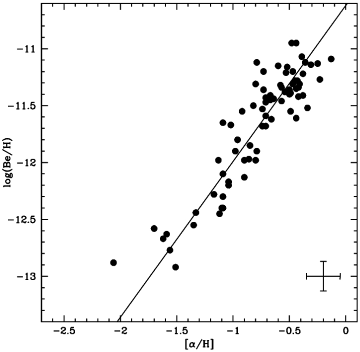
- *Be abundances for 74 (39 halo, 28 thick disk, 7 thin disk).*
- *High resolution ($>$ 40,000), high S/N, UVES/VLT spectra.*
- *Abundances of α-elements from the literature.*
- *Better understanding of the evolution of Be in the Galaxy and investigate its use as a cosmochronometer.*

Linear relations

$$\log(\mathrm{Be/H}) = (-10.37 \pm 0.08) + (1.23 \pm 0.07)\,[\mathrm{Fe/H}]$$

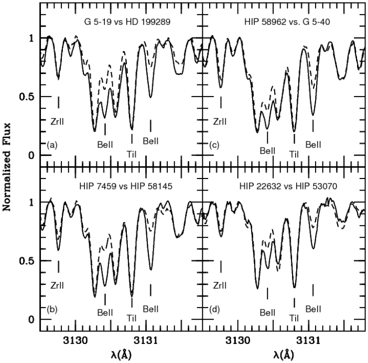
$$\log(\mathrm{Be/H}) = (-10.62 \pm 0.08) + (1.37 \pm 0.07)\,[\alpha/\mathrm{H}]$$

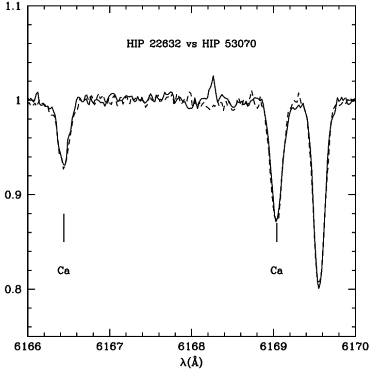




Is the scatter real?

Some stars with same atmospheric parameters and same metallicity but different Be abundances (also same $[\alpha/H]$):

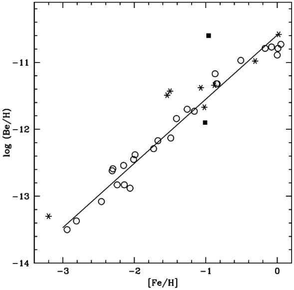




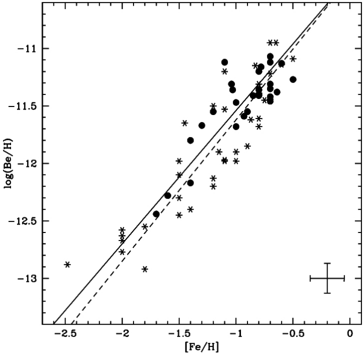
What is the origin of the scatter?

Two interpretations:

1. Local effects: proximity to SNe, or as HD106038 to a hypernova (Smiljanic et al. 2008).
2. Different stellar populations, different Fe abundances for halo and thick disk stars at a given Be (at a given *time*)



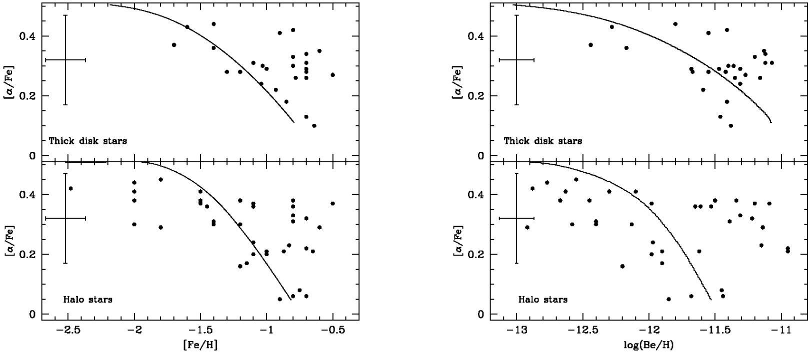
Stellar populations



- Larger scatter among halo stars
- rms = 0.26 for halo stars (starred symbols)
- rms = 0.19 for thick disk stars (filled circles)

The log(Be/H) vs. [α/Fe] diagram

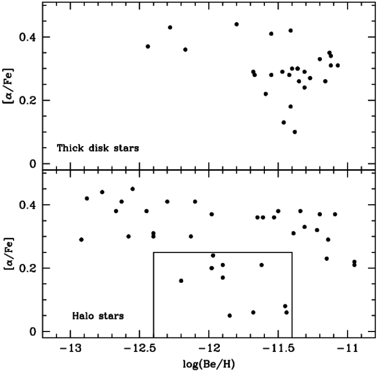
The halo splits in two components.



