



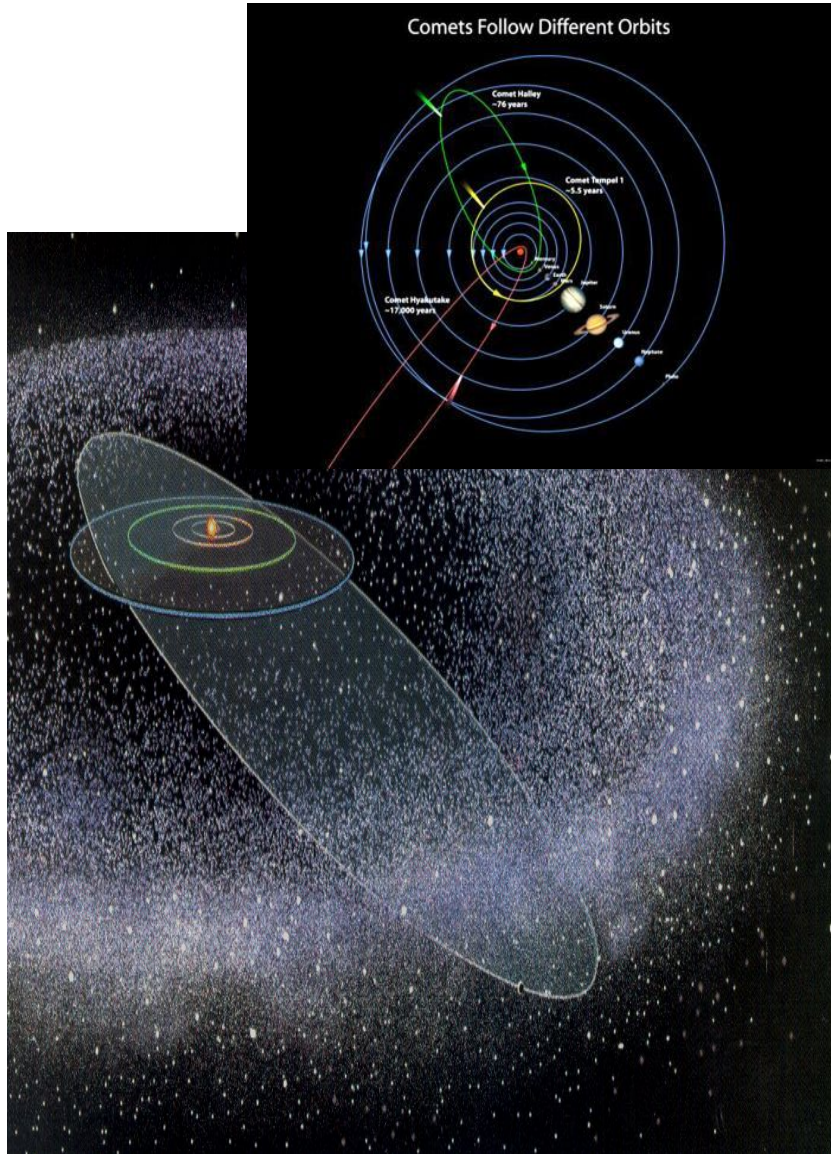
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# Comparative analysis of gas and dust properties in comets of different dynamical groups

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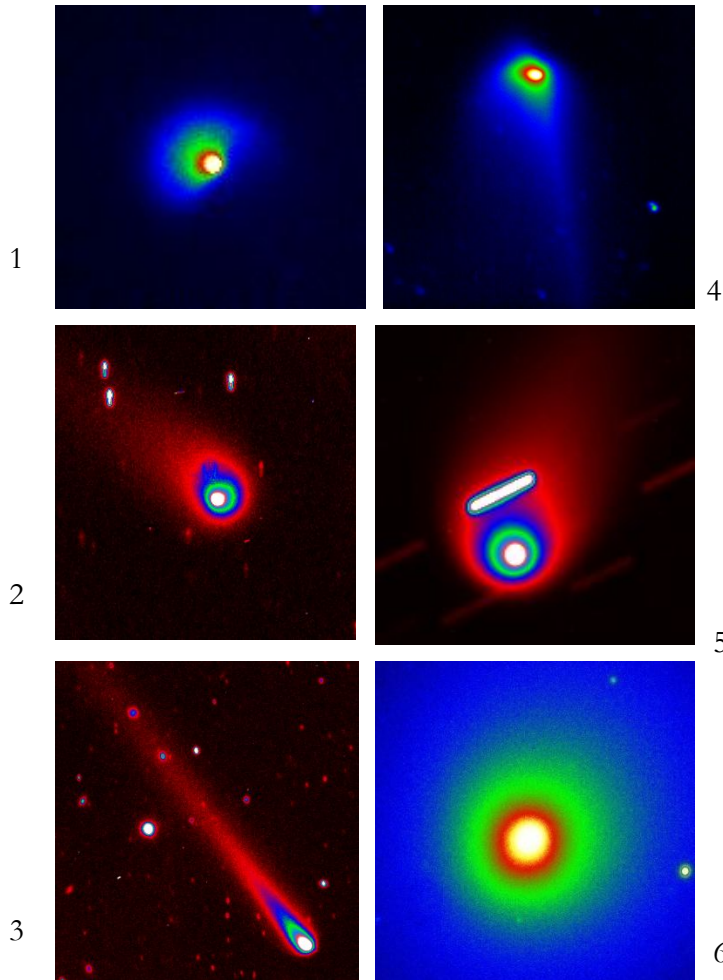
Ivanova Oleksandra

# Main goal of analysis



- Comparison of physical properties of the atmospheres and tails in the short- and long-period comets, including dynamically new comets too.
- Analysis of evolution of physical activities of the comets, as function from their distances from the Sun.
- Understanding, how to relate the physical properties of comets from their place of origin

# Objects



- Object, which is coming to the inner Solar System for the first time (long-period comets and including dynamical new comets)
- Short-period comets.
- Centaurs

# Telescopes

- 6-m telescope SAO RAS (Russia)
- 4.1-m telescope SOAR (Chile)
- 2-m telescope (p. Terskol, Russia)
- 2-m Faulkes Telescope of South Siding Spring Observatory (Australia)
- 1.6- m telescope of the National Laboratory for Astrophysics (LNA, Brazil)
- 1.3-m telescope Skalnaté Pleso (AI SAS, Slovakia) (in future)
- 1.0 -m telescope (SAO RAS)
- 1.0 -m telescope (Kaurovka observatory, Russia )
- 0.70 -m telescope KAO (p. Lisnyky)
- 0.61 - m telescope Skalnaté Pleso (AI SAS, Slovakia)
- 0.60- m telescope (p. Terskol, Russia)





