Cosmic ion induced
color changes

Rosario Brunetto
Dipartimento di Fisica, Università di Lecce, 73100 Lecce, Italy
INAF - Osservatorio Astrofisico di Catania, 95123 Catania, Italy
rosario.brunetto@le.infn.it

TNOs - Dynamical and Physical Properties
Catania, 3-7 July 2006
Outline

→ Overview - experimental approach

→ Silicates (olivine, pyroxene, etc.)

→ Ices (CH$_4$, CH$_3$OH, C$_6$H$_6$)

→ Organics (bitumens) and carbonaceous meteorites

→ Conclusions

» Are TNOs’ spectra indicative of irradiated surfaces?
» Is it possible to observe weathered silicates on TNOs?
» Do different ices produce different-colored residual refractories?
» How do color variations relate with elastic vs. inelastic energy loss?
» Is it possible to infer a TNO’s history from its color?
Overview

- TNOs and Centaurs show a great variety of spectral colors.
- These objects are exposed to bombardment by various populations of solar wind and high energy cosmic ions.

Laboratory experiments attempt to simulate weathering effects on reflectance spectra, by irradiating:

1. silicates
2. ices
3. organics
4. meteorites

Further applications:
- comets, icy satellites
- Near-Earth Objects and Main Belt Asteroids
Overview

How to extrapolate laboratory results?

The energies of cosmic-ray and solar wind particles span a larger range than that used in laboratory experiments;

⇒ laboratory results can be extrapolated to the astrophysical environment only if we understand the physical mechanism that causes the observed effect;

⇒ elastic (nuclear) vs. inelastic (electronic) energy loss

(e.g. Cooper et al., 2003, Strazzulla et al. 2003)
Experimental approach

ANALYSES:
1) UV-VIS-IR Reflectance Spectroscopy
   (0.2-2.7 µm – 2.5-20 µm)
2) UV-VIS-IR Transmittance Spectroscopy
   (0.2-20 µm)

For details, see poster: Baratta et al.

Catania Laboratory:
Ions: H^+, He^+, N^+, Ar^+, etc.
Energy: 30 - 400 keV

Several ion species and energies are required

TNOs - Dynamical and Physical Properties
Catania, 3-7 July 2006
Cosmic ion induced color changes

Rosario Brunetto

**Silicates**

Inner Solar System: space weathering processes progressively change the surfaces of minor bodies, whose reflectance spectra become redder and darker.

**Astrophysical timescale in the Inner Solar System ~ 10^4-10^6 years**

Irradiated Epinal (Ordinary Chondrite, H5)

![Graph showing bidirectional reflectance vs. wavelength with labels a, b, c, and d for different irradiation levels.](graph.png)

- Band I
- Band II
- BI slope

**EPINAL**

- a. as prepared
- After 60 keV Ar^{++}
- b. 1.3 x 10^{15}/cm^{2}
- c. 4.3 x 10^{15}/cm^{2}
- d. 17 x 10^{15}/cm^{2}


(Irradiation of HED meteorites, see poster: Brunetto, Blanco, Fulvio, Strazzulla)

TNOs - Dynamical and Physical Properties

Catania, 3-7 July 2006
Weathered silicates: observations and experiments

1. **Laboratory experiments** – Irradiation of silicates & meteorites.
2. **Main Belt asteroids** – MBAs (52).
3. **Near-Earth objects** – NEOs (31).
4. **Meteorites** (ordinary chondrite - OCs) (184).

---

![Graph showing space weathering and area ratios](image-url)

- MBAs
- NEOs
- Eifel
- Epinal
- Jackson
- Bamble
- San Carlos

---

Cosmic ion induced color changes

Rosario Brunetto

Reddening by elastic collisions

A similar effect is observed in the forsterite amorphization experiments:

Cosmic ion induced color changes

Rosario Brunetto

TNOs - Dynamical and Physical Properties

Catania, 3-7 July 2006
Cosmic ion induced color changes

Rosario Brunetto

TNOs - Dynamical and Physical Properties
Catania, 3-7 July 2006
Cosmic ion induced color changes

Rosario Brunetto

Dose required to observe reddening > 2 eV/16-amu in elastic collisions (nuclear dose).

In the TNO region (termination shock), silicates would redden with timescale of ~ $10^9$ years, if close to surface (1-10 µm).

Weathered silicates can be observed on TNOs.

[2 eV/16-amu in elastic collisions]

Spectral reddening

Logarithmic fit

What silicates on Pholus?

Preliminary results indicate that the spectrum of Pholus is compatible with the presence of irradiated olivine.

(R. Brunetto & T. Roush)

Cosmic ion induced color changes

<table>
<thead>
<tr>
<th>Material</th>
<th>Original Fit (Cruikshank et al., 1998)</th>
<th>New Fit, using irradiated olivine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivine</td>
<td>53% d=21 μm</td>
<td>75% d=22 μm</td>
</tr>
<tr>
<td>Titan Tholins</td>
<td>17% 1.6 μm</td>
<td>9% 1.3 μm</td>
</tr>
<tr>
<td>Water Ice</td>
<td>10% 9 μm</td>
<td>5% 10 μm</td>
</tr>
<tr>
<td>Methanol Ice</td>
<td>19% 3.8 μm</td>
<td>11% 4.2 μm</td>
</tr>
</tbody>
</table>

(Hapke model – intimate mixtures)

TNOs - Dynamical and Physical Properties

Catania, 3-7 July 2006
Ices

Ion irradiation of frozen hydrocarbons produces an organic residue, whose VIS-NIR spectrum is very red and dark.


