

Cometary activity in the solar system

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Outline of this talk:

- The « usual » comets
- Search for cometary activity at large heliocentric distance
- The case of 174P/Echeclus
- The Main Belt Comets (MBC) and Ceres

1. The « usual » comets

Orbital characteristics:

- **Nearly-isotropic comets:** - long-period comets ($P > 200$ years)
- Halley-type comets ($20 < P < 200$ years)
- **Ecliptic comets** (low i , low P (< 20 years)): **Jupiter family comets**

Dynamical indicator: **Tisserand parameter** (interaction with Jupiter):

$$T_J = (a_J/a) + 2 [(a/a_J)(1-e^2)]^{1/2} \cos i$$

Jupiter family comets: $2 < T_J < 3$

Long period and Halley-type comets: $T_J < 2$

(asteroids: $T_J > 3$)

→ Recently (Hsieh and Jewitt, 2006) : new class of comets, the **Main Belt Comets**

Reservoir of comets:

→ **Long period comets:** Oort cloud

→ **Ecliptic comets:** Scattered disc of the Kuiper Belt

(Halley Type comets: origin not yet well understood)

Origin of comets:

→ **Nearly-isotropic comets:** Jupiter-Uranus region →
Oort cloud → long period comet (back to the Sun) →
Halley Type comet

→ **Ecliptic comets:** intra-Neptunian region →
scattered disc

Definition of a comet...

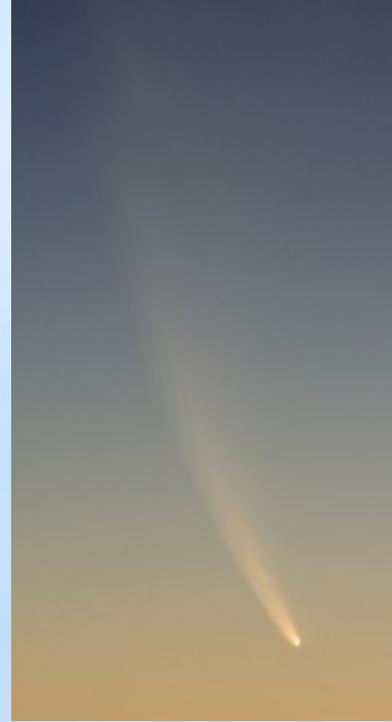
Not so obvious, because the different definitions are not mutually consistent...

Main criteria for distinguishing comets from asteroids:

→ Presence of a **coma**

→ **Composition**: substantial fraction of ice (object condensed beyond the « snow line »)

→ **Orbital characteristics** (Tisserand parameter)



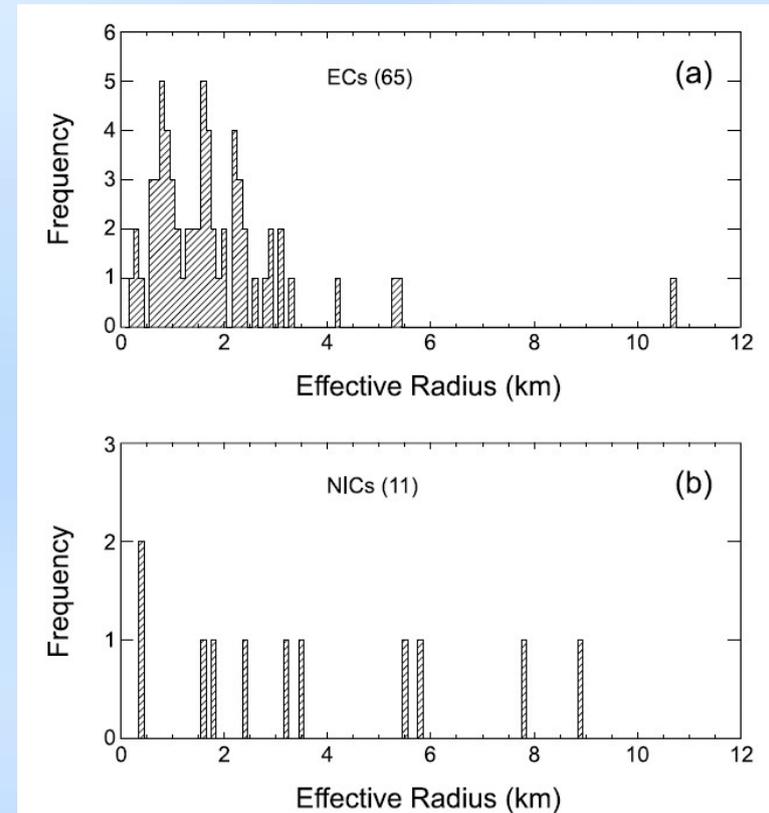
Everything comes from the nucleus...

Cometary nuclei can have very different physical characteristics (size, density, composition, color...). Main characteristics:

→ **Size**: from a few hundredths of meters up to ≈ 70 km (Hale-Bopp)

→ **Albedos**: cometary nuclei are dark. Geometric albedo varying from about 2 to 6% (except 29P/Schwassmann-Wachmann 1, with possibly $p_v = 13\%$)

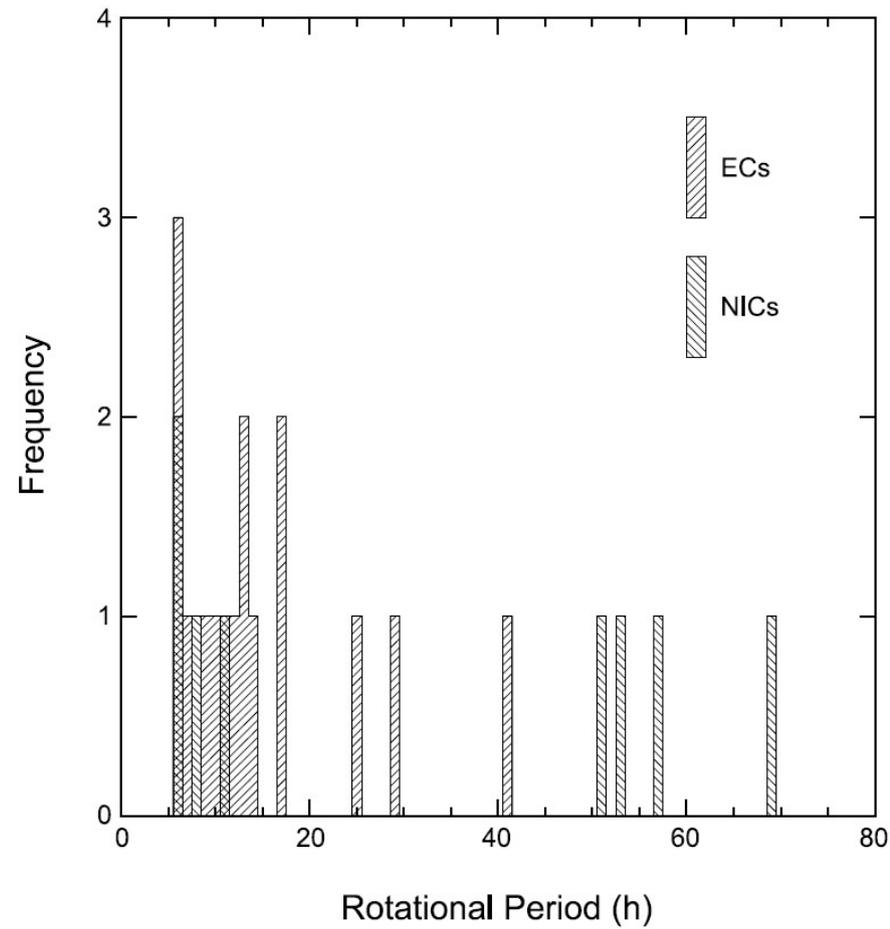
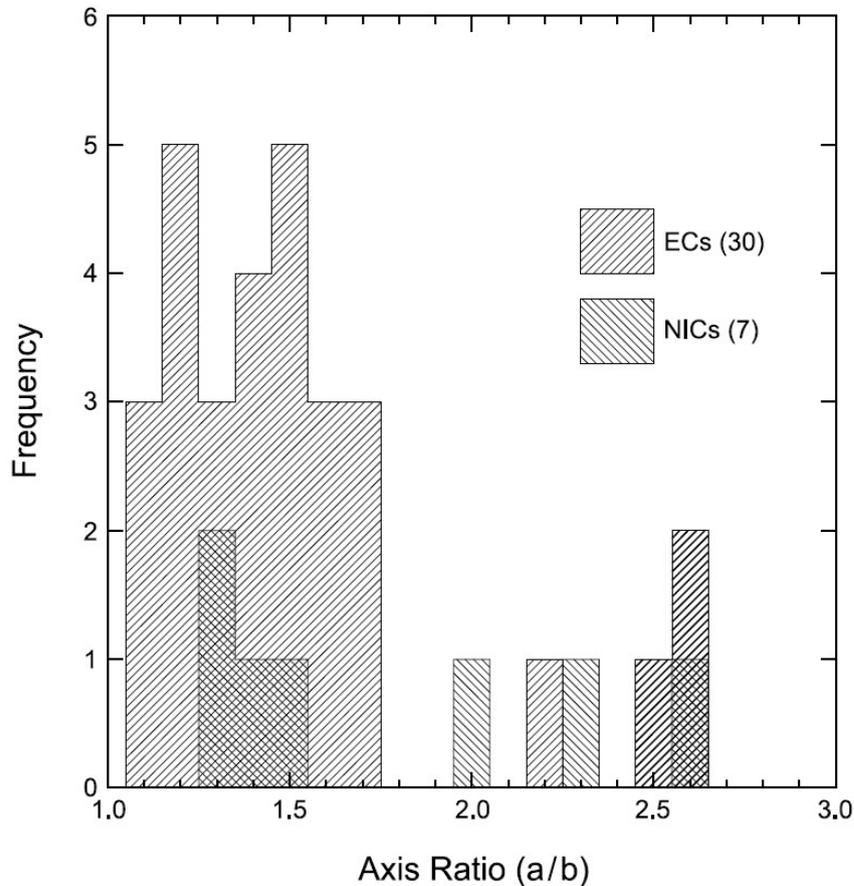
→ **Colors**: cometary nuclei are redder than the sun. $\langle V-R \rangle = 0.41$ (0.35 for the Sun). The colors are very divers.



