Fe and Ni atoms in cometary atmospheres

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A work in collaboration with
Jean Manfroid and Emmanuël Jehin

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Outline

- ➔ Iron and nickel in comets : a brief history
- ➔ The discovery of Fe and Ni atoms in cold cometary atmospheres
- ➔ FeI and NiI line formation and abundance measurements
- ➔ Statistics and correlations with other cometary properties
- ➔ Possible interpretations and implications

Based on

- Manfroid, Hutsemékers, Jehin, 2021, Nature 593, 372
- Hutsemékers, Manfroid, Jehin, et al., 2021, A&A 652, L1

First detection of FeI and NiI

Copeland and Lohse (1882) reported the detection of several FeI emission lines in the spectrum of the Great Comet of 1882 just after perihelion ($r_h \simeq 0.1$ au).

240 *Spectroscopic Observations of Comets* 1881–82.

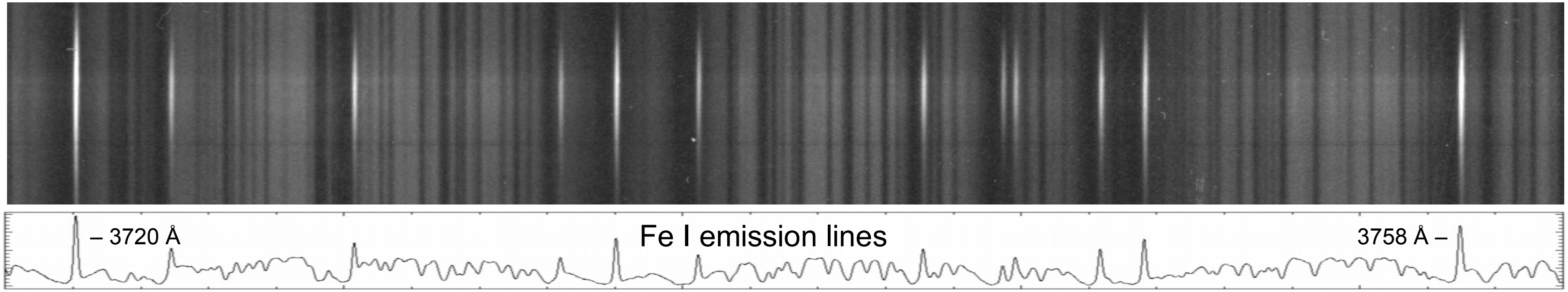
	Wave-length. mmm.	Lines in the Solar Spectrum or in the Spectrum of Iron (B). mmm.
Bright line, to the redward side of a dark line.	533·0	
Same,	533·0	532·73 Fe
Same,	532·6	
Bright E-line, to the redward side of the dark E-line,	526·9	
Same,	526·9	526·90 Fe, Ca
Same,	526·9	
Bright part } The second luminosity is a little brighter; there	520·7	
Bright part } is a black line between them.	520·3	
A brightness to redward side of a dark line, between b_1 and b_2,	517·6	Great band of the comet.
Soft band,	511·5	
Bright band (with open slit),	510·5	
End of continuous spectrum,	457·5	

The ***visual*** observations of this sungrazing comet ($q \simeq 0.01$ au) were done during daytime with the 15-inch refractor at Lord Crawford's observatory in Dunecht (UK).

The identification of the lines was later challenged (e.g., Greenstein & Arpigny 1962).

Almost a century later : Ikeya-Seki

Comet C/1965 S1 (Ikeya-Seki) also approached the Sun at a perihelion distance q ≃ 0.01 au and was targeted at various observatories.



Spectrum obtained with the KPNO MacMath Solar telescope (Slaughter 1969)

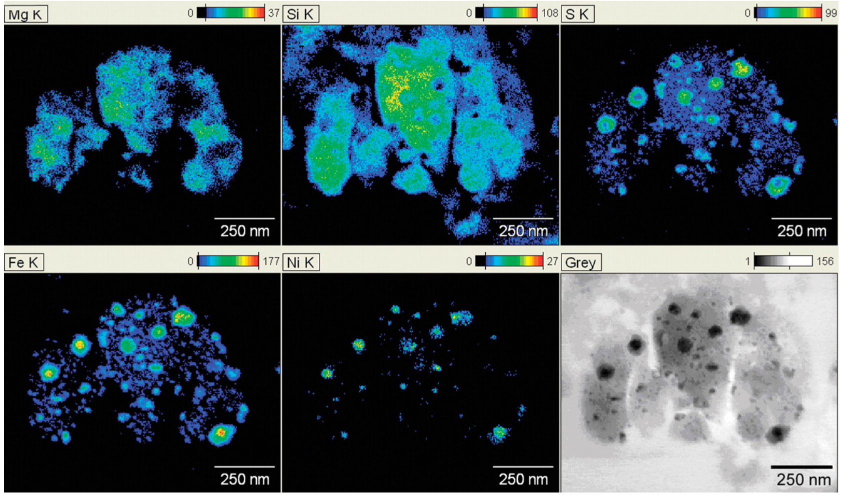
FeI lines were observed pre-perihelion at heliocentric distances r_h = 0.09 to 0.05 au, while lines of all iron-group elements (Fe,Ni,Cr,Mn,Co) were observed post-perihelion at r_h = 0.04 to 0.14 au. About 80 FeI and NiI emission lines were identified in the ultraviolet spectrum (Dufay+ 1965, Thackeray+ 1966, Preston 1967, Slaughter 1969).

The NiI/FeI abundance ratio in the coma was found to be comparable to that of chondrites and the solar photosphere (Preston 1967, Arpigny 1978).

In-situ experiments and sample return

→ Iron and nickel were found in the dust of comets 1P/Halley and 67P/C-G by in situ experiments on board the Giotto and Rosetta spacecrafts (Jessberger+ 1988, Stenzel+ 2017).