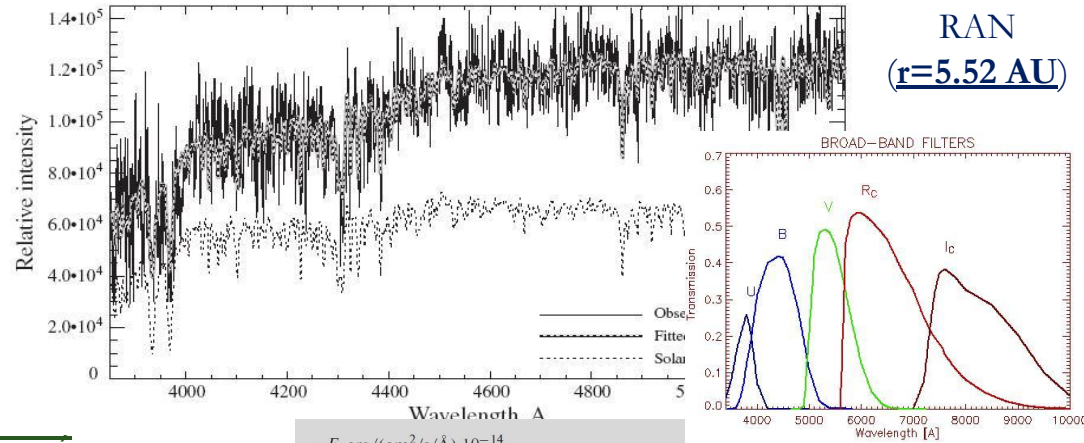
# Methods

# Photometry

## Broad band filters BVR (heliocentric distances from 8 to 4 AU)

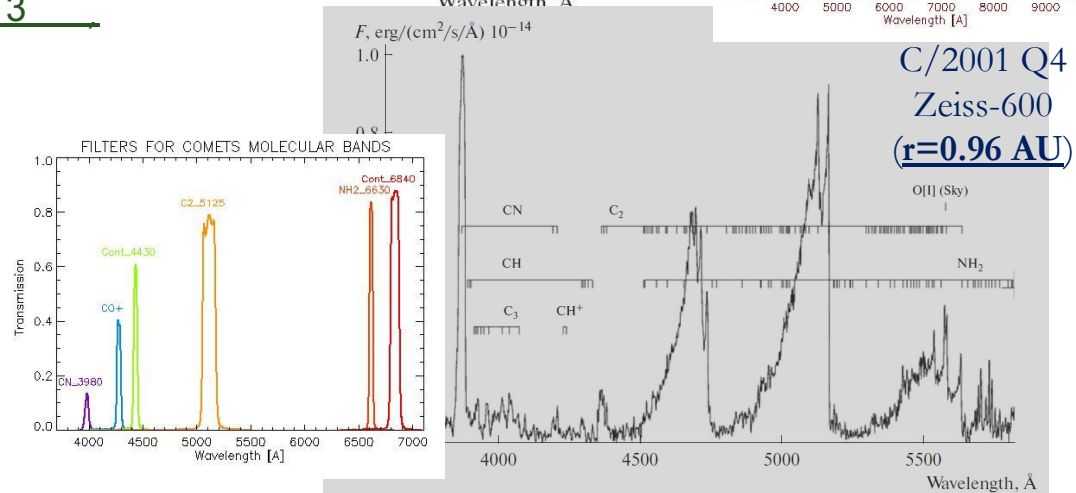
- Dust production rates
- Radius of cometary nucleus
- Morphology of cometary coma
- Color indexes
- Period rotation of cometary nucleus
- Outburst and long lasting activity
- Split of the comets

C/2003  
WT42  
6-m SAO  
RAN  
( $r=5.52$  AU)



## Comet filters (at heliocentric distances $< 3$ AU)

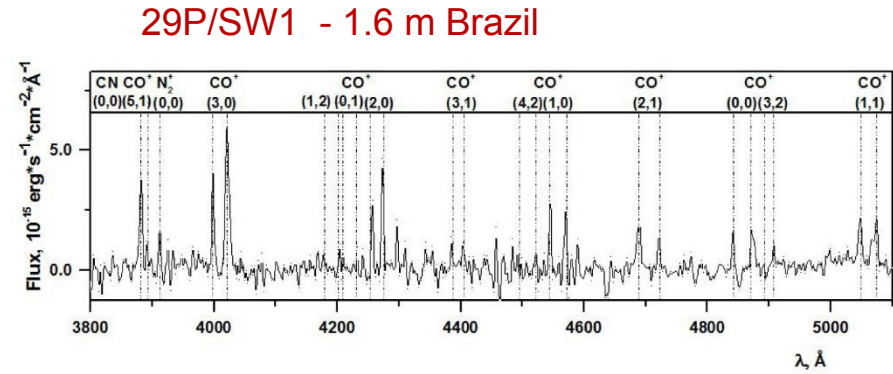
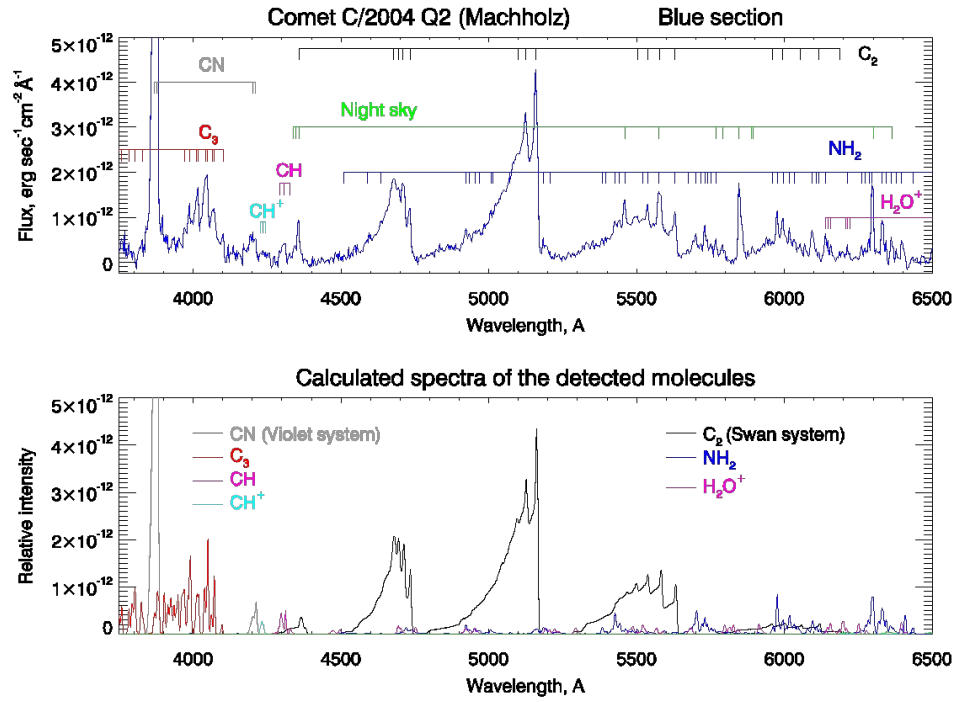
- Gas/Dust production rates
- Modeling of dust tails
- Morphology of cometary coma
- Period of rotation of cometary nucleus



C/2001 Q4  
Zeiss-600  
( $r=0.96$  AU)