(from Lamy et al., 2006)

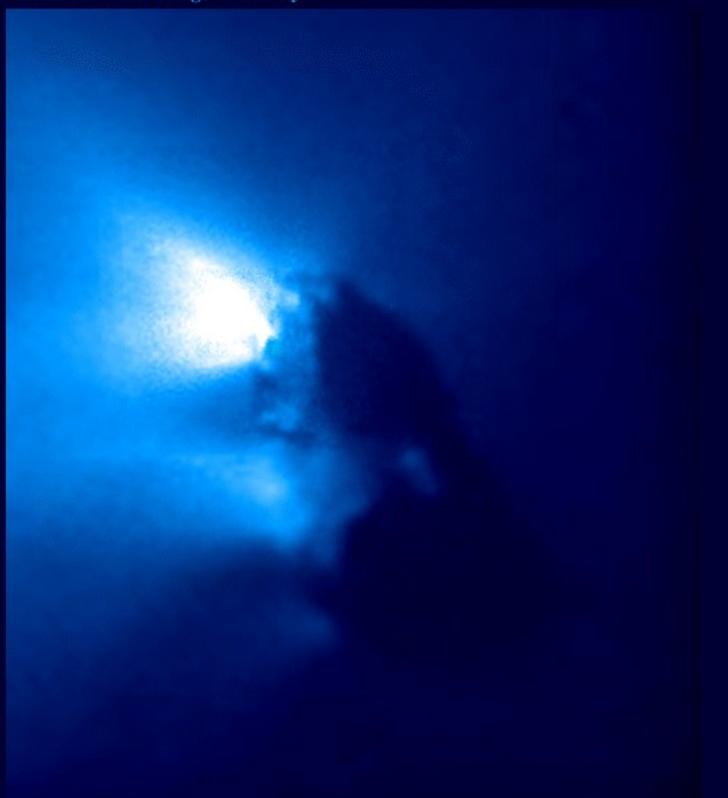
→ **Rotation periods:** from 5 to 70 hrs

→ **Axis ratio (a/b):** median value ~ 1.5 for Ecliptic Comets



(from Lamy et al., 2006)

(from Lamy et al., 2006)



→ Structure of cometary nuclei:

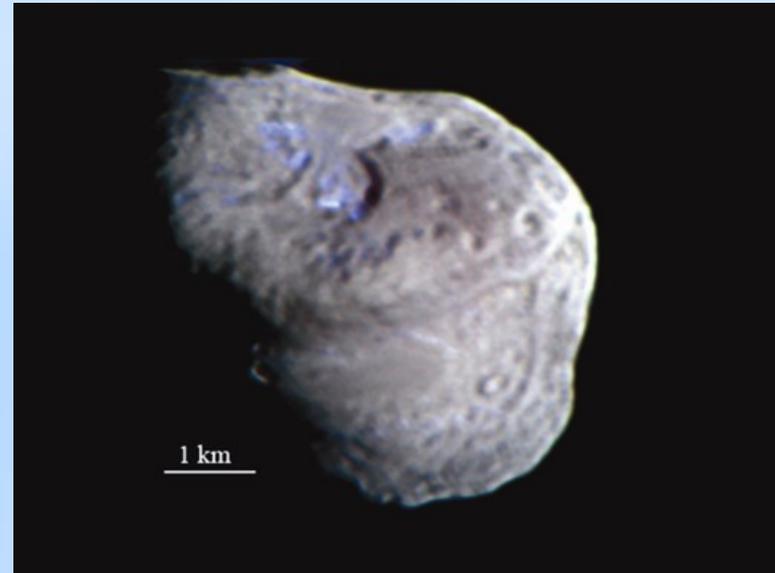
← Halley's comet
(Giotto, 1986)

Borrelly (Deep
Space 1, 2001) →



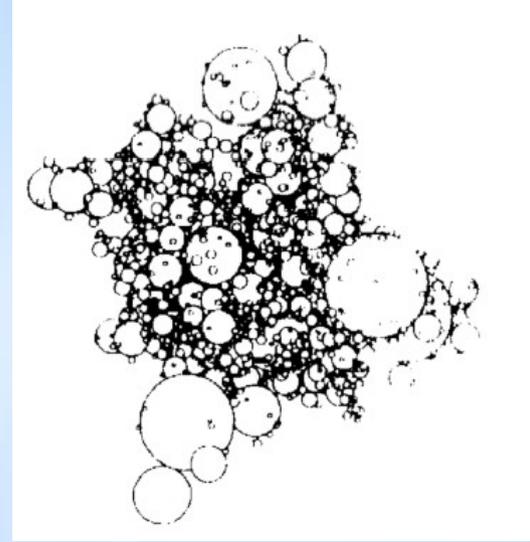
← Wild 2
(Stardust, 2004)

Tempel 1 (Deep
Impact, 2006) →

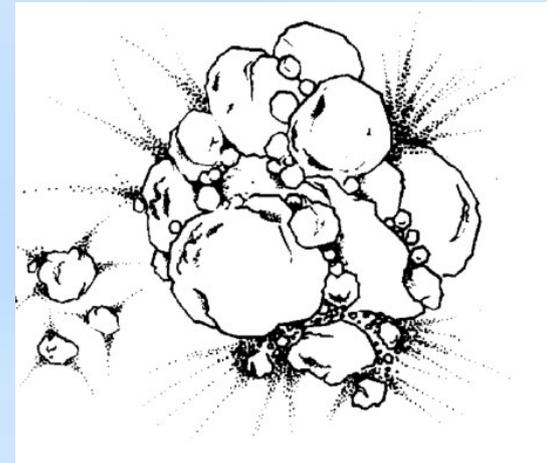


Two main models:

- **Fluffy aggregate** (Donn et al. 1985; Donn and Hugues, 1986)



- **Primordial rubble pile** (Weissman, 1986)



Both these models consider cometary nuclei as aggregates of smaller icy planetesimal brought together at low velocity in a random fashion.

Both models predict a high porosity, i.e. a low bulk density. Bulk density (estimated from non gravitational forces for the mass) $\approx 0.6 \text{ g.cm}^{-3}$ (large uncertainty).

Composition of comets:

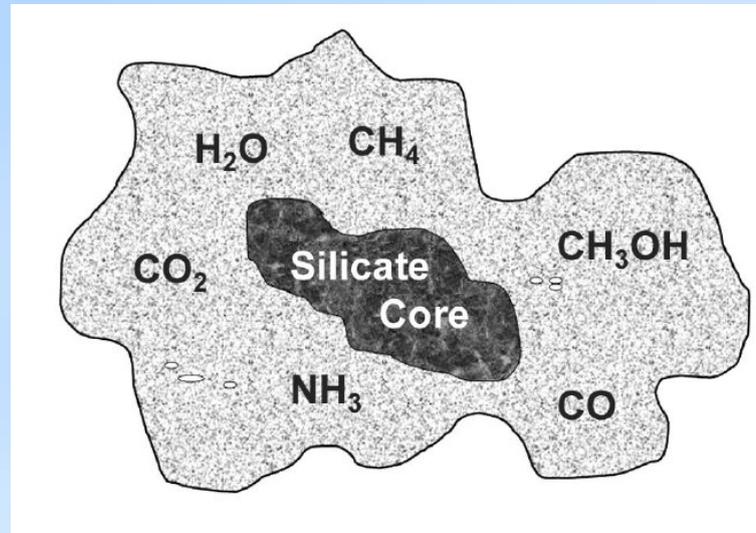
Silicates: $\approx 25\%$

Organic refractory material: $\approx 25\%$

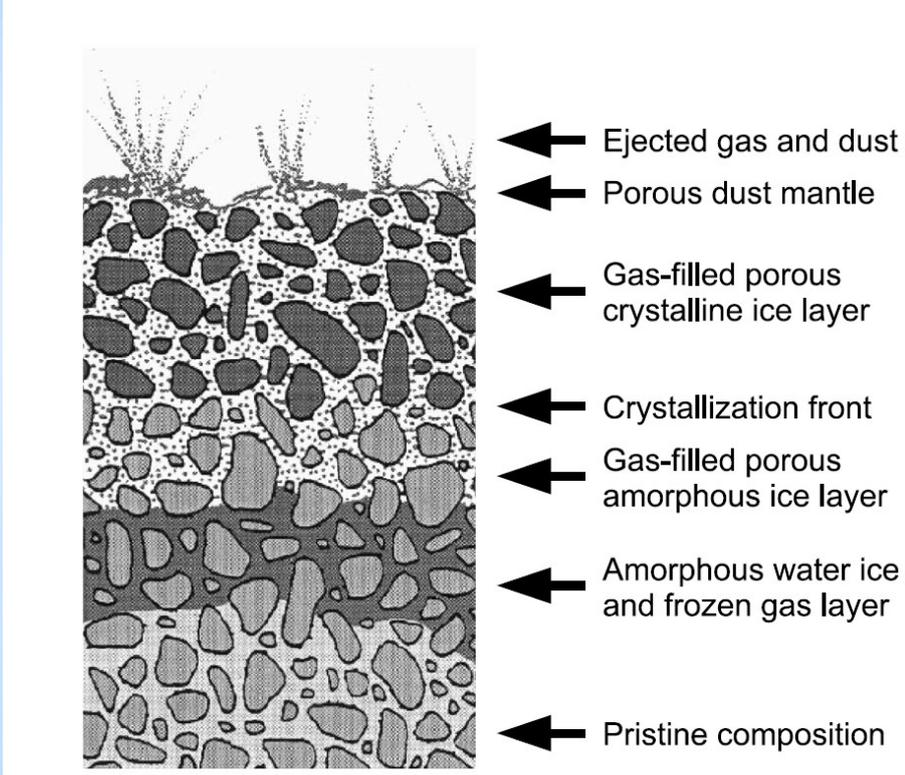
Water ice: $\approx 50\%$

+ small carbonaceous molecules (a few percents)