→ They were also found in the dust particles from comet 81P/Wild2 collected by the Stardust space probe (e.g., Zolensky+ 2006, Keller+ 2006, Gainsforth+ 2019).



Fragment of a grain from comet 81P/Wild2 collected by the Stardust space probe. Nanophase FeNi metal and sulfide inclusions are seen within the amorphous silicate matrix (from Keller+ 2006).

Iron and nickel essentially appear in silicates, sulfides and metal dust grains

The average Ni/Fe abundance in dust is consistent with CI meteorite and solar photosphere composition (Jessberger+ 1988, Flynn+ 2006).

Dust sublimation in comets

The equilibrium blackbody temperature at the cometary surface is

$$T\ (K) \sim 280\ r_h^{-1/2}$$

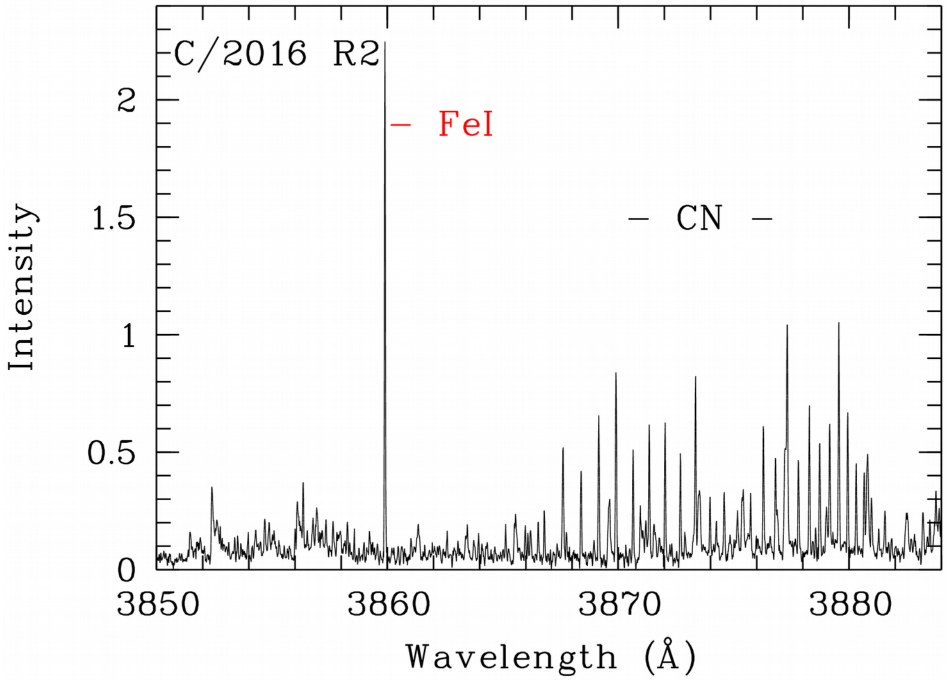
assuming low albedo and r_h in au.

At small heliocentric distances ($r_h \lesssim 0.1$ au), sulfides ($T_{sub} \sim 600K$) and silicates ($T_{sub} \sim 1200$ K) can sublimate and release metal atoms.

The presence of FeI and NiI in the coma of sungrazing comets was thus explained by the vaporization of refractory dust grains.

Free iron and nickel atoms were unexpected in more distant, colder, comets.

Discovery of FeI in a comet at 2.8 au

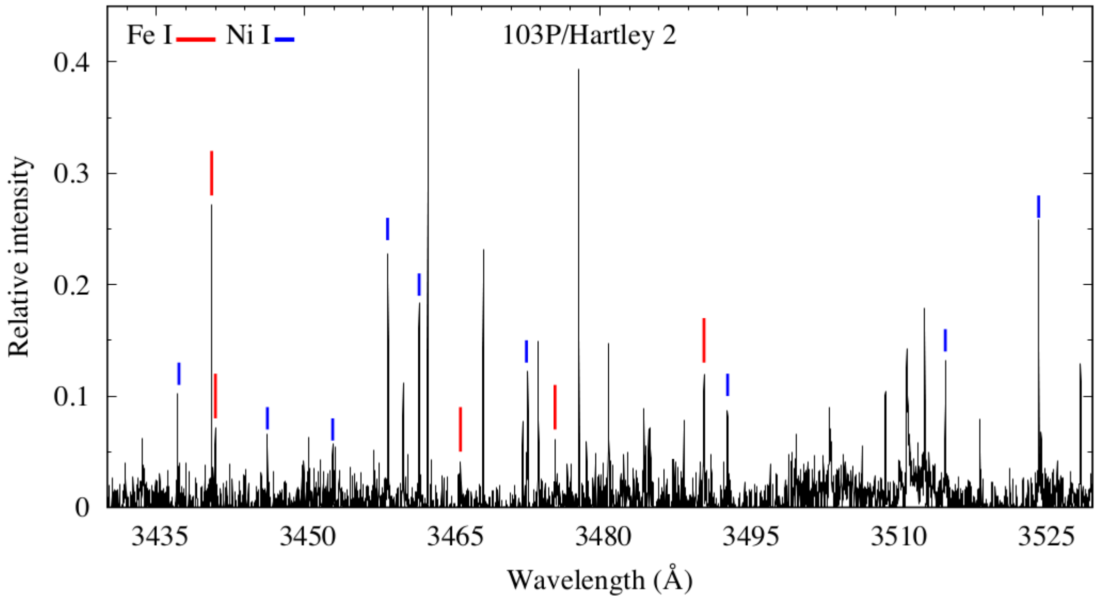


First identification of FeI λ3860
by Jean Manfroid (11/10/2018)

Thanks to the very faint CN
in the unusual comet C/2016 R2

Spectrum obtained with the ESO VLT high-resolution (R ~ 80000) spectrograph UVES
(Opitom+ 2019)

FeI and NiI lines are ubiquitous



Initially overlooked, *FeI and NiI lines were found in the good S/N spectra of all (19) comets* observed with UVES during the last 20 years (r_h = 0.68 to 3.25 au).