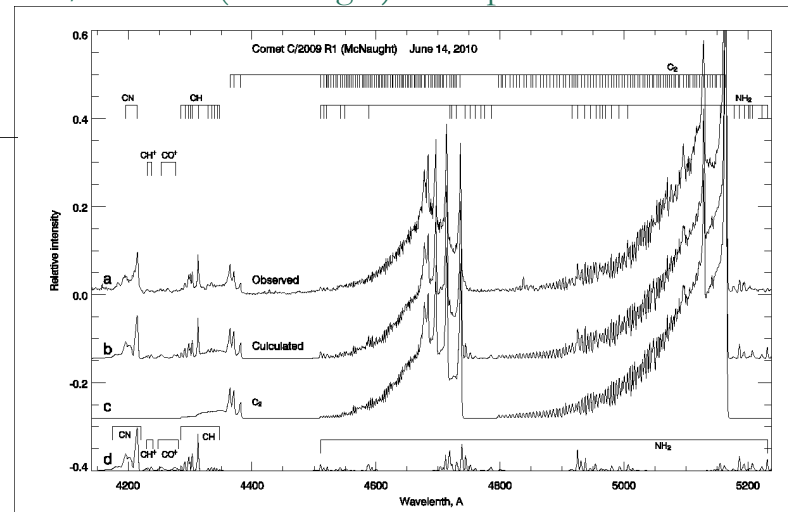
# Methods

# Spectroscopy



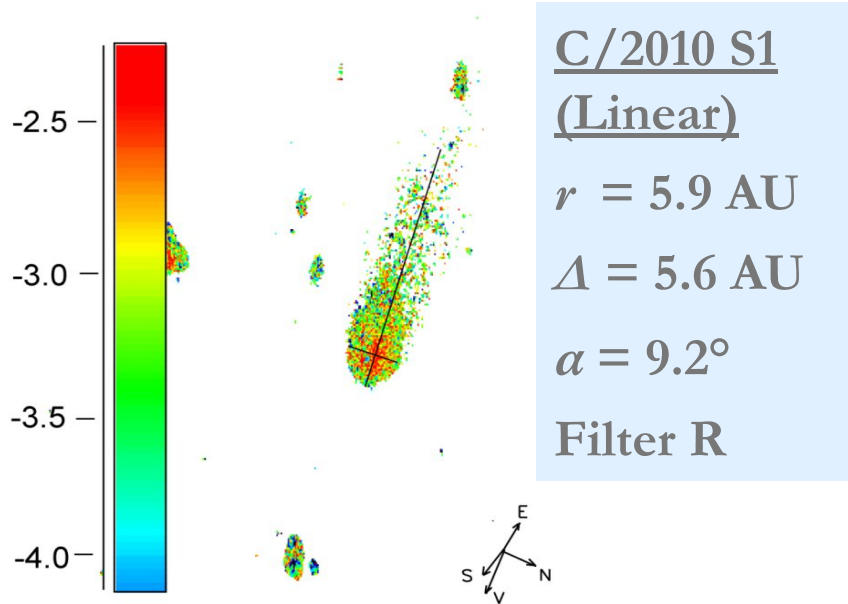
C/2004 Q2 (Machholz) – 60 cm AAO

C/2009 R1 (McNaught) – 2m p.Terskol



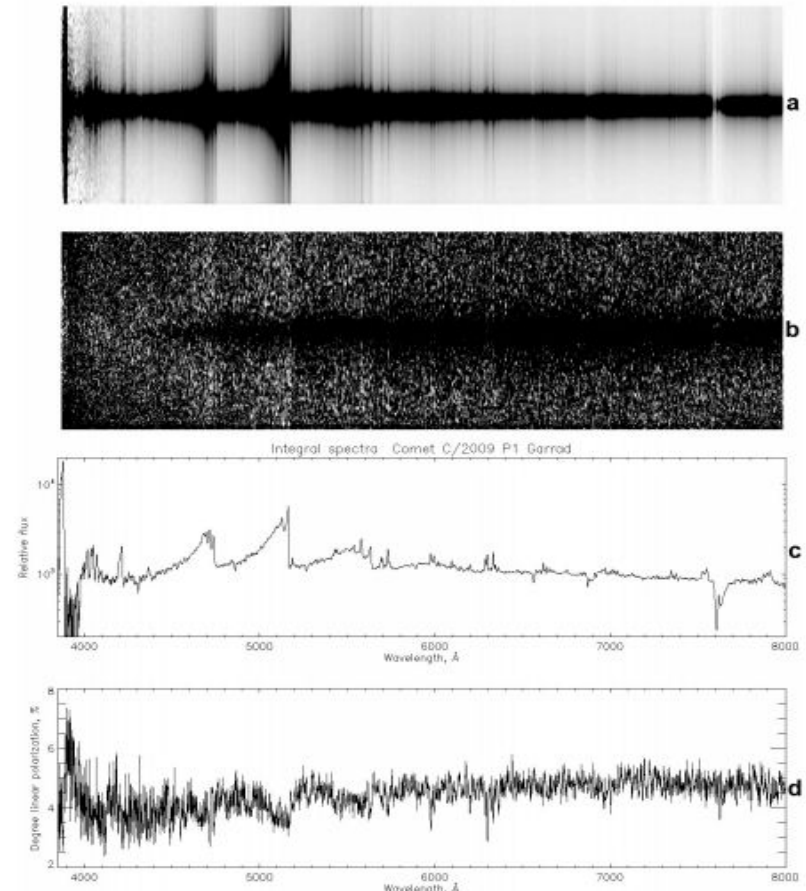
- Dust production rates
- Gas production rates
- Detection of emission

# Methods



Study of physical properties of the dust in comets at different heliocentric distances are very important for study of their evolution.

# Polarimetry



## C/2009 P1 (GARRADD)

$r = 1.71$  AU,  $\Delta = 1.38$  AU,  $\alpha = 35.2^\circ$

# 67P/ Churyumov-Gerasimenko

The Jupiter family comet.

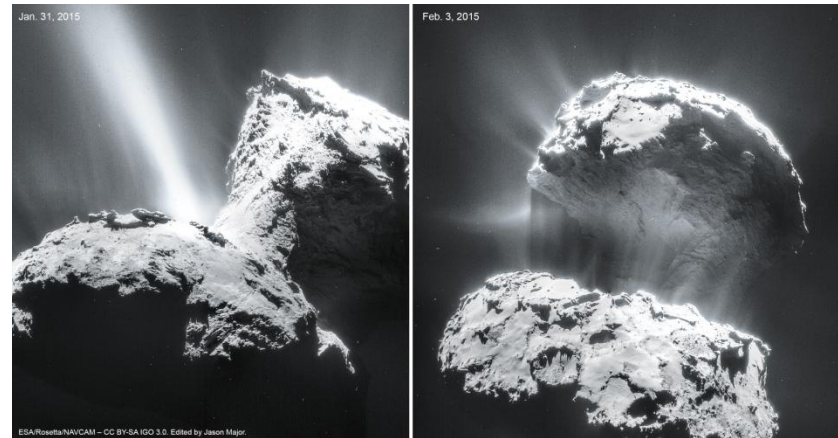
The short period comets have orbital periods <20 years and low inclination. Their orbits are controlled by Jupiter. The short period comets are believed to originate from the Kuiper Belt.

$$q=1.242335 \text{ au}$$

$$e=0.6404361$$

$$P=6.44$$

$$i=7.04 \text{ deg}$$



**November 8, 2015**

$$r=1.62 \text{ au}$$

$$\Delta=1.80 \text{ au}$$

$$\alpha=33.2^\circ$$

**December 9, 2015**

$$r=1.84 \text{ au}$$

$$\Delta=1.72 \text{ au}$$

$$\alpha=31.8^\circ$$

**April 5, 2016**

$$r=2.72 \text{ au}$$

$$\Delta=1.81 \text{ au}$$

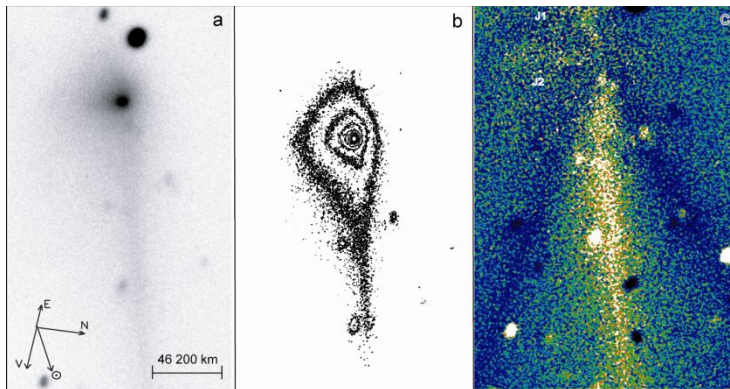
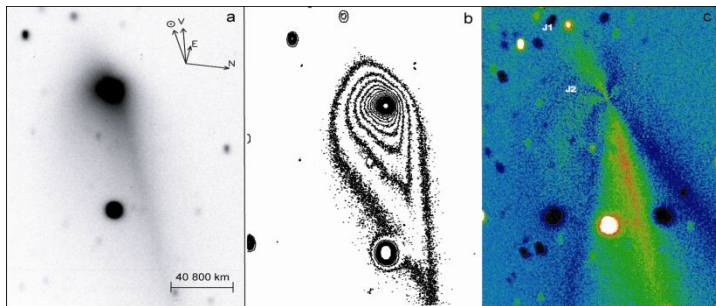
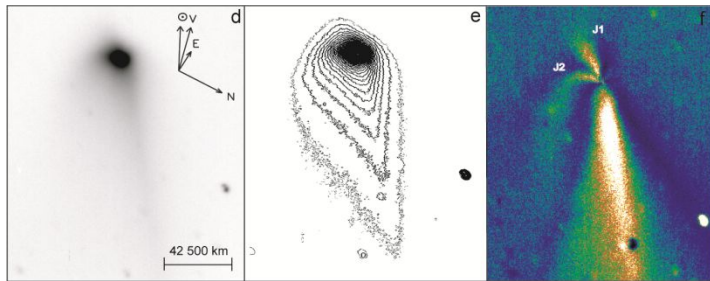
$$\alpha=10.4^\circ$$



# Methods

# Photometry

Two jets and tail are clearly apparent.