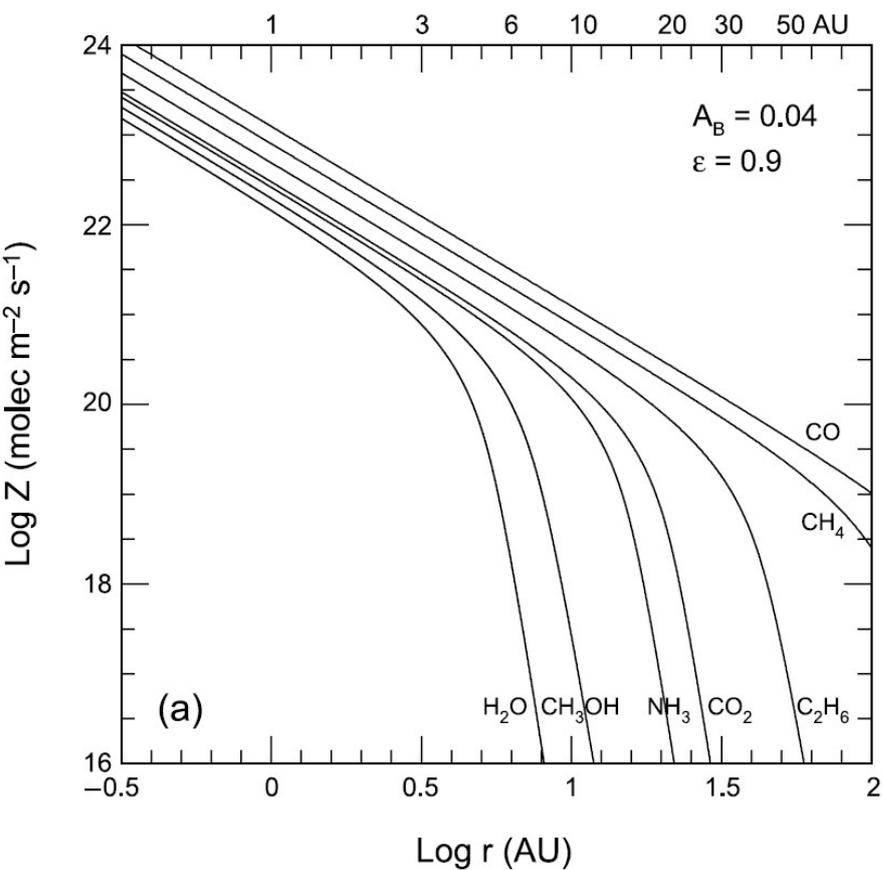
Cometary nuclei formed by interstellar grains processed during the formation of comets in the solar system (some cometary molecules such as CS_2 and C_2H_6 not identified in the molecular clouds).



Cometary activity:



Schematic layered structure of a cometary nucleus (arbitrary scales). (from Prrialnik, 1999)



How to measure cometary activity:

A'Hearn (1984) introduced the $Af\rho$ parameter to measure the cometary dust production rate.

A: bond albedo ($=4p_v$)

f: filling factor

ρ : linear radius of the field of view (FOV)

advantage: $Af\rho$ less sensitive than the dust production rate expressed in $\text{kg}\cdot\text{s}^{-1}$ to poorly known parameters (albedo, grain radius and density etc...).

$$Af\rho = (qR^2\Delta F_{\text{com}}) / \alpha$$

α : apparent diameter of the FOV (arcsec)

q: numerical constant

F_{com} : flux received from the coma

For a « typical » comet (intensity distribution proportional to r^{-1}) $Af\rho$ does not depend of the FOV. $Af\rho \approx 10^2$ to 10^5 cm

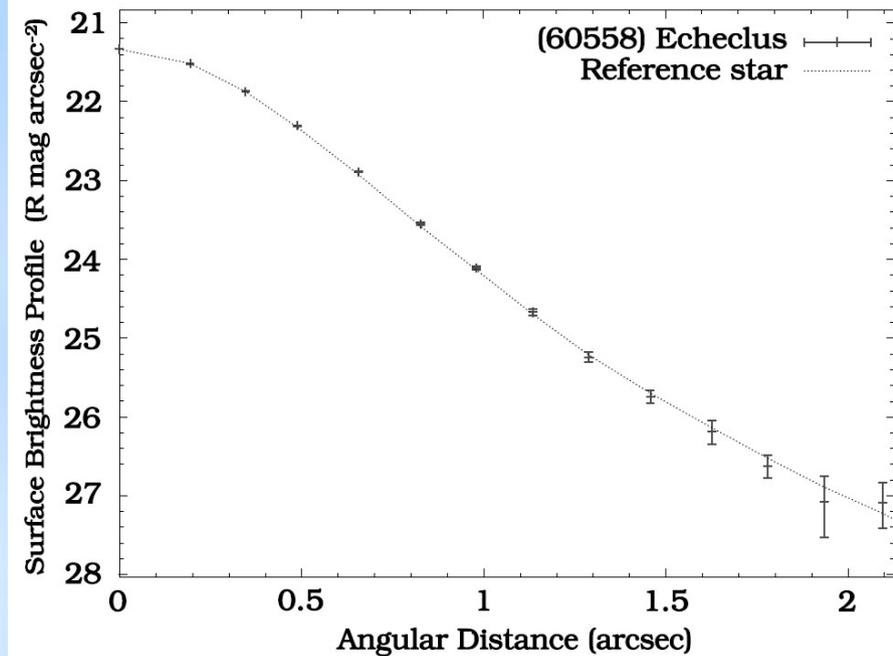
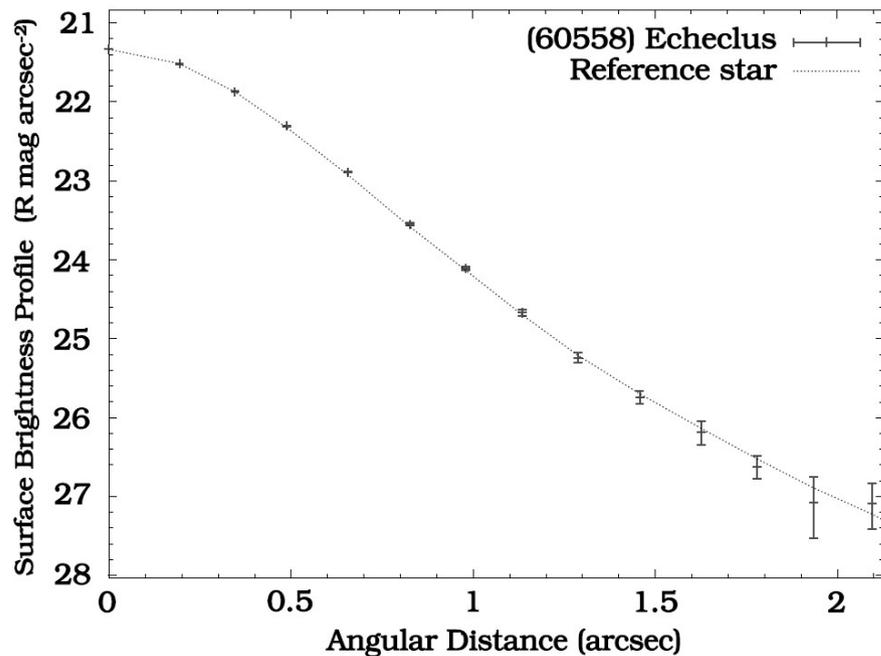
2. Search for cometary activity at large heliocentric distance

Searching for cometary activity of small solar system objects at large heliocentric distance is important because:

- Better understanding of **physical relationship between comets and Centaurs / Trans-Neptunian Objects**
- Better understanding of **cometary nuclei**

The search for cometary activity is based on the comparison of the radial profile with the the radial profile of a star. Our analysis of a few objects (Lorin & Rousselot, 2007) :

Object	UT date	Telescope	Instr.	R	Δ	α	Sky motion rate (arcsec h ⁻¹)	Predicted V mag.	Total integration time (min)
(29981) 1999 TD ₁₀	2002 Sep. 4	VLT	FORS 1	13.173	12.508	3°4	3.4	20.2	6
(60558) Echeclus	2001 Apr. 27	NTT	SuSI 2	15.159	14.464	2°8	5.1	21.5	71.4
	2001 Apr. 28	NTT	SuSI 2	15.158	14.476	2°9	5.0	21.5	101.9
2000 FZ ₅₃	2001 Apr. 27	NTT	SuSI 2	16.782	15.787	0°5	7.4	23.6	21.8
2000 GM ₁₃₇	2003 June 28	VLT	FORS 2	7.021	6.199	5°2	10.5	22.9	123
(28978) Ixion	2005 May 30	NTT	EMMI	42.477	41.463	0°0	3.0	19.4	146
	2005 May 31	NTT	EMMI	42.476	41.462	0°0	3.0	19.4	72