The lines are essentially detected in the 3000-4000 Å spectral range. Except sodium, *no other metal line was found*, in particular chromium.

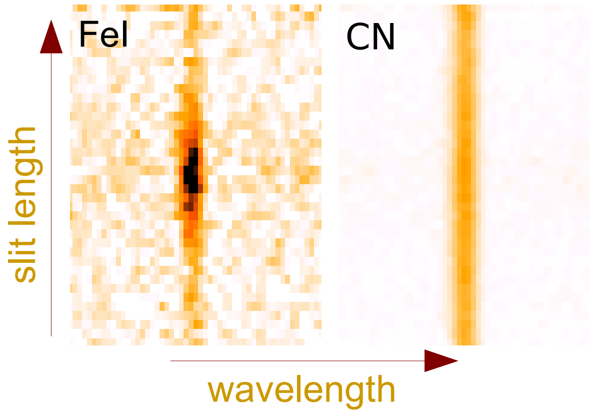
NiI lines were independently found in comet 2I/Borisov (Guzik & Drahus 2021).

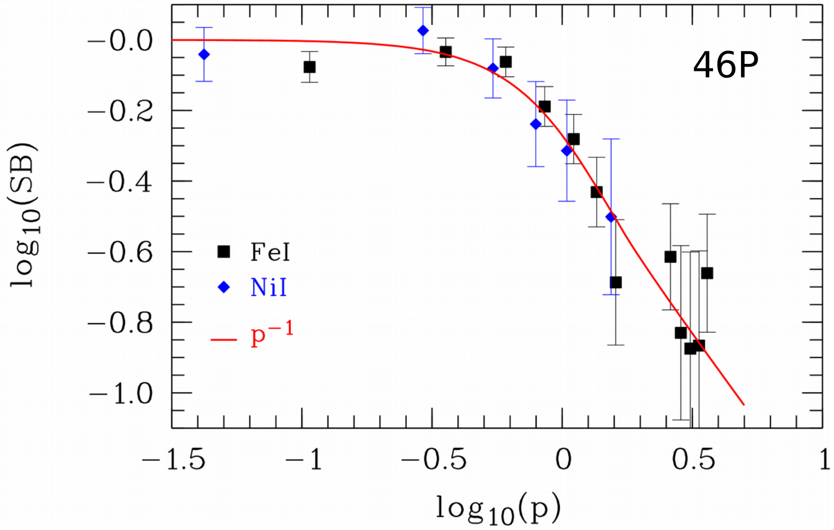
First big question :

How can iron and nickel atoms be released in cold cometary atmospheres? Why only iron and nickel ?

FeI and NiI originate close to the nucleus

The spatial extent of the lines is very short as first reported by Preston (1967) for comet Ikeya-Seki.



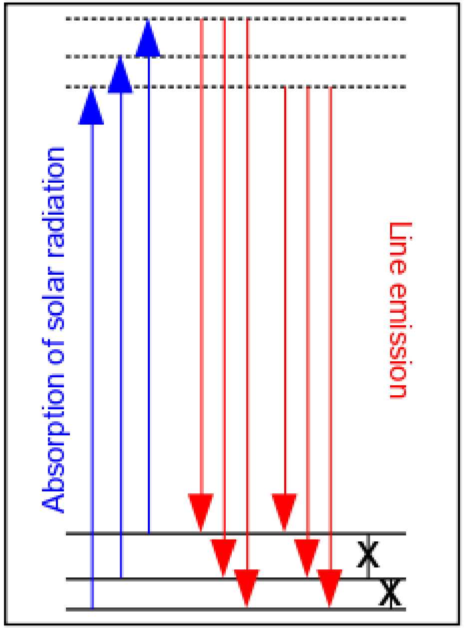


The surface brightness spatial profile can be reproduced with a blurred p^{-1} distribution. Such a profile corresponds to *ejection from the surface of the nucleus or a short-lived parent* and a constant expansion velocity.

For comet 46P/Wirtanen observed at Δ = 0.09 au, FeI and NiI atoms should originate at distances $\lesssim$ 50 km.

FeI and NiI line fluorescence

Preston (1967) and Arpigny (1978) showed that FeI and NiI emission lines in Ikeya-Seki were formed through fluorescence following absorption of the solar radiation. First analyses assumed a 3-level atom and solar blackbody radiation.



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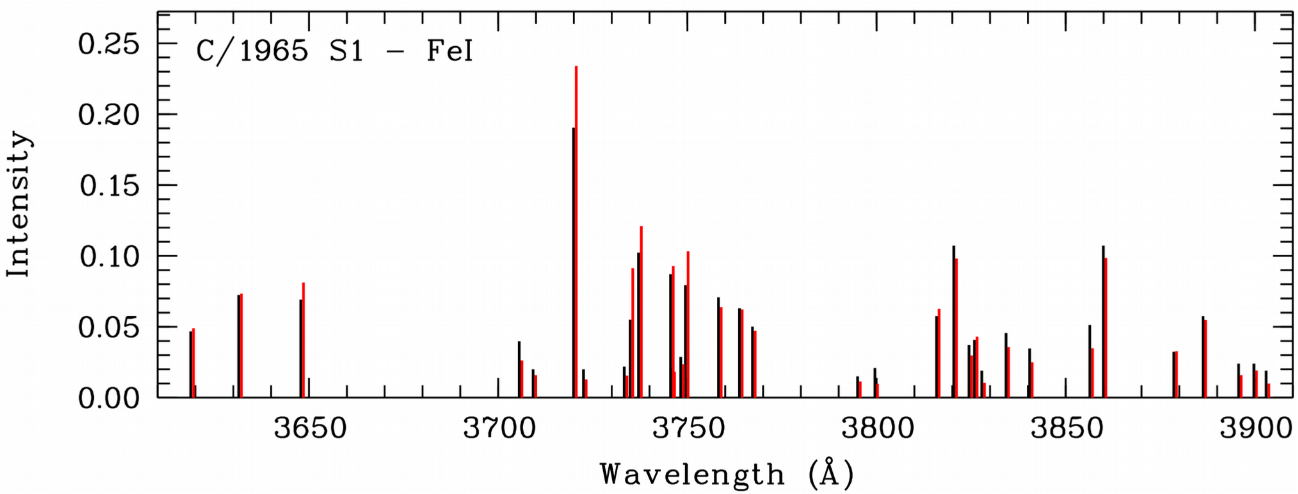
We built a multilevel fluorescence model for both FeI and NiI atoms, taking into account ~80 energy levels and ~500 transitions, as well as the high-resolution structure of the solar spectrum (to account for the Swings effect).