The log(Be/H) vs. [α/Fe] diagram

The halo splits in two components.

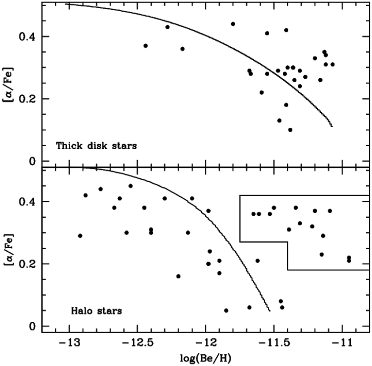
- A group of halo stars with low [α/Fe]?



The log(Be/H) vs. [α/Fe] diagram

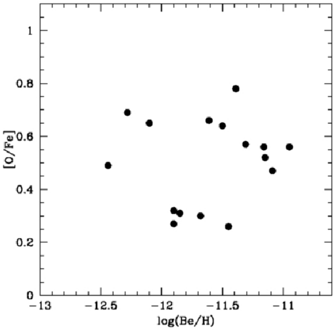
The halo splits in two components.

- A group of halo stars with low [α/Fe]?
- A group of halo stars that behaves as thick disk stars?



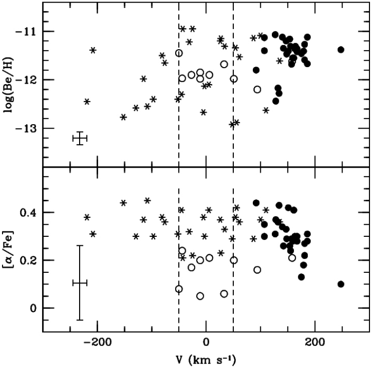
Oxygen abundances (only halo stars)

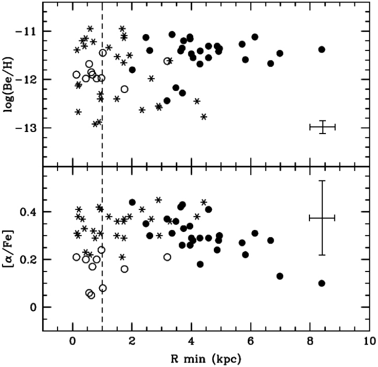
- Preliminary oxygen abundances from the OI triplet 777nm.
- NLTE corrections from Fabbian et al. (2009).
- New reduction of the UVES red spectra.



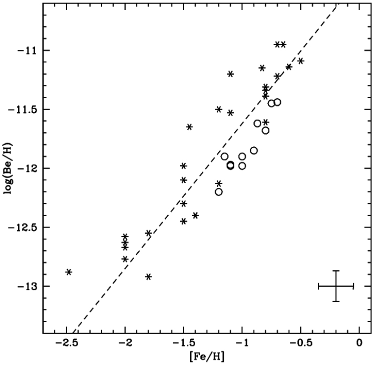
Kinematics of the halo stars

The star with low [α/Fe] have similar kinematics:
$-50\ \mathrm{km\ s^{-1}} \leq V \leq 50\ \mathrm{km\ s^{-1}}$ and $R_{\rm min} \leq 1$ kpc





Halo composed of different components



- Low α stars form a tight sub-sequence in [Fe/H] vs log(Be/H).
- A similar division of the halo using [α/Fe] and [Fe/H] (e.g. Nissen & Schuster 1997, 2009)
- Be amplifies the division: discriminates stellar populations.
- The components have a different star formation history.

The halo division in context.

- The division is likely not due to the outer halo vs. inner halo dichotomy (Carollo et al. 2007).
- Outer halo – distribution peaks at [Fe/H] ~ -2.20 and dominates beyond 15–20 Kpc.
- Inner halo – distribution peaks at [Fe/H] ~ -1.60 and dominates up to 10–15 Kpc.
- Likely most of our halo stars are inner halo (nevertheless it should be checked).