Different Centaurs have also presented a cometary activity far to the Sun ($\approx 5-13$ AU):

- **Chiron**
- **39P/Oterma** (discovered in 1943)
- **29P/Schwassmann-Wachmann 1** (discovered in 1927)
- **C/2000 B4 (165P/LINEAR)**
- **C/2001 M10 (NEAT)**
- **C/2001 T4 (166P/NEAT)**
- **C/2004 PY42 (167P/CINEOS)**
- **P/2004 A1 (LONEOS)**
- **P/2005 S2 (Skiff)**
- **P/2005 T3 (Read)**

Total: **11 objects for ≈ 70 known Centaurs (about 16%) (SDO+ Centaurs: 189)**

Possible cometary activity for the TNO **(19308) 1996 TO₆₆** at 45 AU (Hainaut et al., 2000) and the SDO **(29981) 1999 TD₁₀** at 12.4 AU (Choi et al. 2003)

Case of Chiron:

- First Centaur known to present cometary activity.
- Discovered in 1977 and initially classified as an asteroid.
- 1989: Meech & Belton (1989) were the first authors to present a direct detection of Chiron's coma.
- $a=13.67$ AU and $q = 8.45$ AU (transition object between TNOs and Jupiter-family comets)
- Probable spectroscopic **detection of CO** (Womack & Stern 1995) and **CN** (Bus et al. 1991).
- Presence of **water ice with an absorption band near 2 μm** reported by Foster et al. (1999) and Luu, Jewitt & Trujillo (2000) but not confirmed by Romon-Martin et al. (2003).
- Meech et al. (1997) derived a relatively **low density** for Chiron, about $\rho_{\text{Nuc}} < 10^3 \text{ kg.m}^{-3}$.
- **$Q_{\text{dust}} \approx 3-4 \text{ kg.s}^{-1}$** (Meech & Belton, 1990)

Mechanism for cometary activity ?

- **Water**: too refractory, cannot drive cometary activity farther than 5 AU to the Sun
- **CO**: supervolatile that can drive such an activity but would also be efficient farther than 30 AU (TNOs)
- **Amorphous → Crystalline phase transition of water**: seems to be consistent with the observations (Jewitt, 2006)

Implication: the TNOs must be constituted of amorphous water ice.

But: recent observations reveals that the KBOs observed with sufficiently good S/N show crystalline water ice (and the Centaurs not...);

Previous cometary activity ?

3. The case of 174P/Echeclus

Different objects have presented cometary activity at large heliocentric distance but the case of 174P/Echeclus is unique by its importance.

Before the outburst :

- Centaur called (60558) 2000 EC₉₈.

- Orbital elements :

a (AU)	e	q(AU)	Q (AU)	i
10.772	0.456	5.85	15.69	4.3°

- No cometary activity detected up to magnitude 27/arcsec² (Rousselot et al. 2005; Lorin & Rousselot 2007).

- Rotation period = 26.802±0.042 h (double-peaked lightcurve assumed) and lightcurve amplitude 0.24±0.06 (R band) (Rousselot et al. 2005)

Outburst detected on December 30, 2005 (Choi et al., 2006) during observations with the 5-m Mount Palomar observatory telescope:

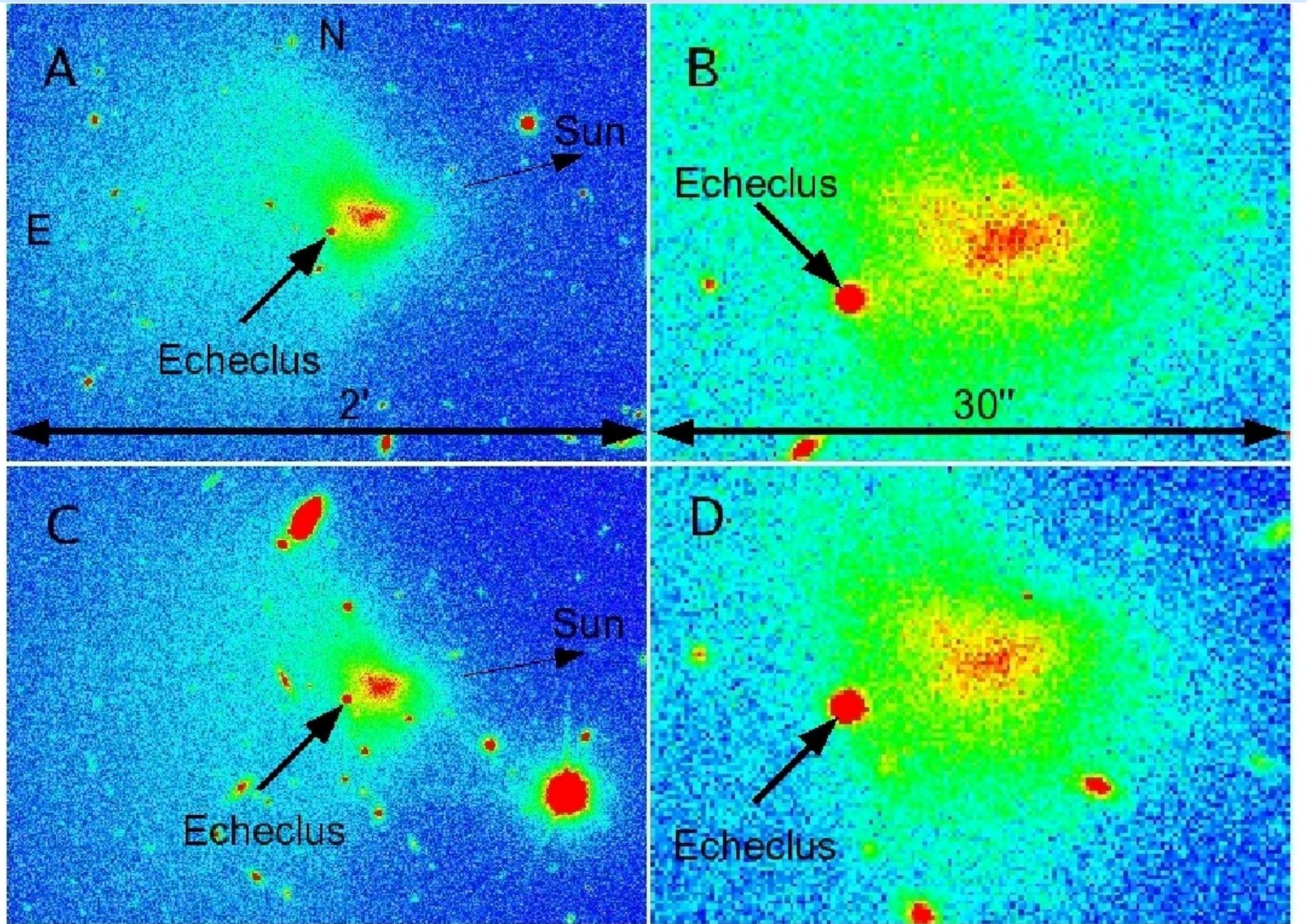
R=13.07 AU

V=21 → 14

Renamed **174P/Echeclus**.