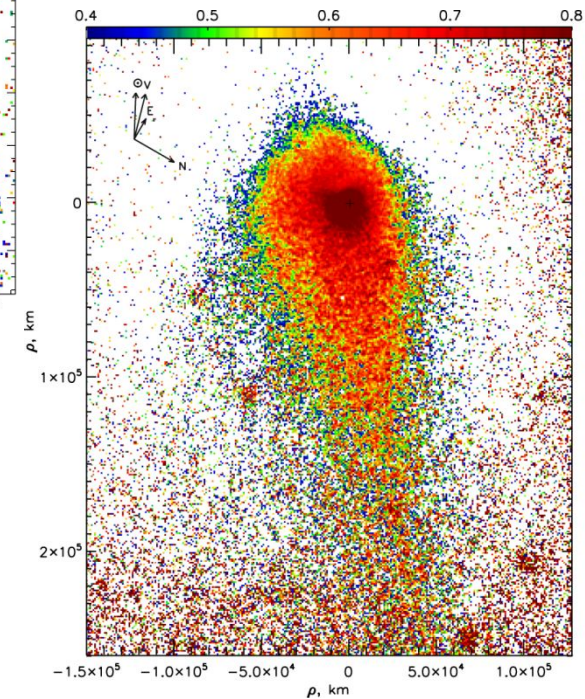
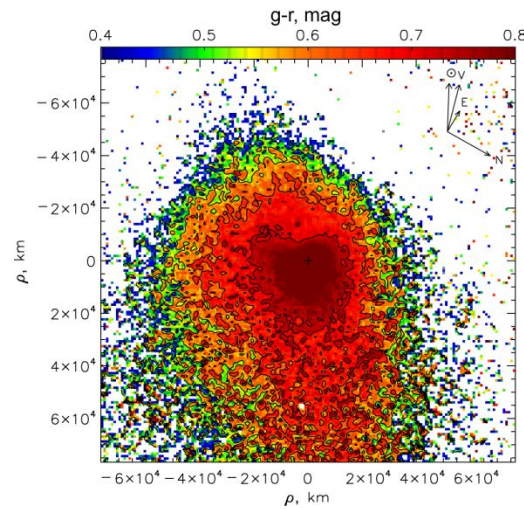


Direct image of the comet

Relative isophots

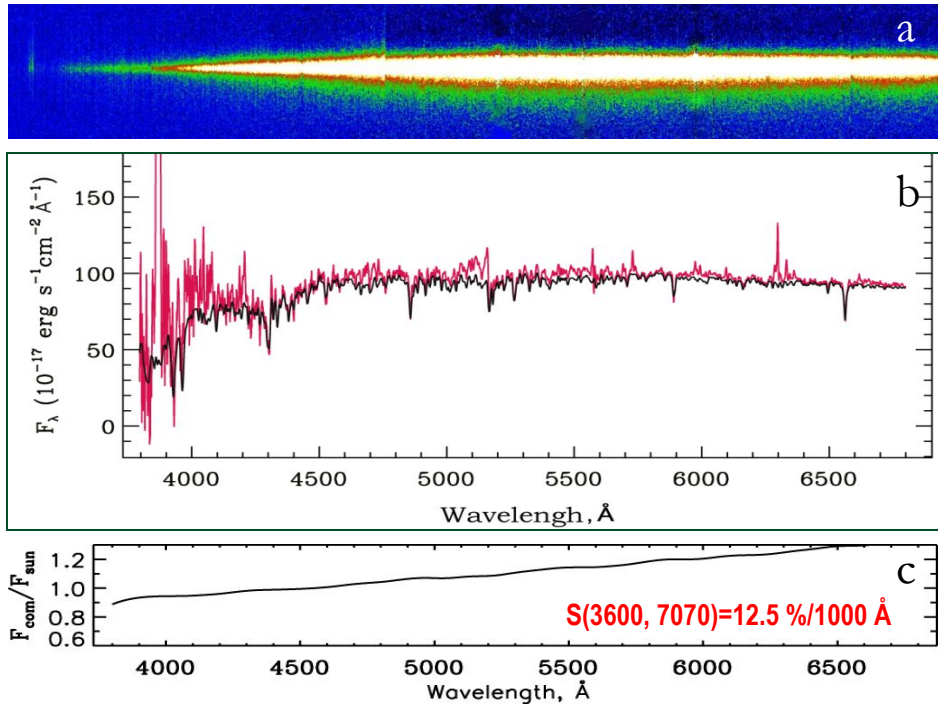
Image treated by digital filters

Color map g-r



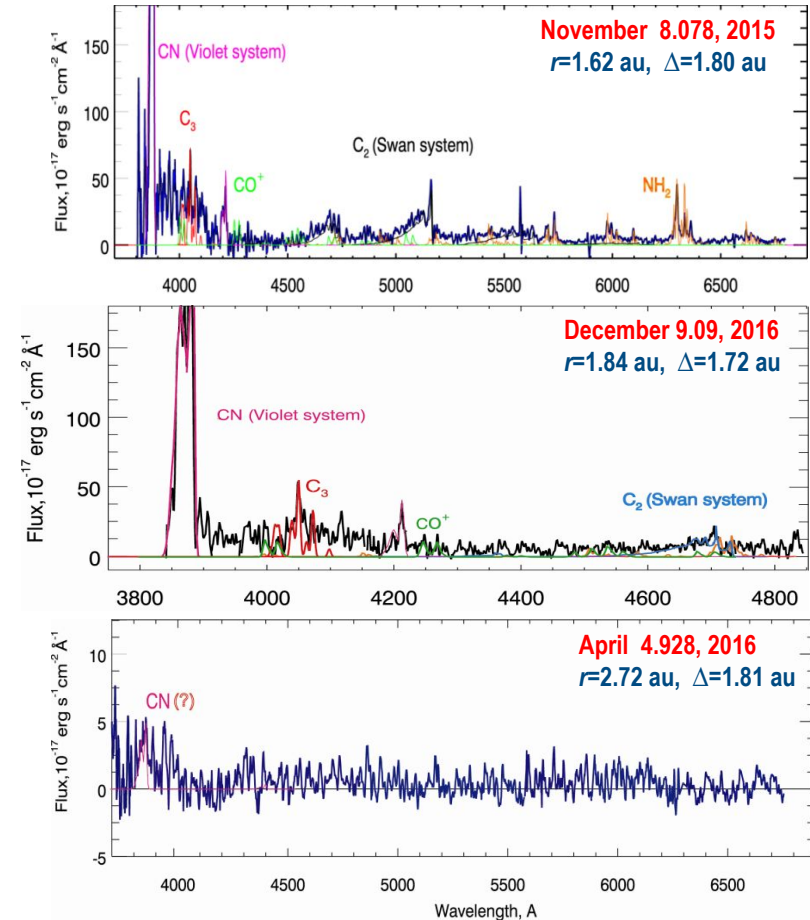
# Methods

Long-slit spectroscopy of the comet was performed at the 6-m telescope BTA with the multi-mode focal reducer SCORPIO-2. The gratings VPHG2400 (3600–7070 Å,  $\Delta\lambda=5$  Å) and VPHG2400 (3600–5100 Å,  $\Delta\lambda=4$  Å) and slits  $6.1' \times 1.0''$ ,  $6.1' \times 2.0''$  were used.



The long-slit spectrum of comet 67P derived on November 8, 2015. (a) – the raw spectrum; (b) – the distribution of energy in spectrum of the comet; (c) – normalized reddening of the dust continuum vs wavelength.

# Spectroscopy



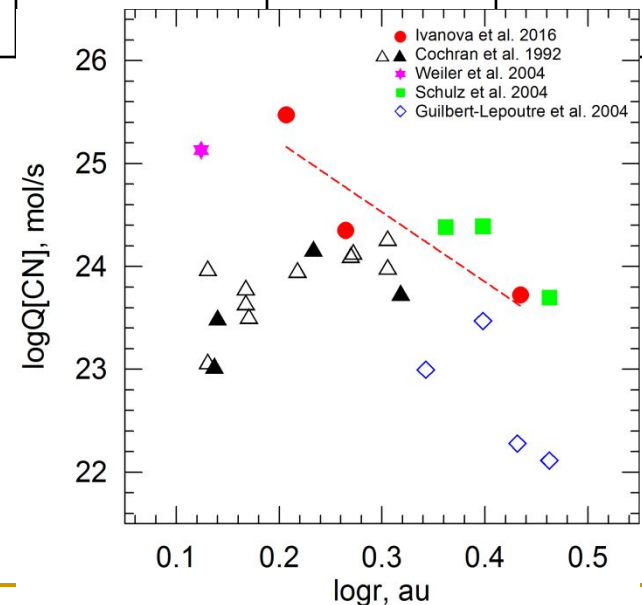
The emission spectra of comet 67P and the modeled spectra for comparison.