**Fig. 3.** The reflectance spectrum (0.3–2.5 μm) of a laboratory produced organic residue is compared with that evaluated (from Bell et al., 1985) for the dark units on the leading hemisphere of Iapetus. The organic sample was produced by bombarding CH₄ (≈10 K) with 200 KeV Ar ions (≈10¹⁵/cm²)
Cosmic ion induced color changes

Rosario Brunetto

CH₄, CH₃OH, C₆H₆

Do different ices produce different-colored residual refractories?

Cosmic ion induced color changes

Rosario Brunetto

**CH$_4$, CH$_3$OH, C$_6$H$_6**

Spectral reddening function of the total dose


Formation of organic residue

TNOs - Dynamical and Physical Properties

Catania, 3-7 July 2006
Cosmic ion induced color changes

**CH₄, CH₃OH, C₆H₆**

Is it possible to infer a TNO’s history from its color?

Icy objects may have grown an **irradiation mantle**, produced by cosmic ion irradiation of simple hydrocarbons and/or alcohols.

---

TNOs - Dynamical and Physical Properties
Catania, 3-7 July 2006
The surface layers (1-100 μm) of bodies between 85 AU and the very local ISM accumulate 100 eV/16amu on time-scales of $10^6$-$10^9$ years.

Chiron < 10 eV/16amu
Pholus ~ 100 eV/16amu
Ixion ~ 10-50 eV/16amu
Sedna ~ 10-50 eV/16amu

Cosmic ion induced color changes

Multi-layer experiment

Irradiation of a thick ice sample (T = 16 K).

The formation of a red organic residue after ion implantation can alter the band ratio of underlying molecules.

After annealing, virgin CH₄ sublimates, but the residue remains on top. H₂O is lost after further annealing, and the residue is left over.

TNOs - Dynamical and Physical Properties
“In spectral properties and chemical structure, asphaltite and kerite appear to be reasonably good reference analogs for refractory extraterrestrial organic matter.”

“The H/C atomic ratios of asphaltite and kerite appear higher, and carbon aromaticities lower, than found in organic material from known carbonaceous chondrites. We suggest that the chemical composition and structure of asphaltite and kerite may be most similar to the less evolved organic matter of TNOs and comets.”

[Moroz et al., 2004]
Cosmic ion induced color changes

Rosario Brunetto

Irradiation of asphaltite

Reflectance spectra flatten after ion irradiation; sample temperature plays a minor role.


TNOs - Dynamical and Physical Properties

Catania, 3-7 July 2006
Irradiation of asphaltite

Loss of hydrogen, and carbonization of the target.
Asphaltite samples, which were completely soluble in chloroform, became insoluble after irradiation.

Spectral flattening due to formation of displacements (elastic collisions).

In the TNO region, spectra of bitumens would flatten with timescales of ~ $10^9$ years.
Irradiation of carbonaceous chondrites

Silicates are major components of CC meteorites. Carbon is present only as few wt percent.

We observe a reddening trend similar to OC meteorites and terrestrial silicates.

The surface of Quaoar is compatible with the presence of organics. Preliminary results using irradiated methane and asphaltite:

Hapke model – intimate mixture:

- Irradiated asphaltite: 5% 52 µm
- Irradiated CH$_4$: 17% 80-240 µm
- Crystalline H$_2$O: 78% 156 µm

(Irradiation effects on the 1.65 µm band, see poster: Brunetto, Leto, Licandro, Pinilla-Alonso, Strazzulla)

- What about tholins?
  “We emphasize that the tholins in our model are considered representative of a very broad class of complex organic solids produced by energy deposition in gases and ices having compositions of planetary relevance.” (Cruikshank et al., 2005)
Conclusions

- Cosmic ion irradiation produces:
  a. Darkening and reddening of silicate spectra (elastic dose) → about $10^9$ years
  b. Darkening and reddening of ice spectra (total dose) → $10^6-10^9$ years
  c. Flattening of bitumen spectra (elastic dose) → about $10^9$ years
  d. Darkening and reddening of CC spectra (elastic dose?) → about $10^9$ years

(Timescales at the termination shock)

→ Weathered silicates, ices, and carbons can be present on TNOs.
→ Different ices produce differently colored residual refractories.
→ Icy objects grow irradiation mantles (1-100 µm).

Cosmic ion induced color changes

→ Weathered silicates, ices, and carbons can be present on TNOs.
→ Different ices produce differently colored residual refractories.
→ Icy objects grow irradiation mantles (1-100 µm).
Further investigation

→ Optical constants of irradiated materials have to be calculated, in a wide spectral range.

→ Albedo measurements are fundamental to discriminate fresh from heavily irradiated surfaces.

→ We still need to discriminate processing effects from composition effects.