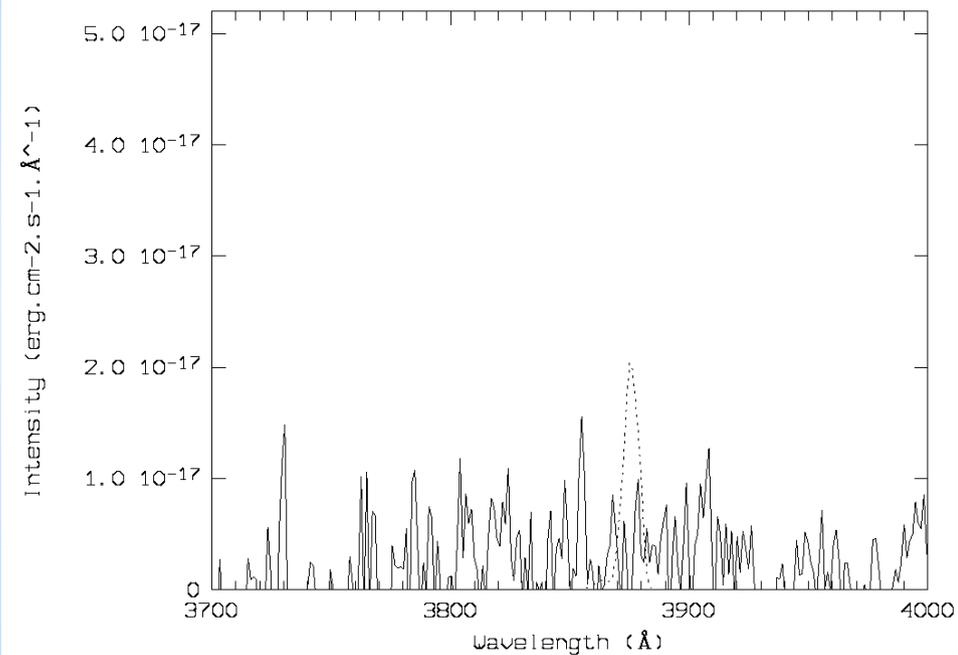
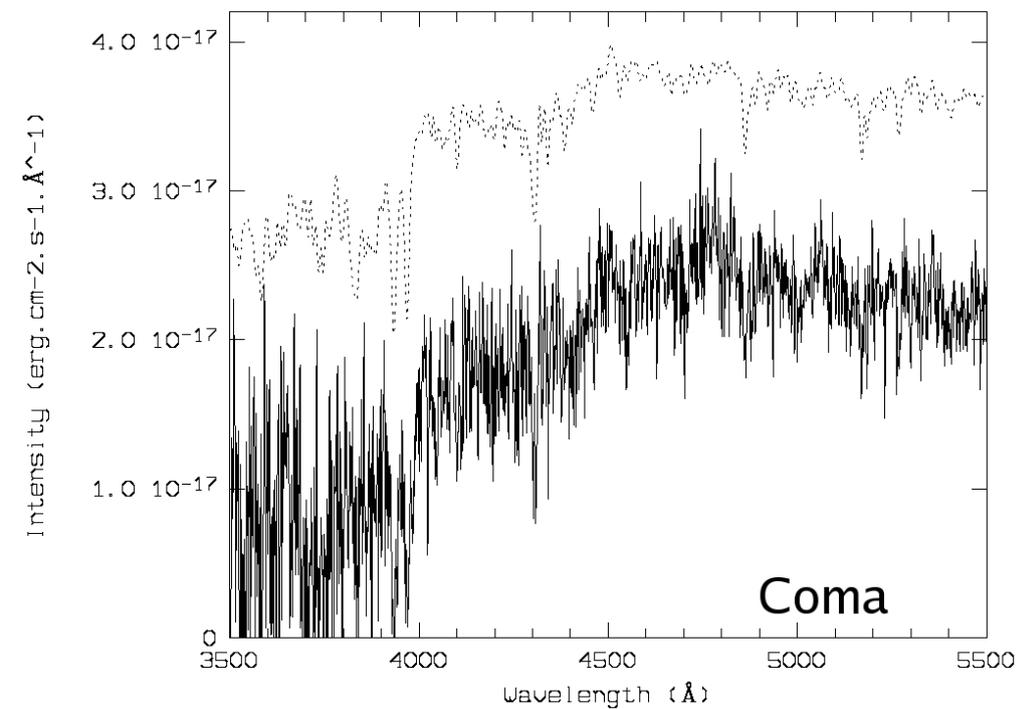
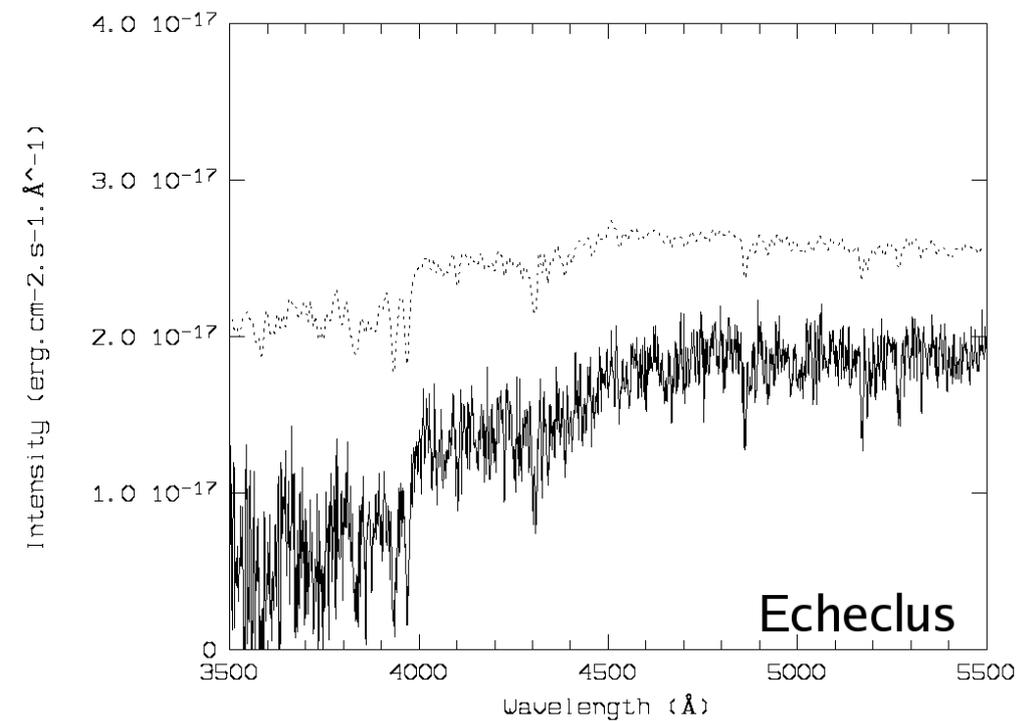
DDT with FORS1 at VLT to get more information about this outburst: visible images and spectra on March 23 and 30, 2006.

Images (R-band) obtained with FORS 1:

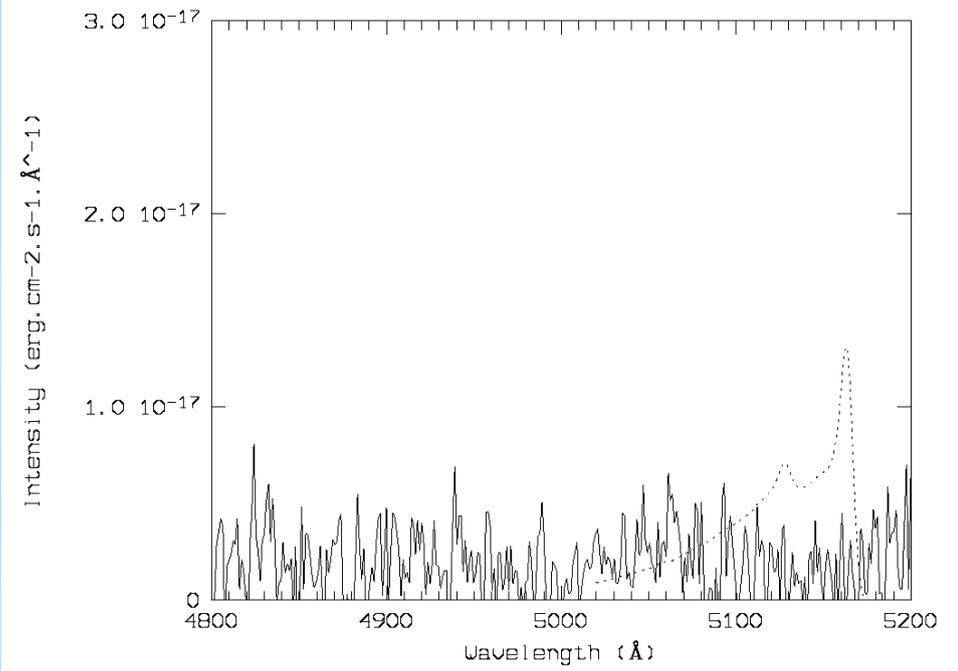


A/B: March 23, 2006. C/D: March 30, 2006

Spectra obtained with FORS 1:

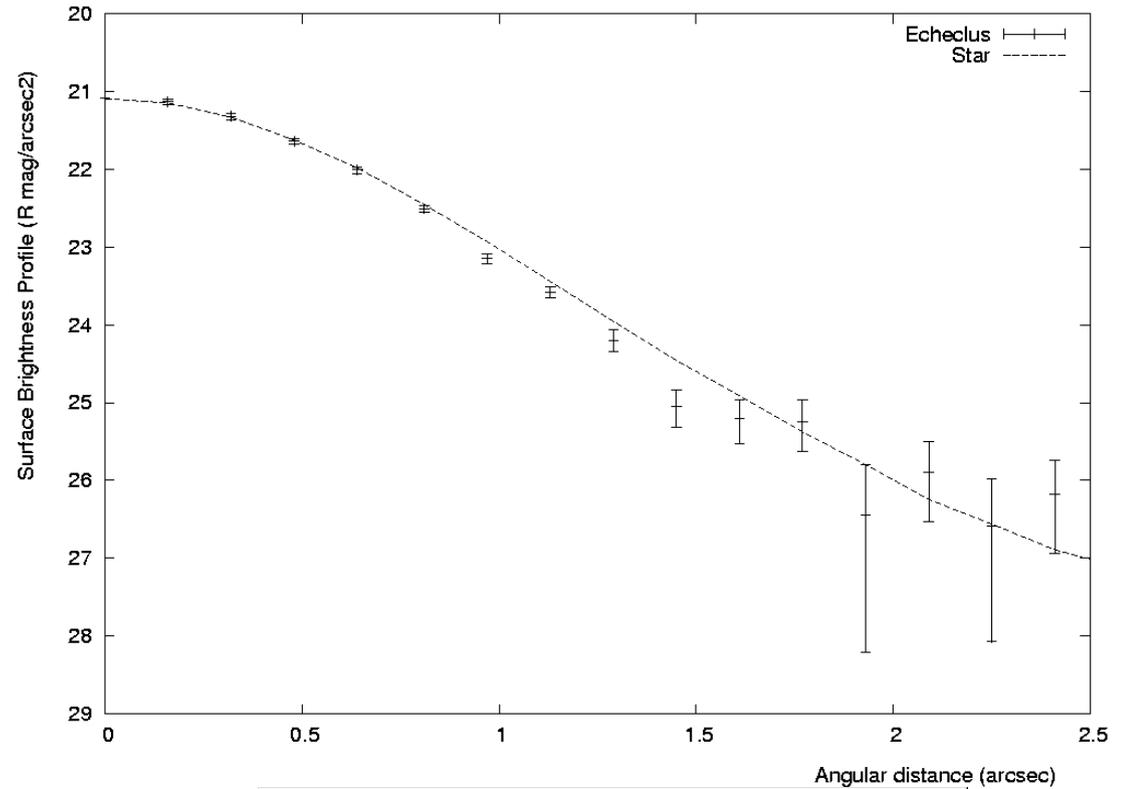
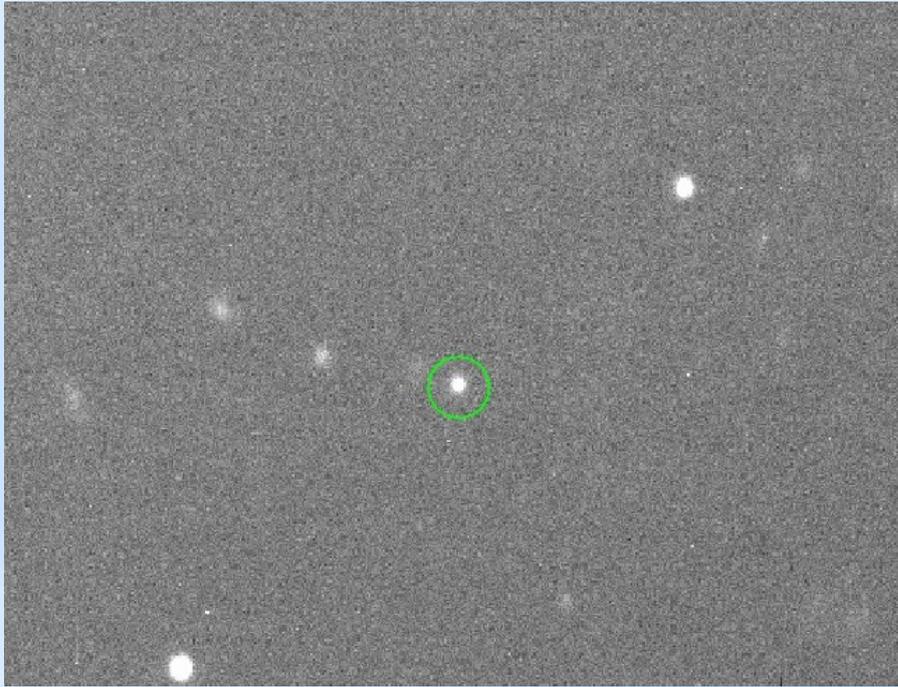