# Gas production rates in comet 67P

Date of observation, UT (Post-perihelion)	Q, [mol/s]				
	CN	C <sub>3</sub>	C <sub>2</sub>	NH <sub>2</sub>	Log[C <sub>2</sub> /CN]
<b>Nov. 8.078, 2015</b> <i>r</i> =1.61 au, $\Delta$ =1.79 au, $\alpha$ =33.2°	7.05×10 <sup>24</sup>	1.01×10 <sup>24</sup>	2.62×10 <sup>24</sup>	3.54×10 <sup>23</sup>	-0.43
<b>Dec. 9.093, 2015</b> <i>r</i> =1.84 au, $\Delta$ =1.72 au, $\alpha$ =31.8°	2.24×10 <sup>24</sup>	0.72×10 <sup>24</sup>	—	—	—
<b>Apr. 4.928, 2016</b> <i>r</i> =2.72 au, $\Delta$ =1.81 au, $\alpha$ =10.4°	<5.3×10 <sup>23</sup>	—	—	—	—

## Summary:

- CN, C<sub>2</sub>, C<sub>3</sub>, and NH<sub>2</sub> emissions were identified in the spectra of comet 67P on November 8 and December 9, 2015;
- Only CN emission was detected in the spectrum of the comet on April 4, 2016;
- The value  $\log[C_2/CN]=-0.43$  corresponds to “Depleted” comets (A’Hearn et al. 1995)



The dependence of CN production rate on the heliocentric distance according to data of different authors. Open and filled symbols are data before and after perihelion.



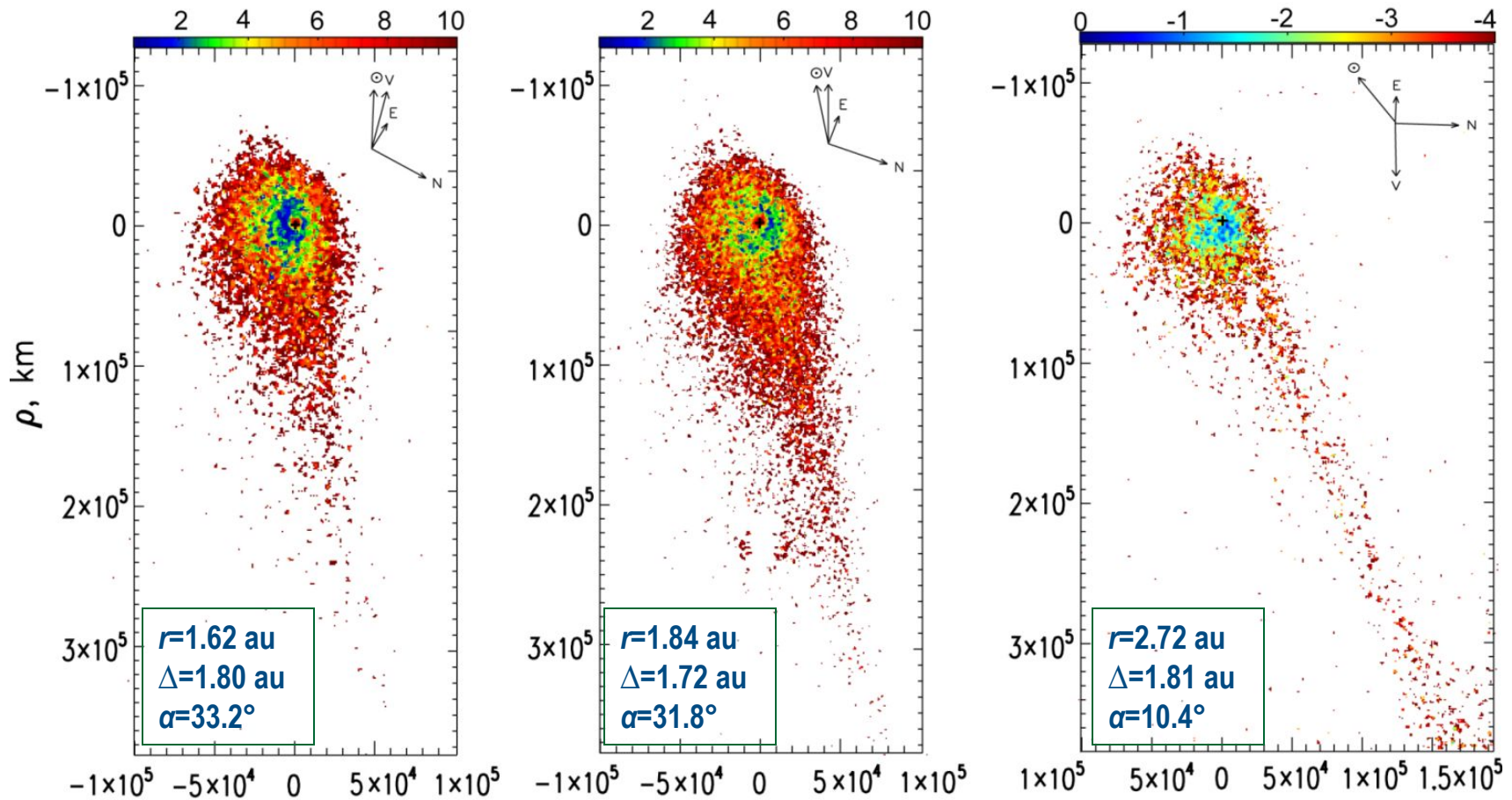
# Methods

# Polarimetry

November 8, 2015

December 9, 2015

April 5, 2016



Distribution of linear polarization over the coma of comet 67P.

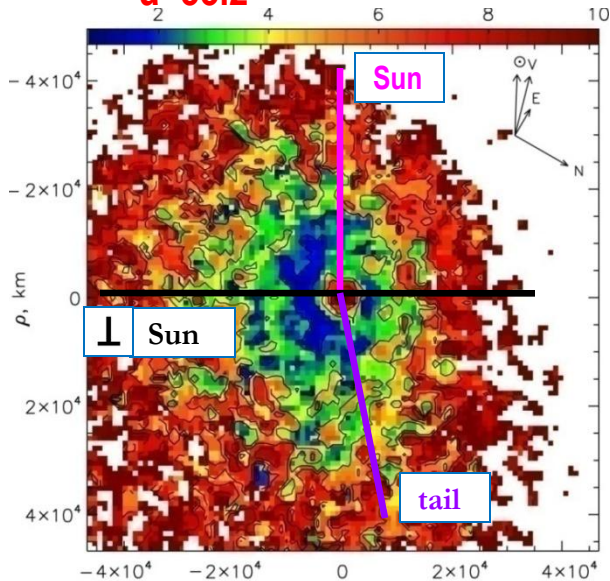
**Linear polarization maps:** there is a complex structure of the coma in polarized light with areas of high and low polarization