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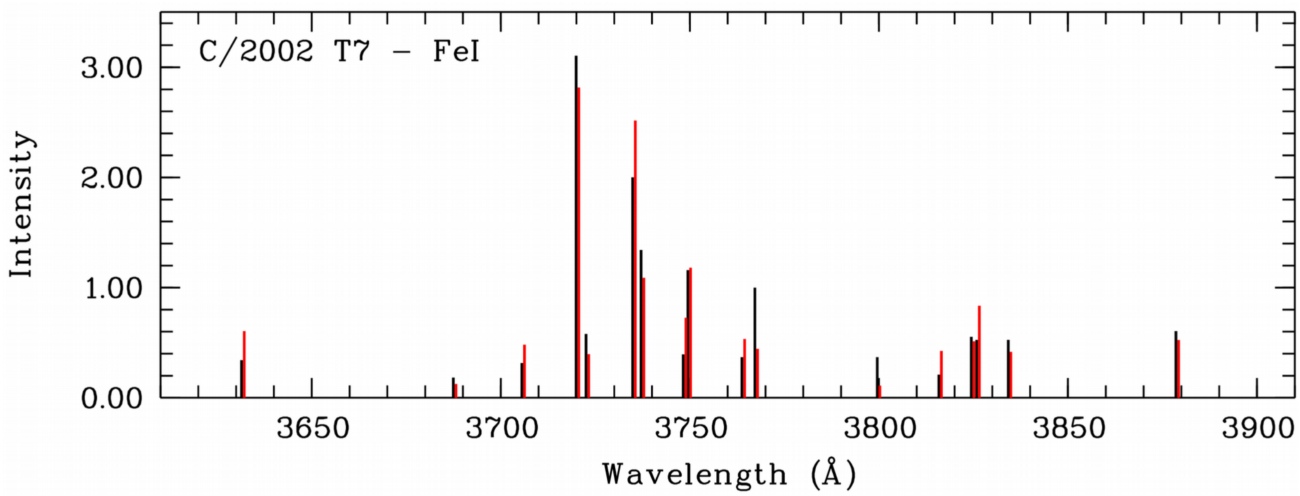


FeI and NiI line fluorescence

Overall good agreement between computed and observed line intensities.

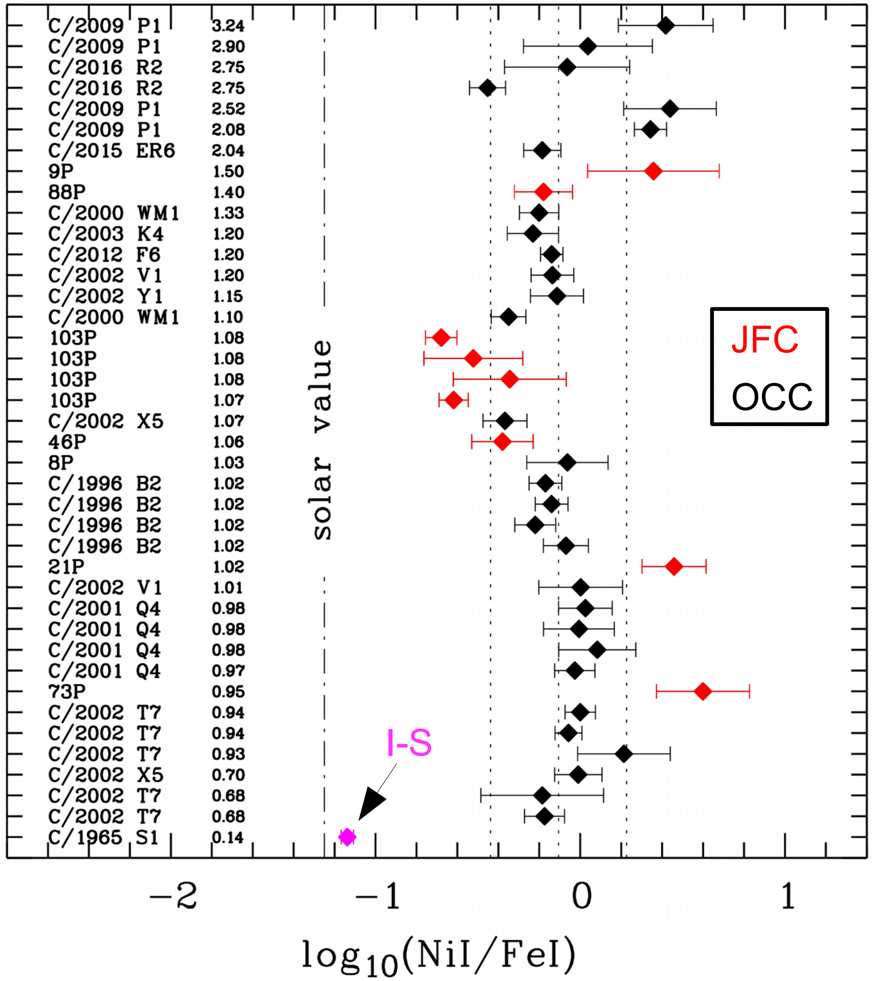
(Similar models were built by Guzig & Drahus 2021 and Bromley+ 2021, with similar conclusions.)