Search for CN

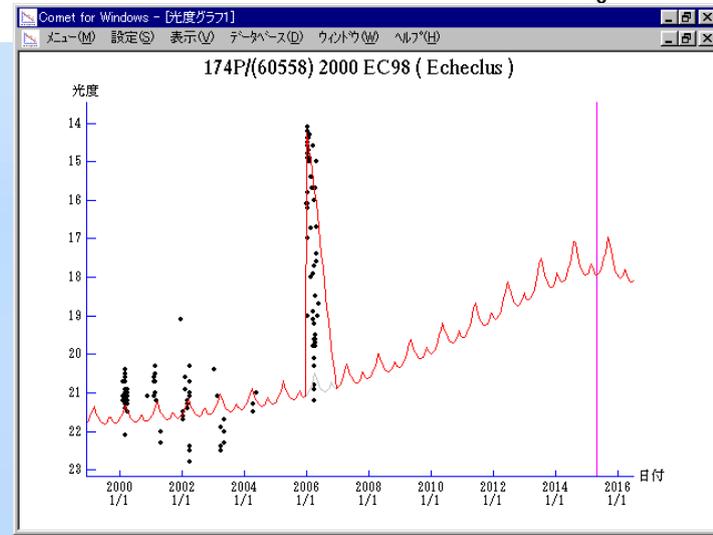


Search for C₂

One year later... the outburst is over (with a smaller heliocentric distance, 12.23 vs 12.92 AU)



SUSI 2 at NTT observations (March 24, 2007)



Main results of VLT observations (Rousselot, 2008):

- **$A_{fp} \approx 10,000$ cm** ($Q_{\text{dust}} \approx 86 \text{ kg.s}^{-1}$, $R = 14,4 \pm 0,2$) [$A_{fp} < 75$ cm on March 2007]
- **No CN or C₂ emission lines detected**: upper limit for CN $\approx 3.8 \cdot 10^{25} \text{ molecules.s}^{-1}$, upper limit for C₂ $\approx 10^{26} \text{ molecules.s}^{-1}$. Gas-to-dust ratio significantly smaller than for other comets.
- **Source of cometary activity distinct from Echeclus itself** (projected distance $\approx 60,000$ - $70,000$ km) and brightness distribution compatible with a diffuse source.

Two main questions:

- What has triggered such an important outburst at such a large heliocentric distance ?
- What phenomenon can create a coma distinct from Echeclus ?

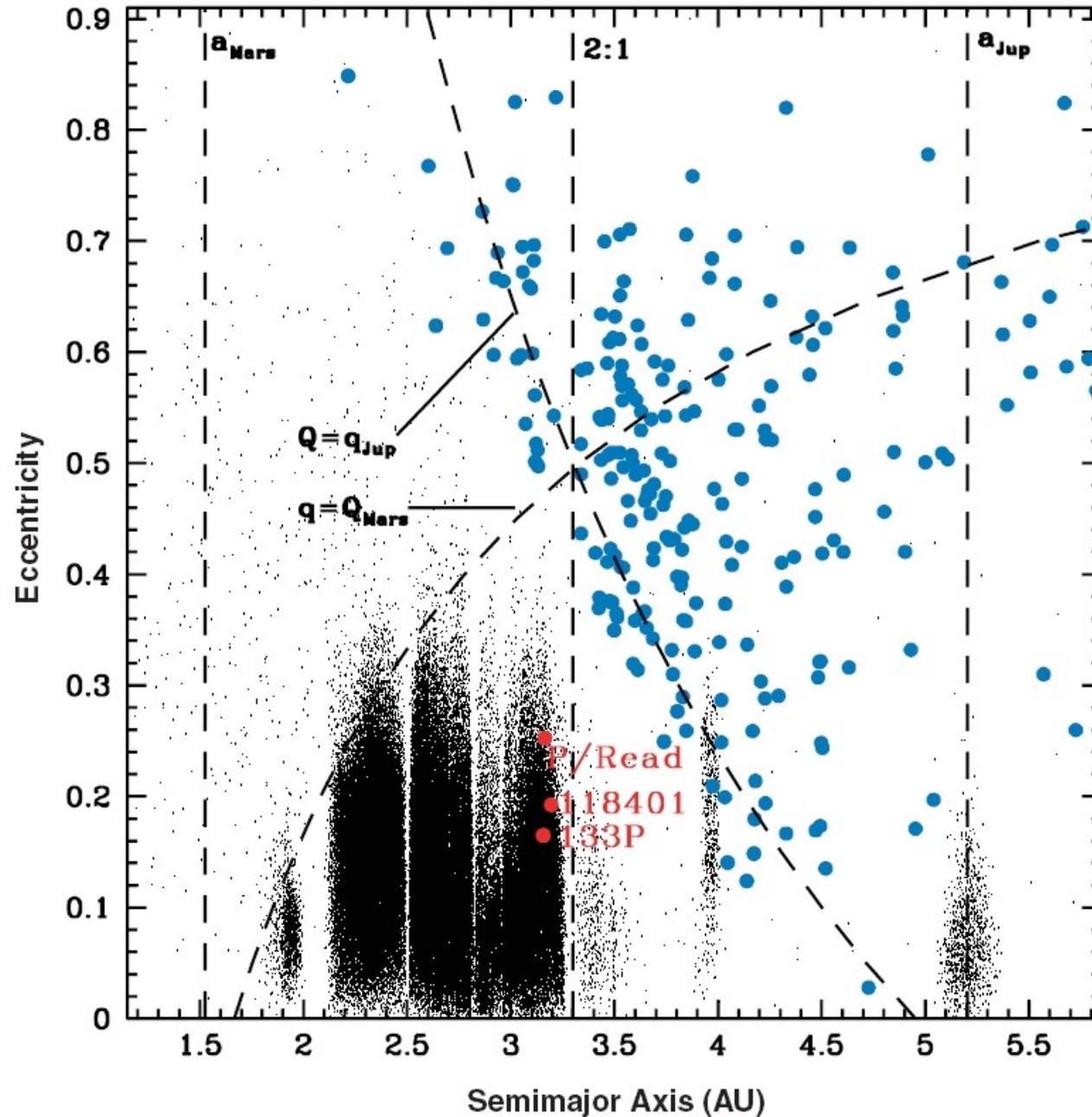
4. The Main Belt Comets and Ceres

Hsieh and Jewitt (2006) pointed out a possible new class of comets: the Main Belt Comets.