# Linear polarization maps in details

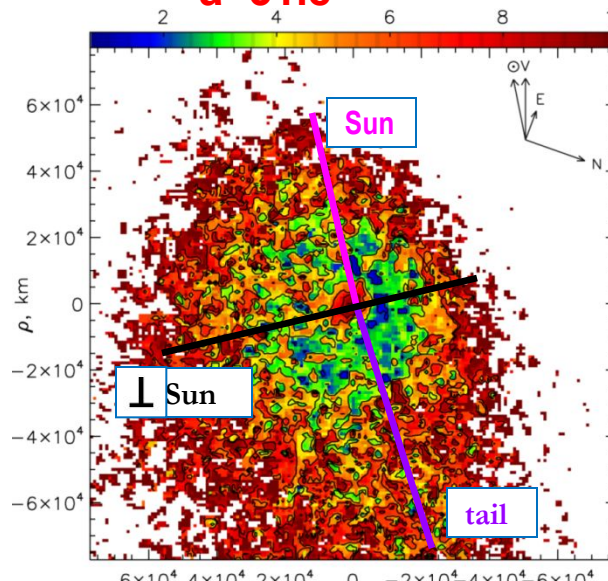
November 8, 2015

$\alpha=33.2^\circ$



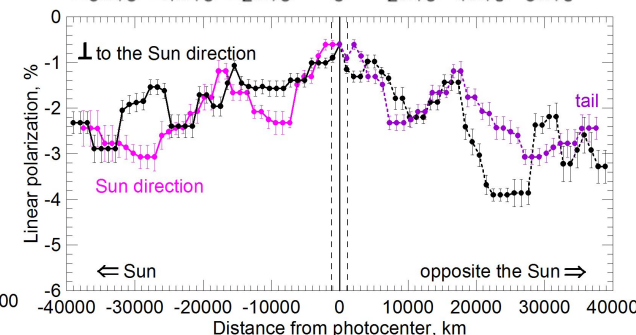
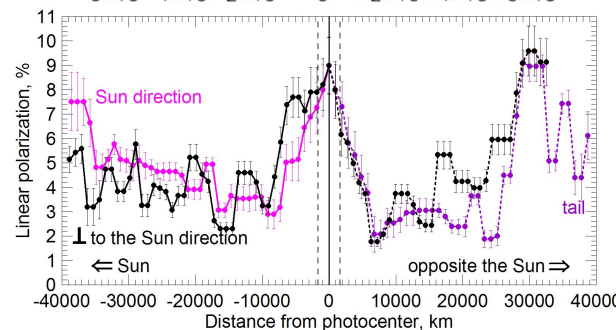
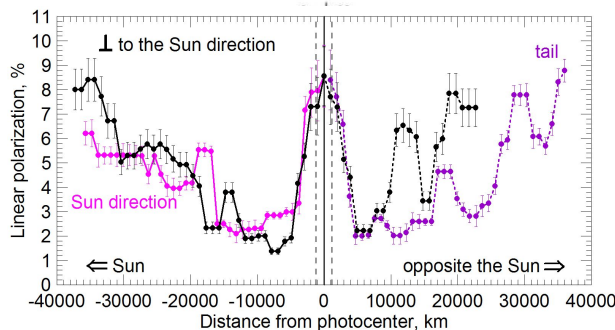
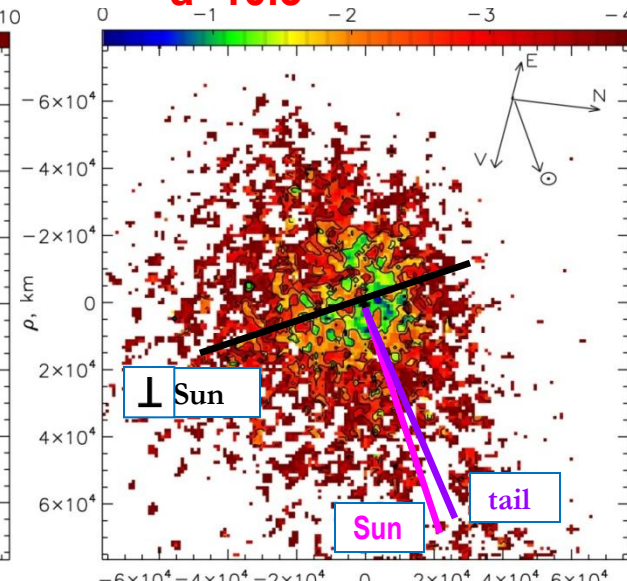
December 9, 2015

$\alpha=31.8^\circ$



April 5, 2016

$\alpha=10.3^\circ$

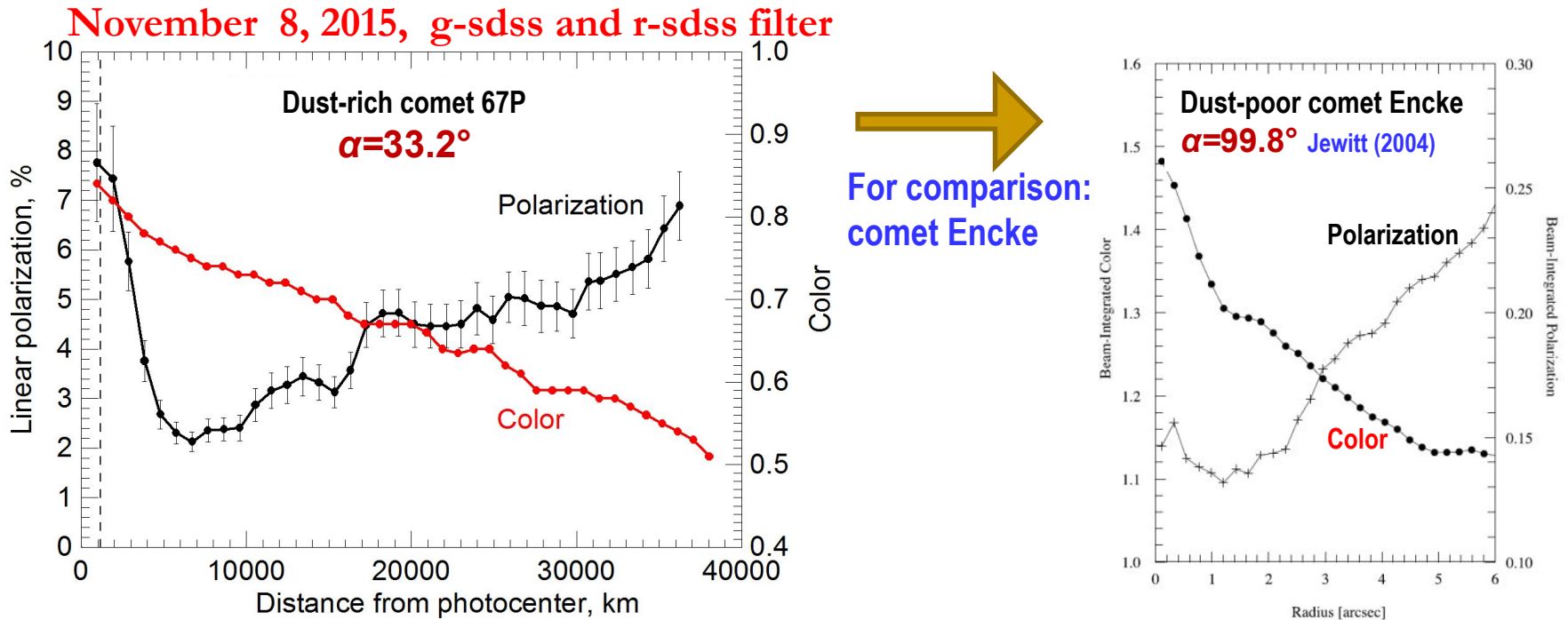


Polarization maps in large scale (top row) and polarization profiles (bottom row)

$\alpha=33-32^\circ$ : - in the near-nucleus area,  $P \approx 8\%$  and drops sharply to  $\sim 2\%$  at projected distance 5000 km;  
- coma polarization increases with distance from the nucleus reaching  $>8\%$  at 36000 km.

$\alpha=10.4^\circ$ :  $P$  varies between  $-0.6\%$  in the near-nucleus area and  $-3 \div -4\%$  in the outer coma.

# Comparison of polarization and color



Polarization and color profiles measured within projected concentric annuli as a function of the annulus radius. Left and right axes show the polarization and color. The figure for comet Encke is taken from [Jewitt \(2004\)](#). Trends of polarization and color are very similar for two comets.