Comparison of observed and computed intensities provides us with column densities, and then production rates assuming isotropic expansion at constant velocity.

Measured FeI and NiI production rates are very small, Q ~ 10^{-6} Q(H_2O).

They are correlated with the production rates of other species (OH, CN, H_2O, CO) and with dust production (Afρ).

NiI / FeI abundance ratio



Mean value:

$\log(Q(NiI)/Q(FeI)) \simeq -0.1 \pm 0.3$

One order of magnitude higher than the solar value !

First big question :

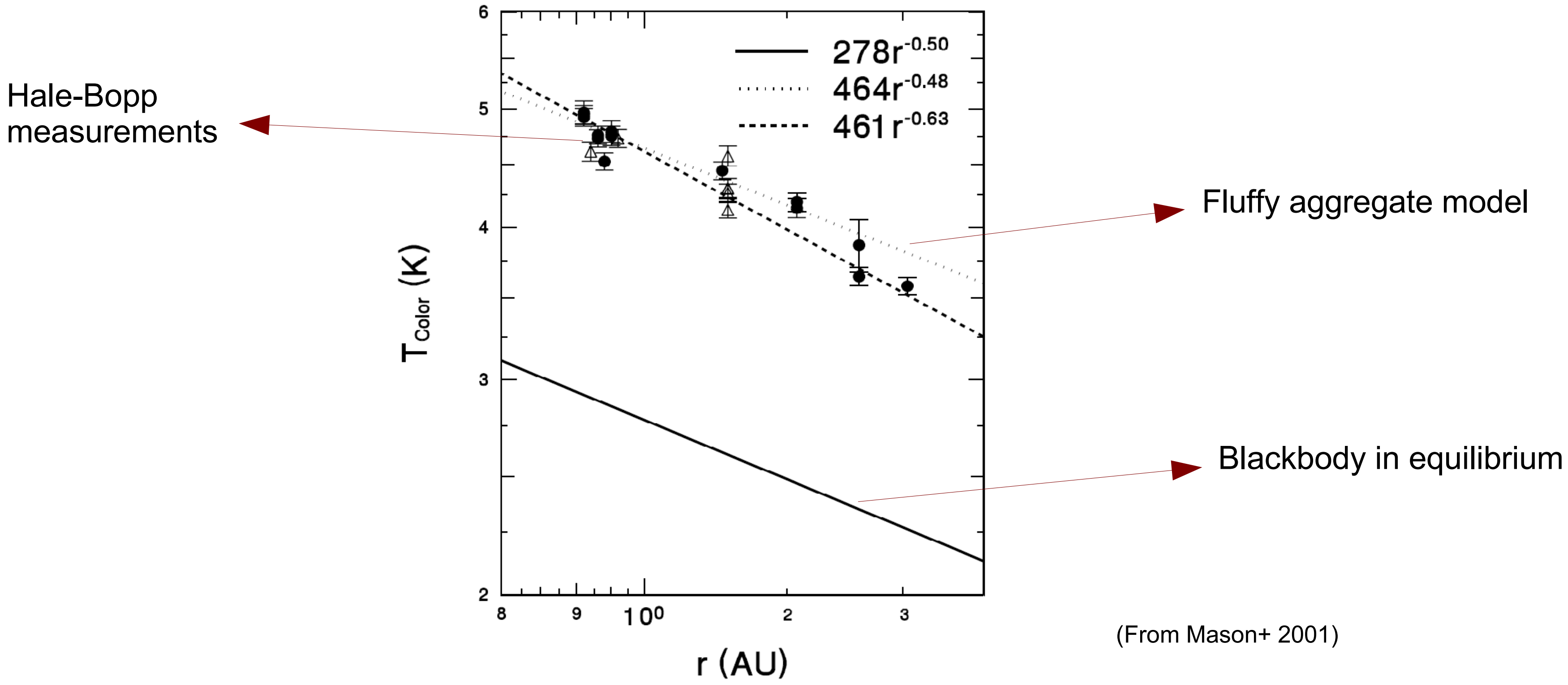
How can iron and nickel atoms be released in cold cometary atmospheres? Why only iron and nickel?

Second big question :

Why is the average NiI / FeI abundance ratio one order of magnitude higher than in the solar photosphere, chondrites, and one sungrazing comet?

Possible mechanisms of production

➔ Superheating of either nanometer-sized or sub-micron fluffy dust grains (e.g., Hensley & Draine 2017, Mason+ 2001). Ni-rich sulfides (e.g., pentlandite) could sublimate first (Lewis 2004).



(From Mason+ 2001)

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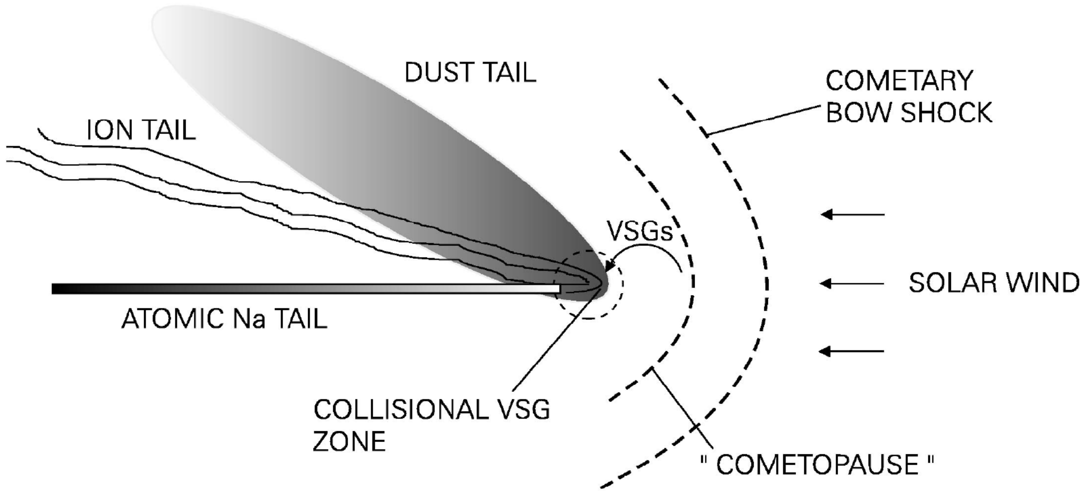