The halo division in context: a dual inner halo

From the observational point of view:

- Morrison et al. (2009): Two components in the inner halo.
- One is moderately flattened (c/a $\sim$ 0.6), no rotation, clumpy distribution in energy and angular momentum, and [Fe/H] < -1.50.
- The other is highly flattened (c/a $\sim$ 0.2), small prograde rotation, and $-1.5 <$ [Fe/H] < -1.00.
- And it is distinct from the metal-weak thick disk.
- The latter could be: (i) gas accreted from satellites before the disk formed or (ii) stars carried to the inner Galaxy by dynamical friction.
- The low-alpha stars have $-1.2 <$ [Fe/H] < -0.70.

The halo division in context: a dual inner halo

From the theoretical point of view:

Zolotov et al. 2009

- *Cosmological SPH + N-body simulations of disk galaxies in ΛCDM universe.*
- *Stars are formed both in sattelite dark matter halos and in the potential well of the galaxy.*
- *Stars from the inner galaxy are displaced to the halo.*
- *The inner halo = accreted + 'in situ' stars.*

The halo division in context: a dual inner halo

From the theoretical point of view:

Zolotov et al. 2009

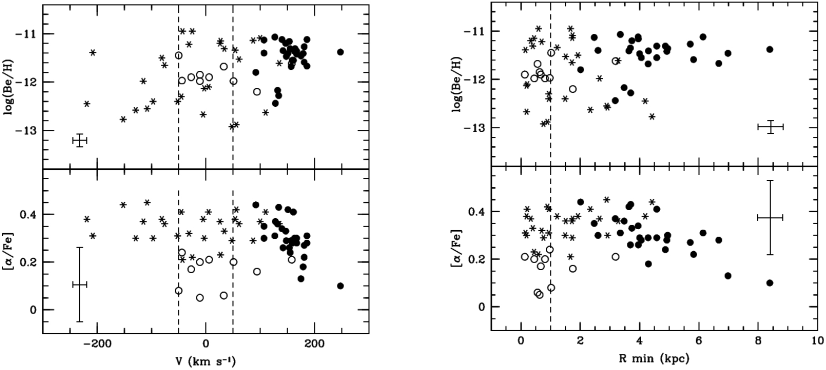
- *Cosmological SPH + N-body simulations of disk galaxies in ΛCDM universe.*
- *Stars are formed both in sattelite dark matter halos and in the potential well of the galaxy.*
- *Stars from the inner galaxy are displaced to the halo.*
- *The inner halo = accreted + 'in situ' stars.*

Purcell et al. 2009

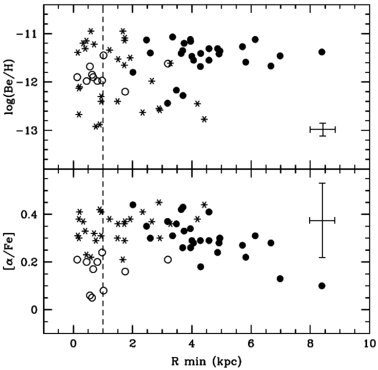
- *Disk heating in a merger with mass ratio $M_{\rm sat}$ / $M_{\rm host}$ = 1:10.*
- *The inner halo = accreted + 'heated' stars.*

Kinematics of the thick disk

A gradient of [α/Fe], but no gradient of log(Be/H) (or [Be/Fe])



Formation of the thick disk



- Be is not affected by local conditions.
- Should be a good cosmochronometer, at least for the thick disk.
- Be range is small suggesting a formation time of 1–2Gyr.
- Low Be stars (older) found only at small Rmin.
- Suggests an inside-out formation.

Summary

- In a log(Be/H) vs. [α/Fe] the halo splits into two components.
  One is predicted by the chemical models, the other one seems chemically similar to the thick disk.
- For the thick disk, no trend of Be with $R_{\rm min}$. Be is not affected by local conditions.
- An inside-out dissipative thick disk formation.
- Be may be a powerful tool to discriminate among stellar populations.

Future Work

- The whole sample with homogeneous atmospheric parameters.
- Homogeneous α and oxygen abundances.
- Statistical tests on the halo division.
- Extension of the sample to the metal weak thick disk and the outer halo.
- 3D and NLTE?
- Ages determined in an independent way?

Open questions

- What is the real magnitude of the scatter in Be vs. Fe and Be vs. α?
- What is the origin of the halo division?
- Does Be make the division clearer? Why?
- Can Be help in desantagling the various thick disk formation scenario?
- How Be behaves in the outer halo? in the inner disk? in the bulge?
- Is Be a good cosmochronometer?