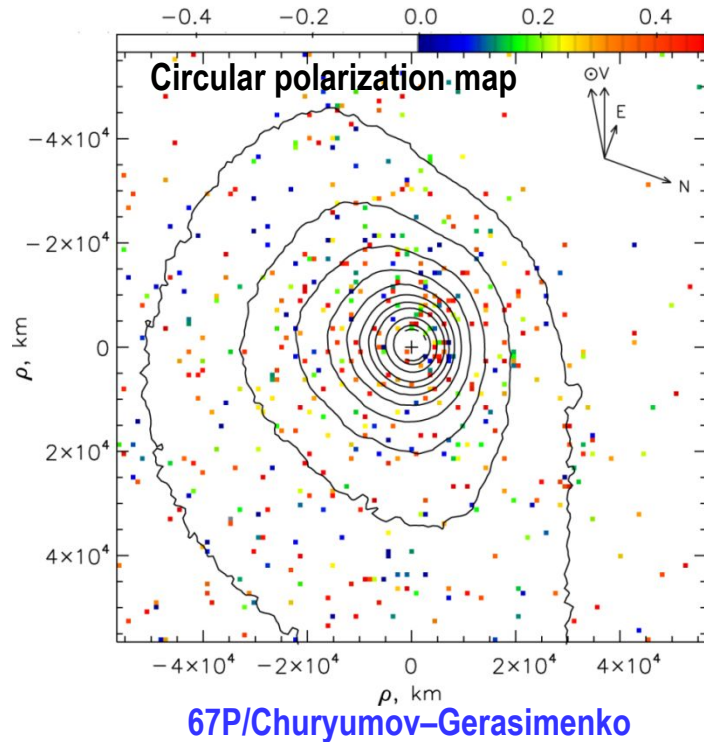
## Summary:

- near-nucleus area is **redder** and **more polarized** than the adjacent coma;
- the coma becomes **more blue** with increasing distance from the nucleus;
- near-nucleus polarization **drops sharply** from  $\sim 8\%$  to  $\sim 2\%$  at 5000 km;
- polarization of the coma **increases** with distance from the nucleus, reaching  $\sim 8\%$  at 40000 km;
- the radial variations of polarization and color suggests an evolution of the particle properties.

Higher polarization and bluer color measured at larger projected radii are consistent with a decrease in the mean grain size with increasing distance from the nucleus that can be caused by disintegration of porous aggregates.

# Circular polarization

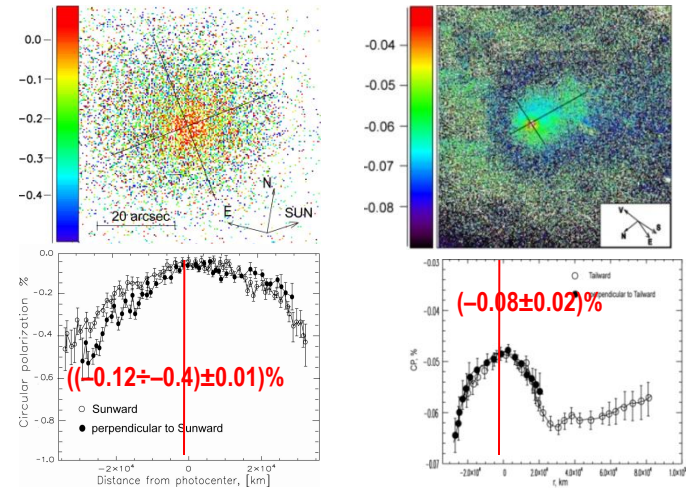
November 08, 2015,  $\alpha=33.2^\circ$



Comparison with comets showing CP and comets with CP  $\approx 0\%$

Circular polarization has not been registered in comet 67P

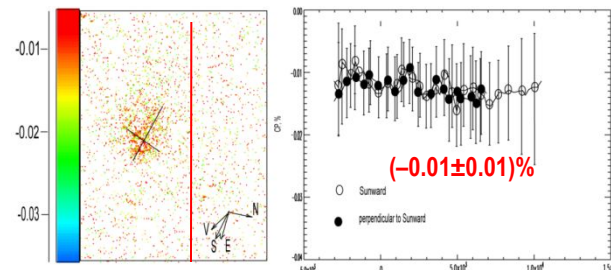
## CP in other comets



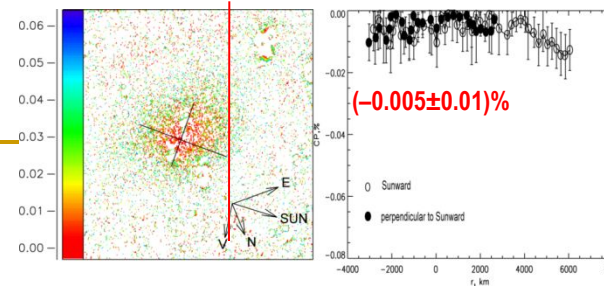
C/2009 P1 (Garradd)

C/2011 R1 (McNaught)

## Comets with CP $\approx 0\%$



290P/Jager



108P/Crieffo

# C/2009 P1 (Garradd)

The Oord cloud comet.

The long period comets are believed to originate from the Oord Cloud.

$$q=1.55126 \text{ au}$$

$$e=1.00024$$

$$i=106.2 \text{ deg}$$

**February 2-14, 2012**

$$r=1.65-1.71 \text{ au}$$

$$\Delta=1.53-1.39 \text{ au}$$

$$\alpha=35.9-35.3^\circ$$

**April 14-21, 2012**

$$r=2.16-2.23 \text{ au}$$

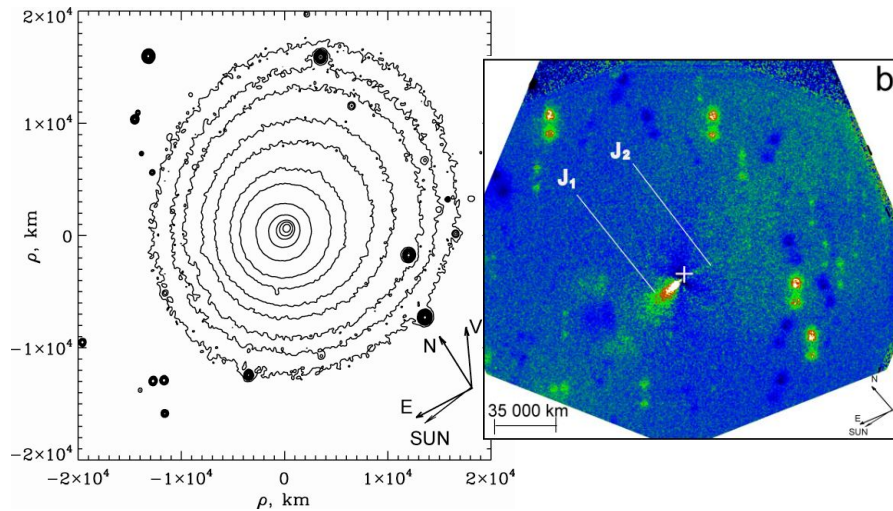
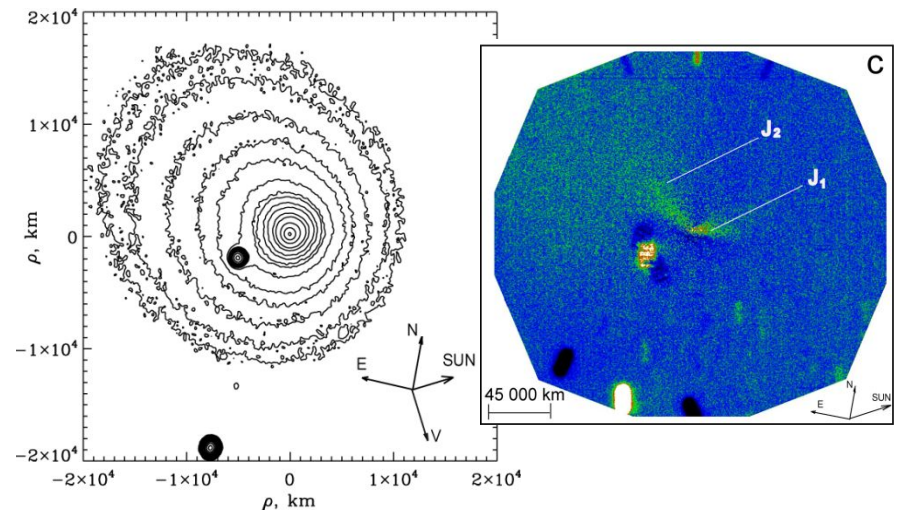
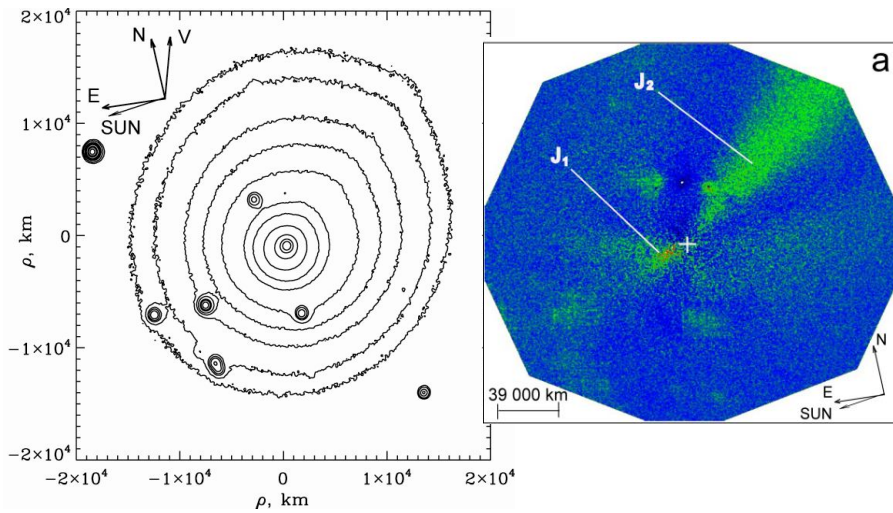
$$\Delta=1.79-1.96 \text{ au}$$