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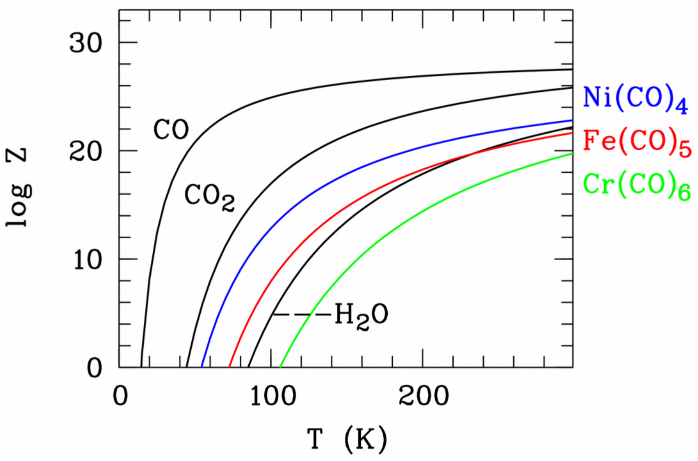
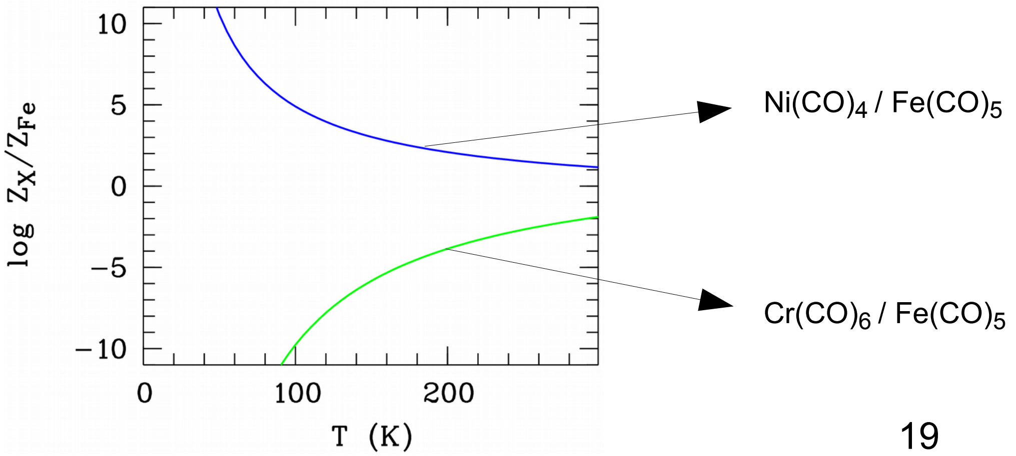
➔ Fe, Ni embedded in volatile organometallic compounds such as $Fe(PAH)^+$ or carbonyls (Klotz+1996, Huebner 1970). For carbonyls, T_{sub} ~ 100 K and $Ni(CO)_4$ sublimates faster than $Fe(CO)_5$.





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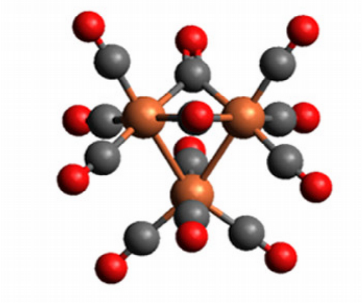
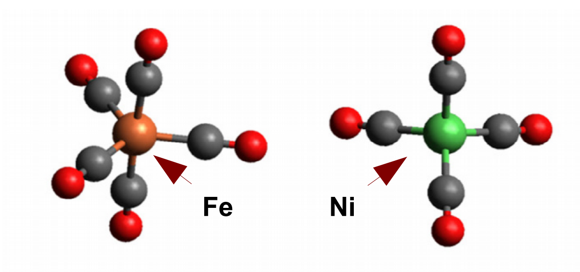
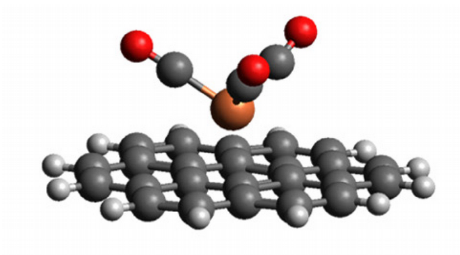
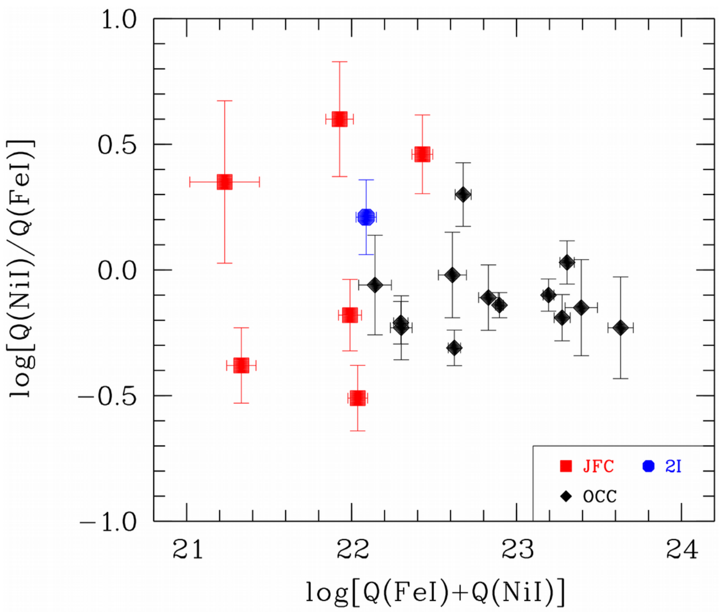