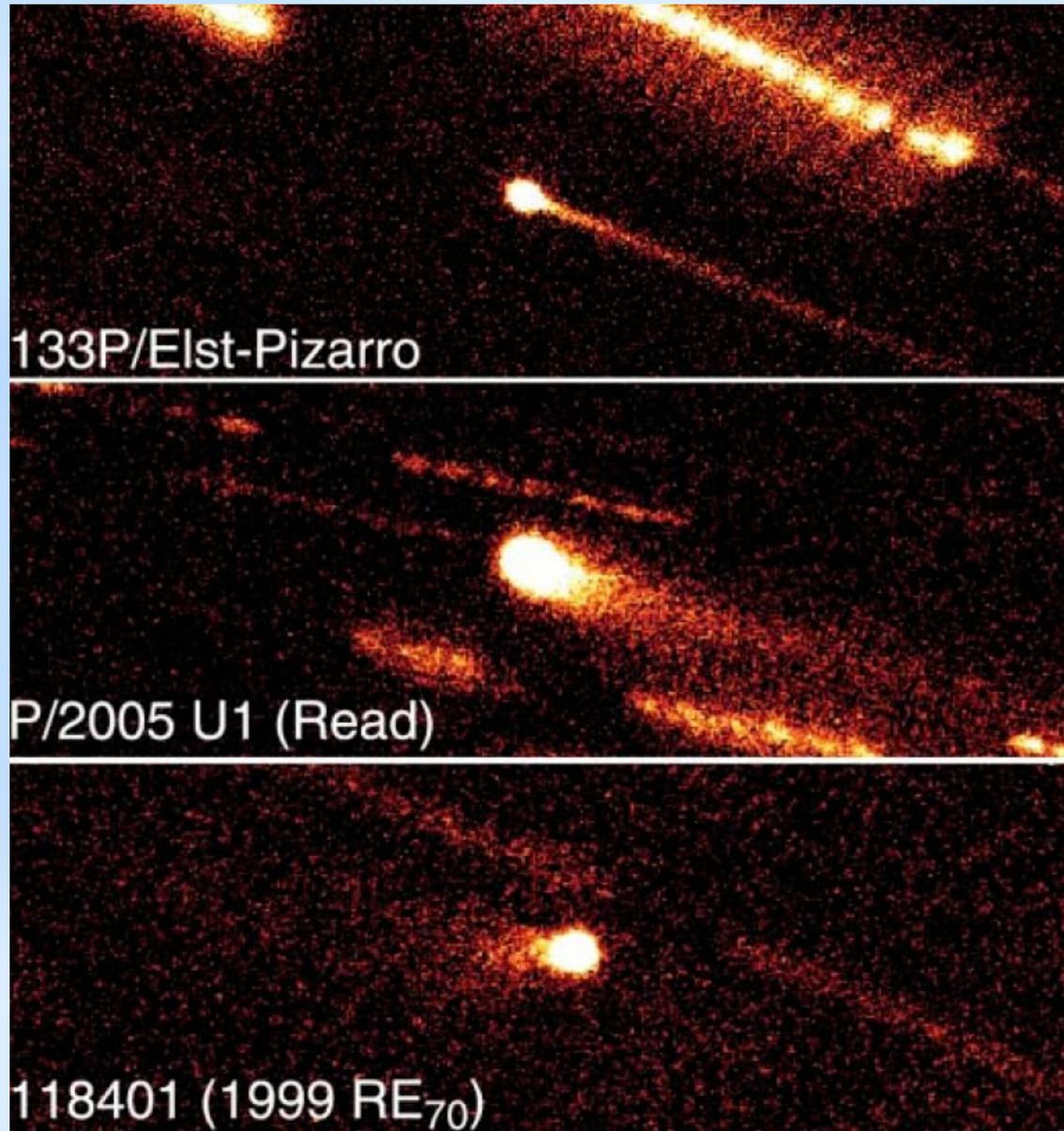
These comets:

- lie entirely in the main asteroid belt with **stable asteroidal orbit** ($T_j < 3$)
- present **cometary activity leading to a lifetime of a few 10^3 years** \ll age of solar system
- their existence throw a new light to the problem of the origin of water on Earth

Orbital elements (a,e) of the 3 known MBCs:



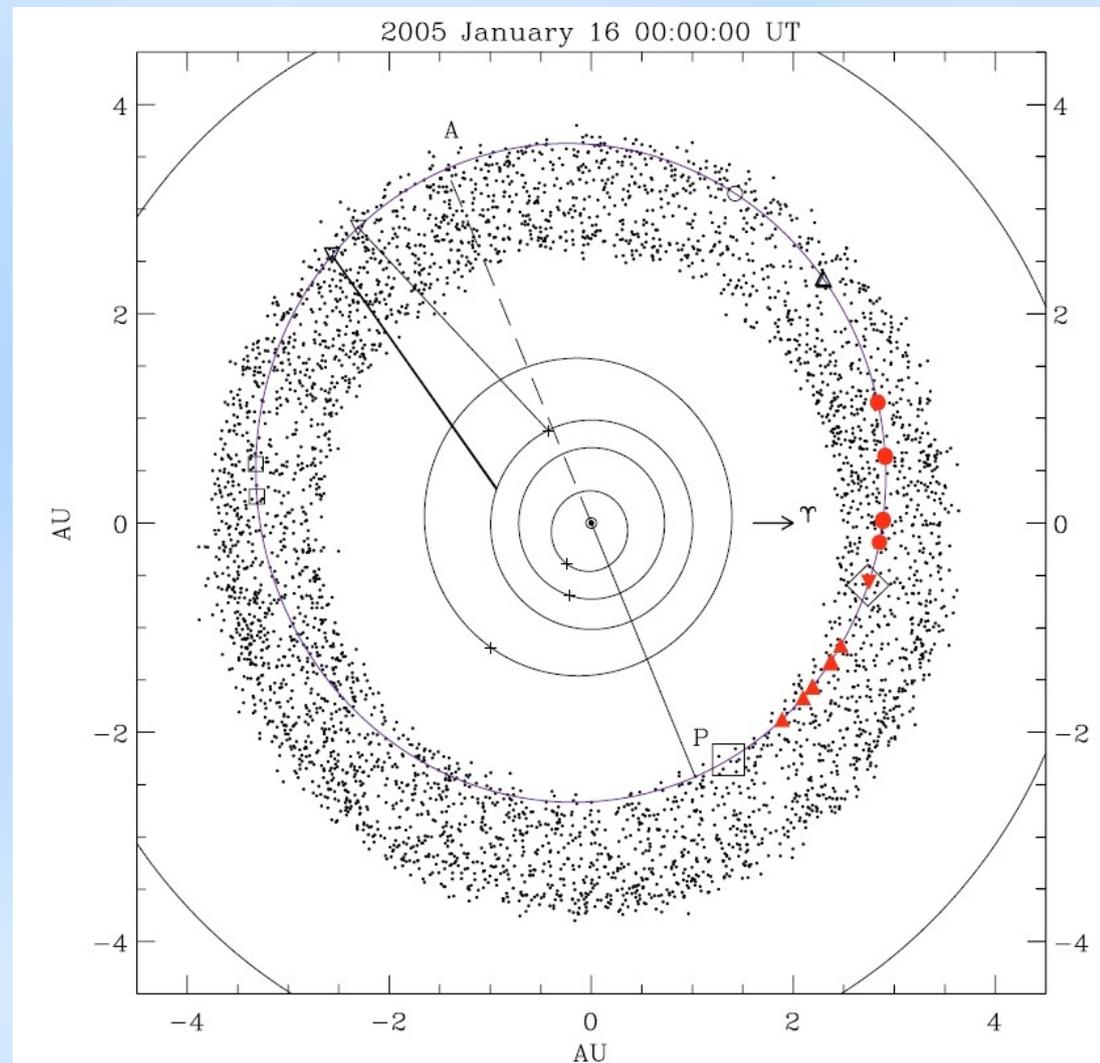
Up to now only 3 MBCs are known:



Case of 133P/Elst-Pizarro (first and best known MBC):

- 1979: discovery as an asteroid (1979 OW7)
- 1996: discovery of its cometary activity (Elst et al. 1996)
- cometary activity detected during 2002 and 2007 perihelion passage
- orbital elements: $q=2.636$ AU $Q=3.677$ AU $P=5.60$ yrs $i=1.39^\circ$

Cometary activity detected in 1996 (red solid triangle) and 2002 (red solid dots) (Toth, 2006):



MBCs are probably intrinsically icy bodies formed and stored at their current locations.

Problem: What has recently triggered the cometary activity ?

At $\approx 2.4-2.9$ AU dirty water ice of an MBC sublimate and recede at $1 \approx$ meter/year. With a diameter equal to 2-5 km \Rightarrow lifetime $\approx 10^3$ years

Cometary activity observed too many times and too closely correlated with perihelion passages to be the result of a simple impact event that only generate a temporary dust tail or trail.

Activity driven by water ice ?

\rightarrow Search for infrared signature of water ice on 133P/Elst-Pizarro with **SINFONI** on August 12 and 13, 2007... Work in progress at ESO SCL with Christophe Dumas.