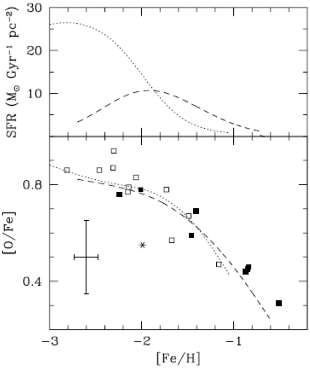
For Further Reading

Beers et al. 2000, Proc. IAUS 198, 425
Boesgaard et al. 1999, AJ, 117, 1549
Duncan et al. 1992, ApJ, 401, 584
Fabbian et al. 2009, A&A, 500, 1221
Gilmore et al. 1992, Nature, 357, 379
Gratton et al. 2003, A&A, 404, 187
Molaro et al. 1997, A&A, 319, 593
Morrison et al. 2009, ApJ, 694, 130
Nissen & Schuster 1997, A&A, 326, 751
Nissen & Schuster 2009, Proc. IAUS 254, 103
Pasquini et al. 2004, A&A, 426, 651
Pasquini et al. 2005, A&A, 436, L57
Pasquini et al. 2007, A&A, 464, 601
Purcell et al. 2009, arxiv:0910.5481
Reeves et al. 1970, Nature, 226, 727.
Smiljanic et al. 2008, MNRAS, 385, L93
Smiljanic et al. 2009, A&A, 499, 103
Suzuki & Yoshii 2001, ApJ, 549, 303
Valle et al. 2002, ApJ, 566, 252
Venn et al. 2004, AJ, 128, 1177
Zolotov et al. 2009, ApJ, 702, 1058.

This work has received financial support from FAPESP (04/13667-4 and 08/55923-8), CAPES (1521/06-3) and ESO DGDF.

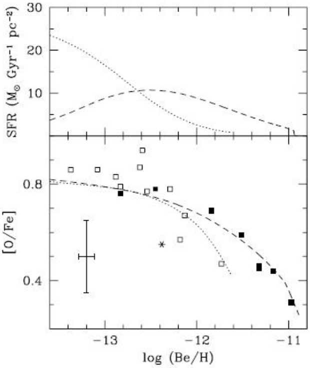
The log(Be/H) vs. [α/Fe] diagram

- Pasquini et al. (2005) extended the idea to 20 stars of Boesgaard et al. (1999)
- [O/Fe] an indicator of Star Formation Rate and log(Be/H) an indicator of time
- Models of Valle et al. (2002)
- Stars divided in dissipative (filled symbols) and accretion (open symbols) components (Gratton et al. 2003)



The log(Be/H) vs. [α/Fe] diagram

- Pasquini et al. (2005) extended the idea to 20 stars of Boesgaard et al. (1999)
- [O/Fe] an indicator of Star Formation Rate and log(Be/H) an indicator of time
- Models of Valle et al. (2002)
- Stars divided in dissipative (filled symbols) and accretion (open symbols) components (Gratton et al. 2003)



Introduction on Be

Intro on Be

- *given in the talks of e.g. D. Lambert, F. Primas, A. Boesgaard, H. Reeves, and N. Prantzos.*

(Unorthodox) Introduction on Be

Intro on Be

- *given in the talks of e.g. D. Lambert, F. Primas, A. Boesgaard, H. Reeves, and N. Prantzos.*

What has not been said yet?

(Unorthodox) Introduction on Be

Intro on Be

- *given in the talks of e.g. D. Lambert, F. Primas, A. Boesgaard, H. Reeves, and N. Prantzos.*

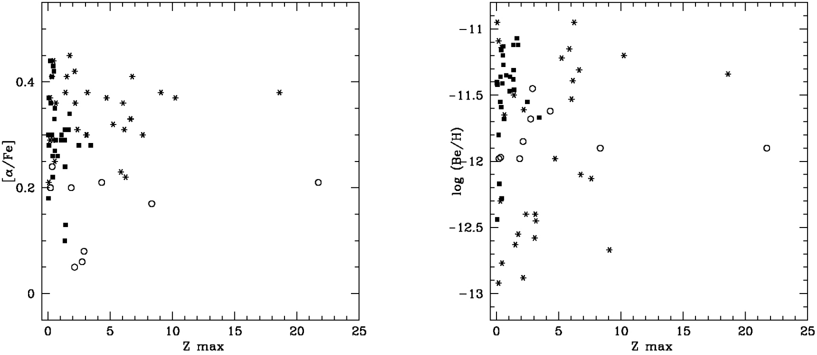
What has not been said yet?