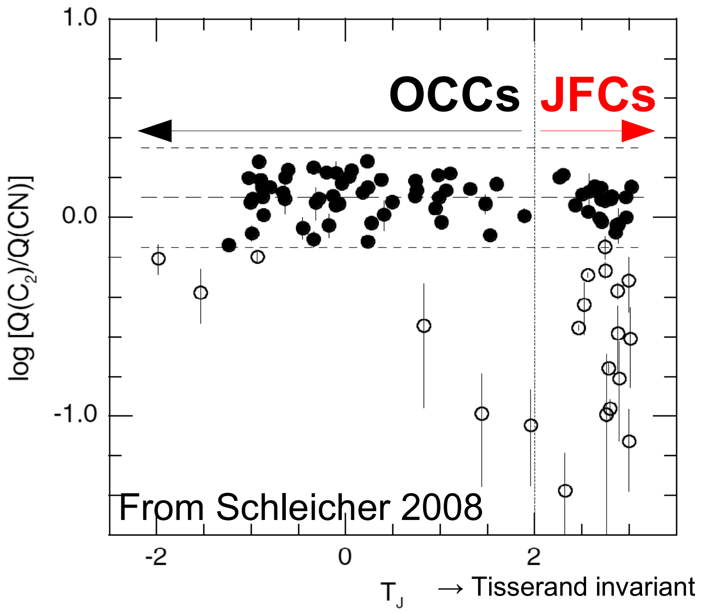




Astro-organometallics from Fiorini 2016

NiI / FeI vs other abundance ratios

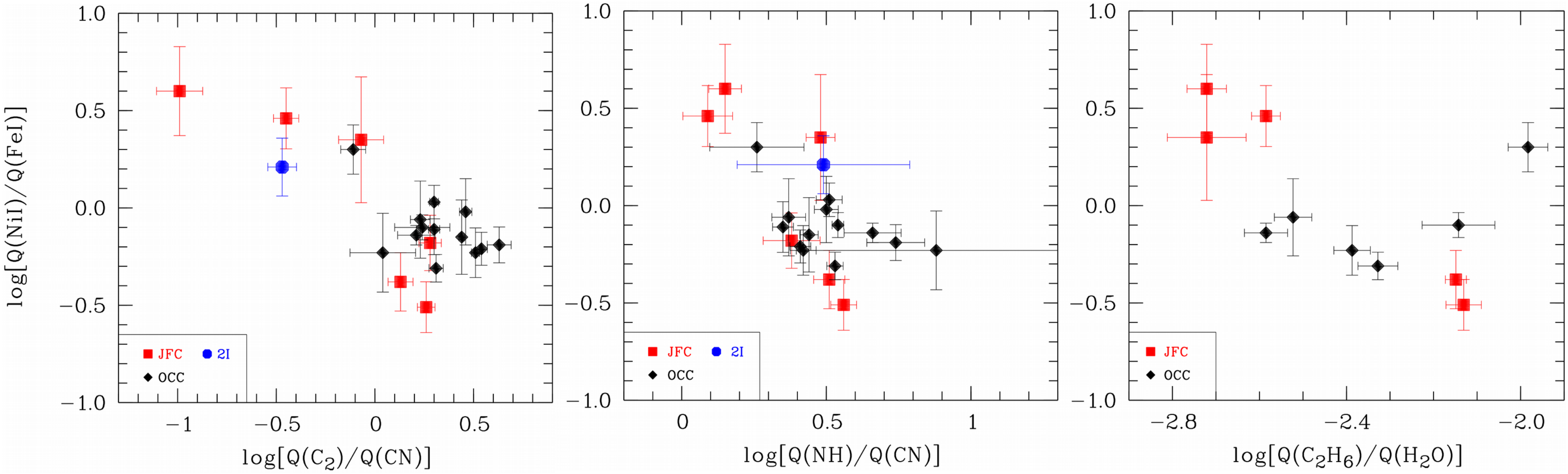




*The **dispersion** of NiI/FeI values is higher for JFCs, like the C_2/CN ratio.*

The depletion of C_2 is thought to reflect the primordial composition at the location of cometary formation rather than subsequent evolution. Depletion observed in a few OCCs and not only in JFCs suggests some mixing of the dynamical reservoirs.