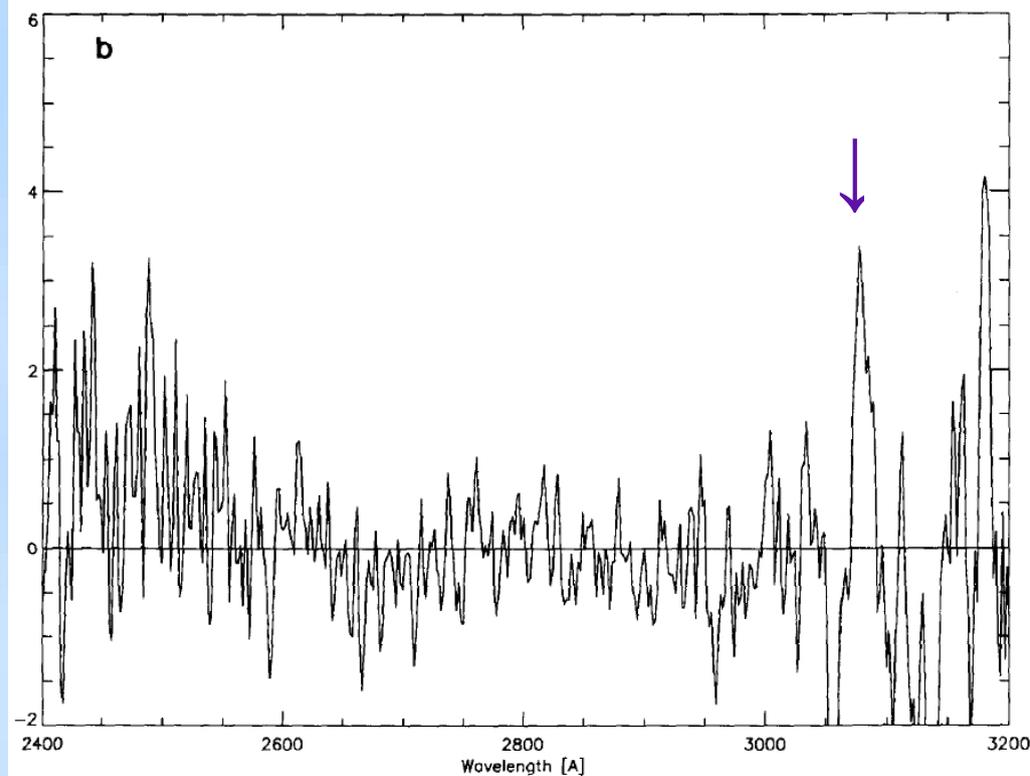
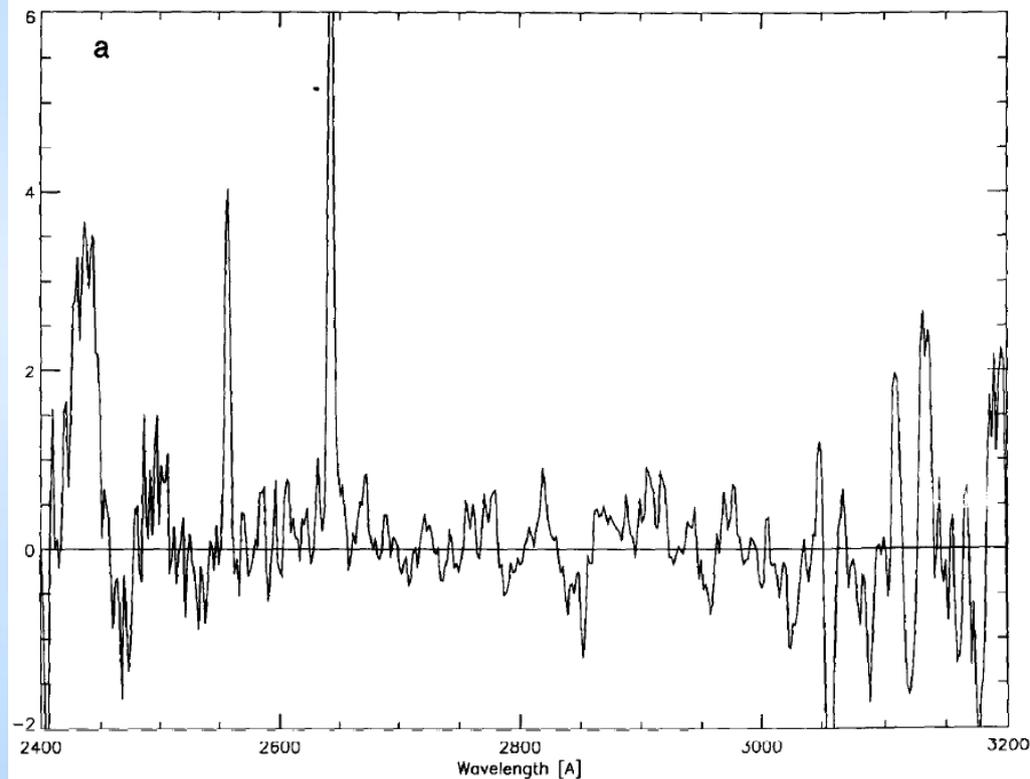
Different studies support the idea that **asteroids could have water ice**:

- Some models predict the possibility of a **migration of planetesimals with ices** located beyond 5 AU to the main asteroid belt, leading to a mixture of rock and ices for present asteroids (Mousis et al., 2008)
- **Bulk density** of some asteroids consistent with a **mixture of rock and ices** (Mousis et al. 2008)
- **Possible detection of OH** (photodissociation product of water) near **Ceres** (A'Hearn and Feldman, 1992) and crystalline water ice on its surface (Vernazza et al., 2005, Carry et al., 2008).

Case of Ceres: unlike Vesta (dry) Ceres shows strong signs of water alteration on its surface (Jones et al., 1990). More similarities with the icy outer satellites of Jupiter than with the dry asteroids that populate the inner region of the Main Belt: mixture of rock planetesimals and icy planetesimal that migrated inward from the outer region ? (Mousis & Alibert, 2005).

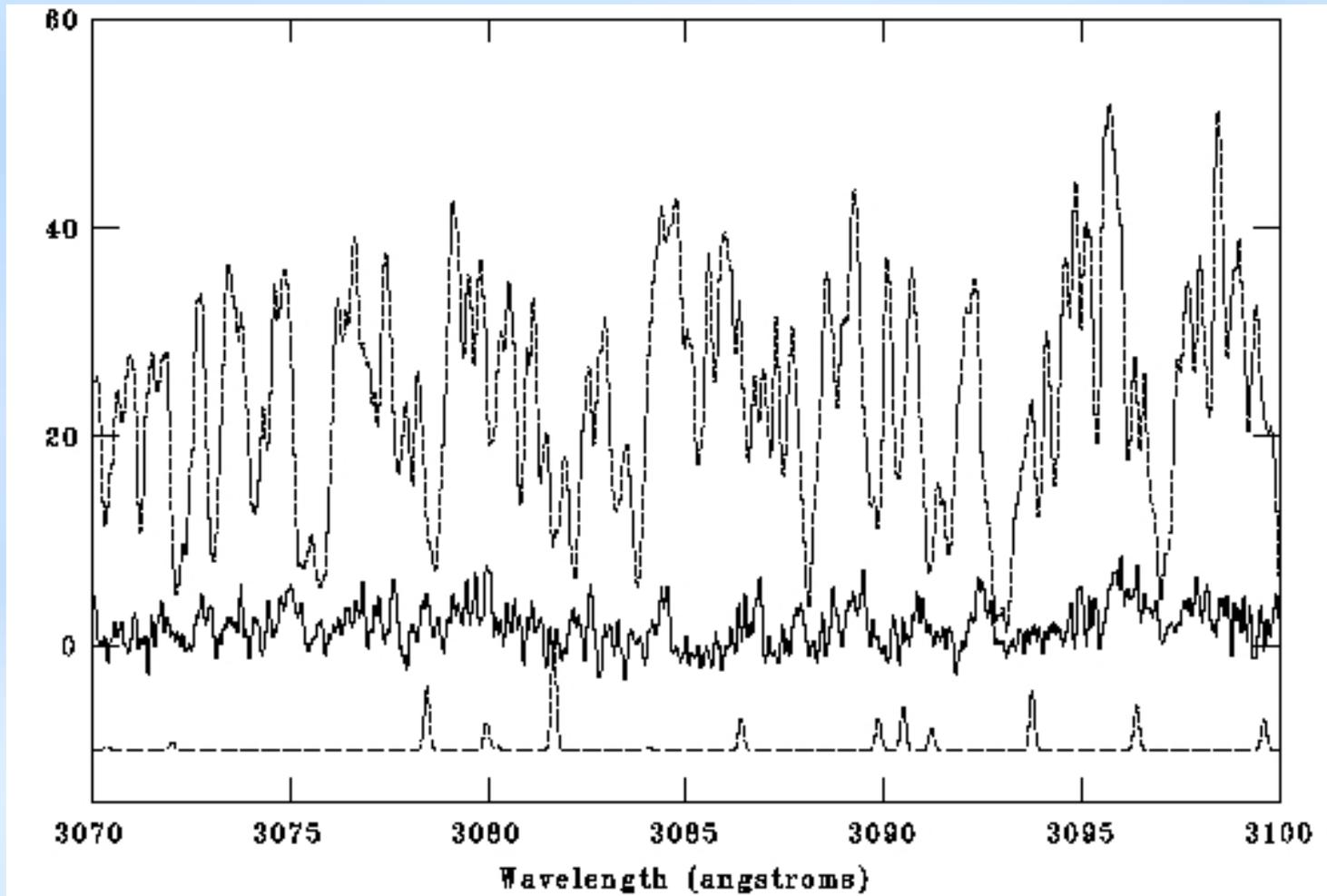
- **possible detection of escaping water:** A'Hearn & Feldman (1992) claim that they have detected OH emission line at 309 nm with IUE (northern limb, 450-mn exposure time on May 29, 1991)

a: southern limb (no OH detection)
b: northern limb (OH detection at 309 nm)



Problem: our recent observations with VLT+UVES (Oct. Dec. 2007) did not permit to detect any emission lines (work in progress)...

3x47,5-mn exposure time on northern limb
1x47,5-mn exposure time on southern limb



Conclusion

- Cometary activity for small solar system objects is a relatively common phenomenon and not only for comets.
- Cometary activity at large heliocentric distances is now observed for different objects : driven by CO or by amorphous → crystalline water ice change.
- The cometary activity observed at large heliocentric distance is often observed as unpredictable outbursts. These outburst do not necessary happen at perihelion and can be very strong (174P/Echeclus).
- Some asteroids can present cometary activity recently triggered by an unknown mechanism (Main Belt Comets)