- *Be was discovered in 1798 by french chemist Louis Nicolas Vauquelin.*
- *He noticed a white unidentified powder while working with aluminium.*
- *It was named Glucinium – glykys (sweet).*

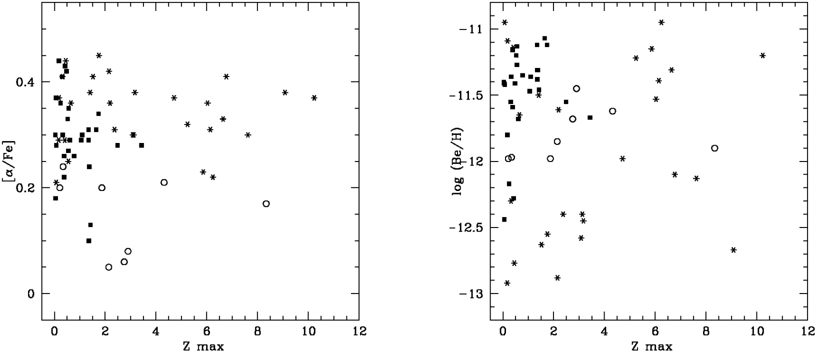
Our analysis (Smiljanic et al. 2009)

- Be abundances for 74 (39 halo, 28 thick disk, 7 thin disk)
- High resolution ($>$ 40,000), high S/N, UVES/VLT spectra
- Using spectrum synthesis
- $-2.00 < [\text{Fe/H}] < -0.50$
- Kinematics from Venn et al. (2004), Gratton et al. (2003)
- Abundances of α-elements from the literature
- Better understanding of the evolution of Be in the Galaxy
- Investigate its role as a cosmochronometer and as a discriminator of different stellar populations in the Galaxy

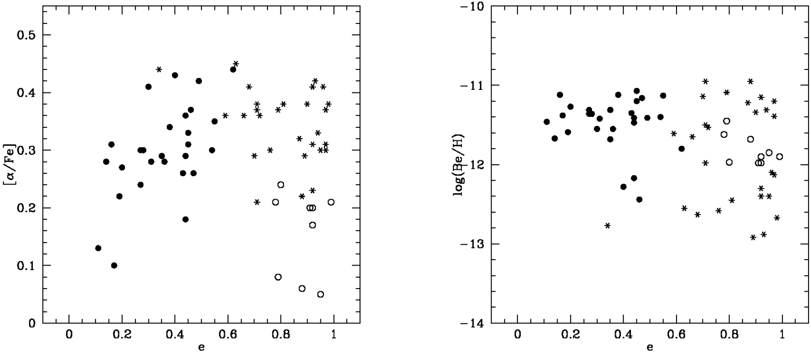
Kinematics of the halo stars – Zmax



Kinematics of the halo stars – Zmax



Kinematics of the halo stars – eccentricity



Uses of Be

- It is not found in nature in a pure form.
- Minerals: Bertrandite ($Be_4Si_2O_7(OH)_2$), Beryl ($Al_2Be_3Si_6O_{18}$), Chrysoberyl (Al_2BeO_4), and Phenakite (Be_2SiO_4).

Uses of Be

- It is not found in nature in a pure form.
- Minerals: Bertrandite ($Be_4Si_2O_7(OH)_2$), Beryl ($Al_2Be_3Si_6O_{18}$), Chrysoberyl (Al_2BeO_4), and Phenakite (Be_2SiO_4).
- Beryl + Mn^{+2} = Morganite – a pink gemstone

Uses of Be

- It is not found in nature in a pure form.
- Minerals: Bertrandite ($Be_4Si_2O_7(OH)_2$), Beryl ($Al_2Be_3Si_6O_{18}$), Chrysoberyl (Al_2BeO_4), and Phenakite (Be_2SiO_4).
- Beryl + Fe^{+2} = Aquamarine – a pale blue gemstone

Uses of Be

- It is not found in nature in a pure form.
- Minerals: Bertrandite ($Be_4Si_2O_7(OH)_2$), Beryl ($Al_2Be_3Si_6O_{18}$), Chrysoberyl (Al_2BeO_4), and Phenakite (Be_2SiO_4).
- Beryl + Fe^{+2} + Fe^{+3} = Emerald – a green gemstone

Uses of Be

- It is toxic, particularly if inhaled.
- It has no documented use in plant or animal life.

Uses of Be

- It is toxic, particularly if inhaled.
- It has no documented use in plant or animal life.

Due to its light weight and stability to a wide range in temperature it is used in:

- Defense and aero-space industries.
- High-speed aircrafts, missiles, space vehicles, and satellites.

JWST mirrors are made of Beryllium

- JWST will face temperatures of 33 K.
- Be remains uniform while cooling to this temperature.