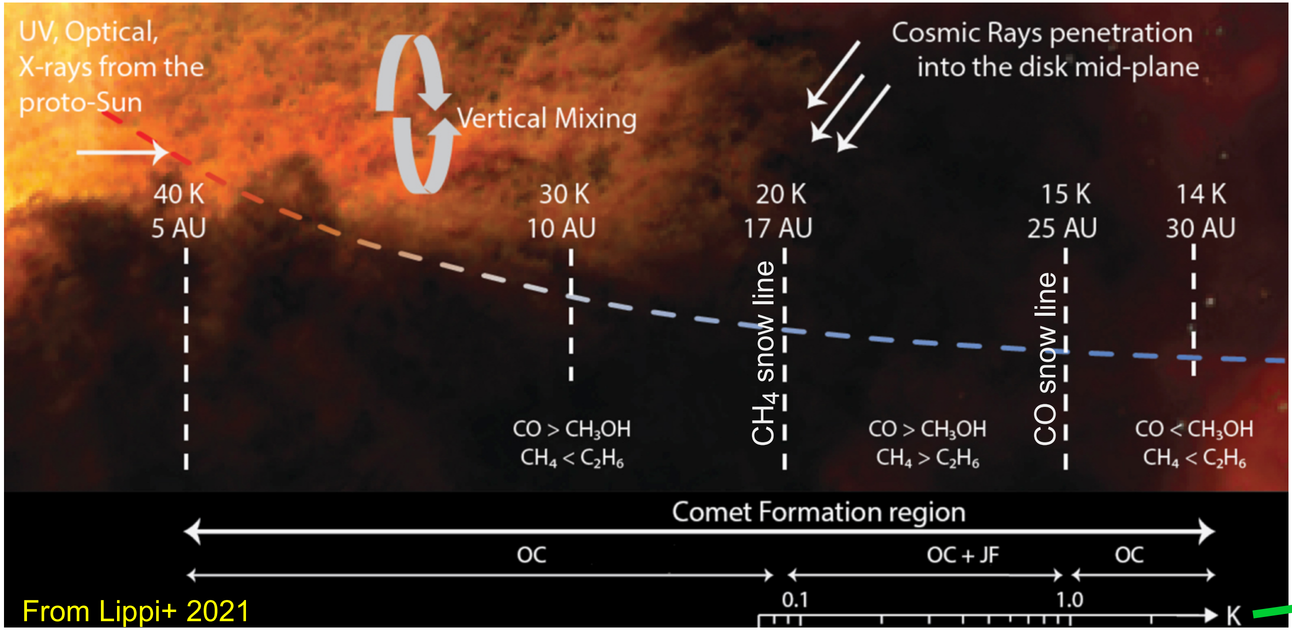
NiI / FeI vs other abundance ratios



Significant correlations of NiI/FeI with C_2/CN, NH/CN, and C_2H_6/H_2O.

As for C_2/CN, the diversity of NiI/FeI ratios could be related to primordial composition rather than to evolutionary effects.

NiI / FeI connection with protoplanetary disk ?



K = $(CH_3OH \times C_2H_6) / (CH_4 \times CO)$

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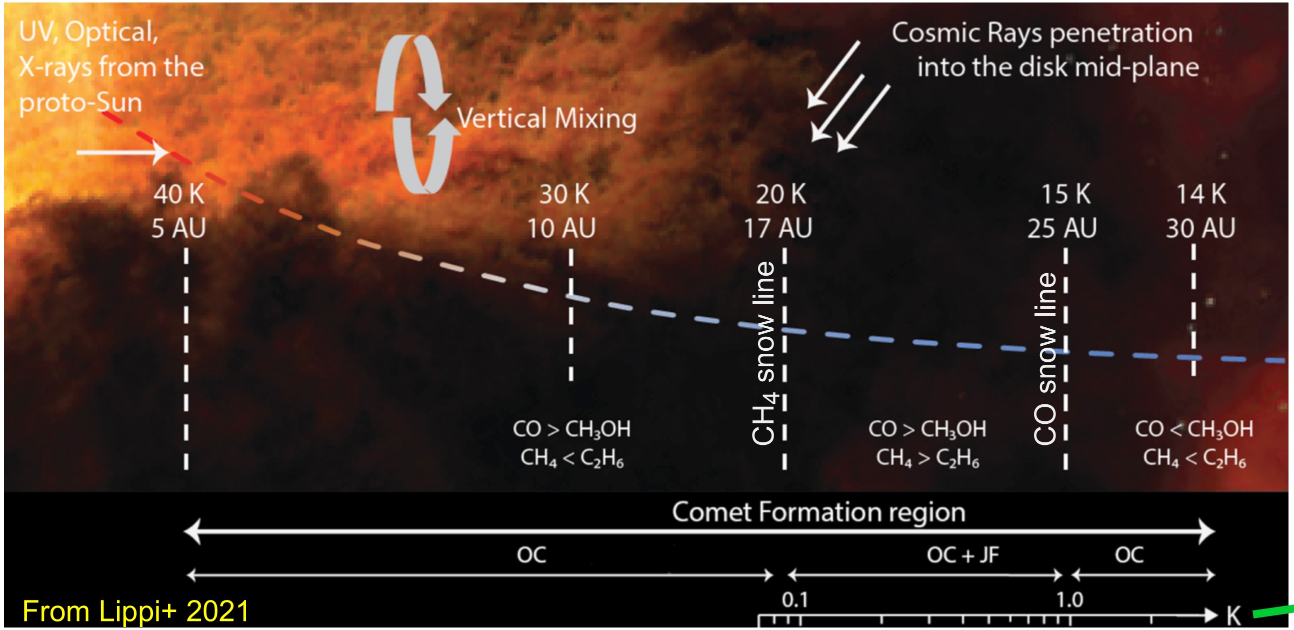

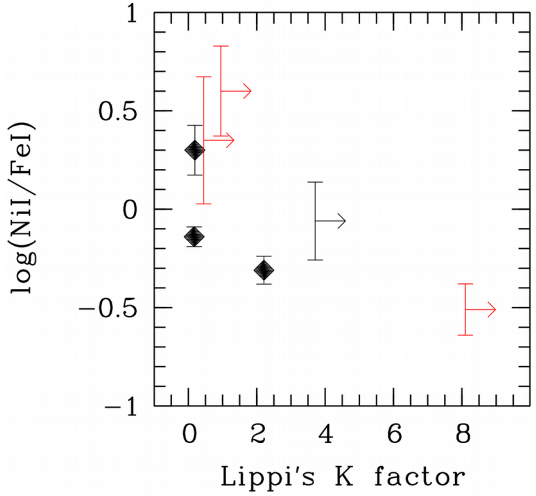

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Fe / Ni ??

In a nutshell

- ➔ FeI and NiI are ubiquitous in cometary atmospheres even far from the Sun
- ➔ Ni/Fe is one order of magnitude higher than in the solar photosphere, chrondrites and sungrazing comets
- ➔ The diversity of Ni/Fe values may be primordial
- ➔ Evidence of unknown heating mechanisms in comets?
  Or the signature of organometallic chemistry?

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Metals in comets could constitute a new important probe of comet formation and evolution