$$\alpha=27.4-26.8^\circ$$



# Methods

# Photometry



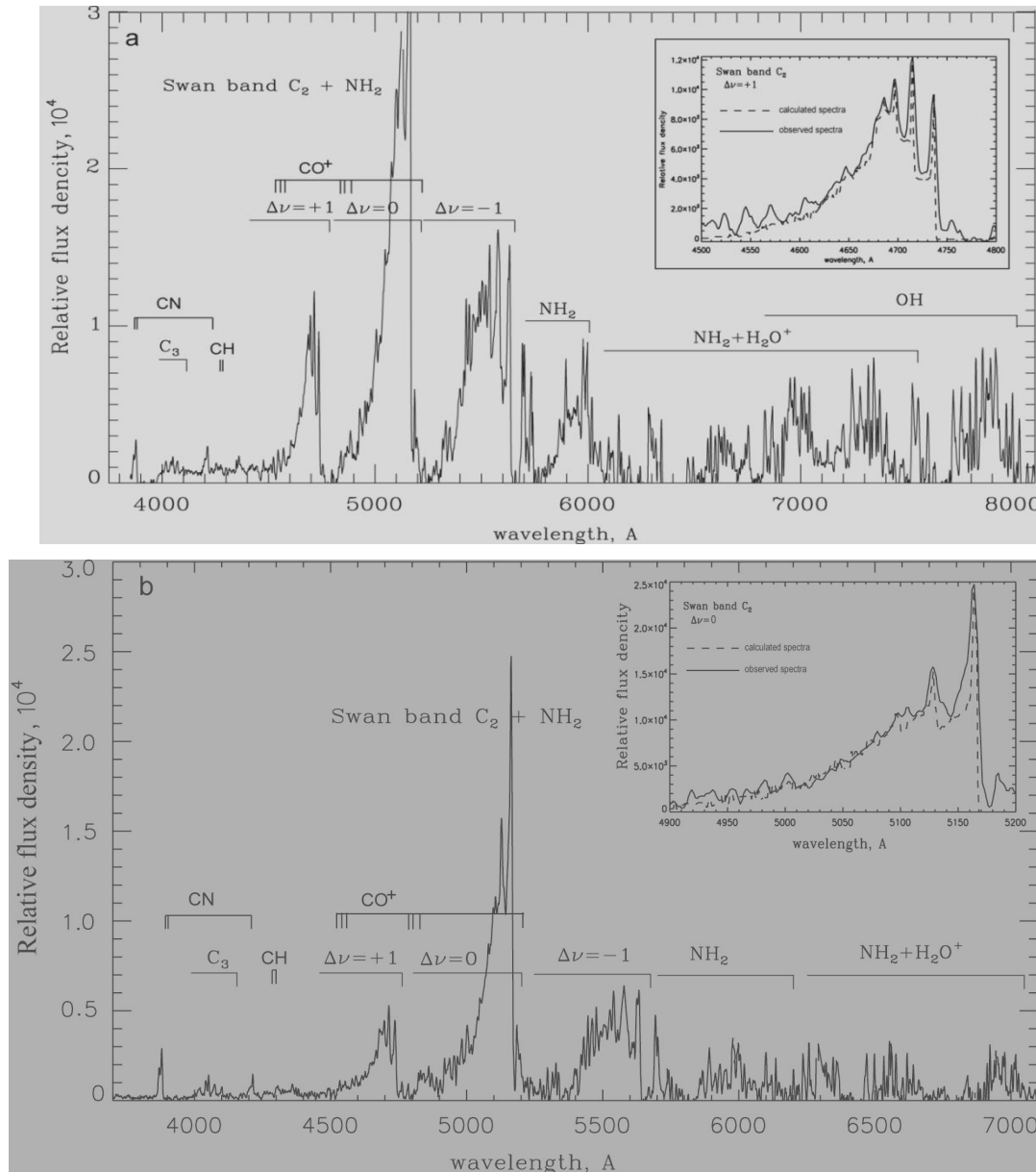
Two features (dust and gas tails) oriented in the solar and antisolar directions were revealed in treated images of comet Garradd that allowed us to determine the period of rotation of the nucleus as  **$11.1 \pm 0.8$**  hours.

# Methods

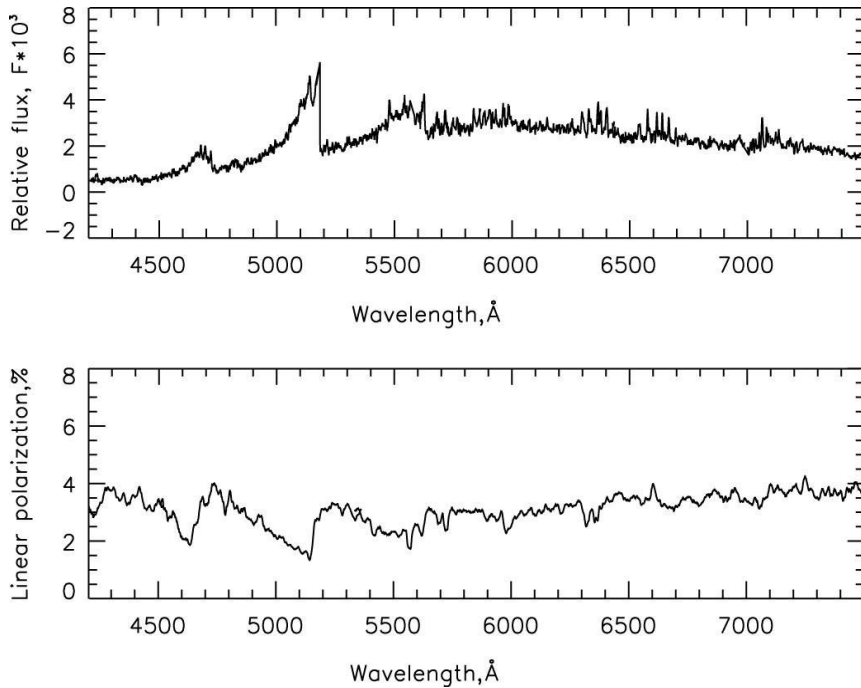
# Spectroscopy

Long-slit spectroscopy of the comet was performed at the 6-m telescope BTA with the multi-mode focal reducer SCORPIO-2. slit  $6.1' \times 1.0''$  was used.

- Emission bands of neutral molecules such as  $C_2$ ,  $C_3$ , CN, CH, and  $NH_2$  as well as  $CO^+$  and  $H_2O^+$  ions were identified in the spectra of the comet Garradd.
- Long-slit spectroscopy of the comet. The comet is “CO-rich”

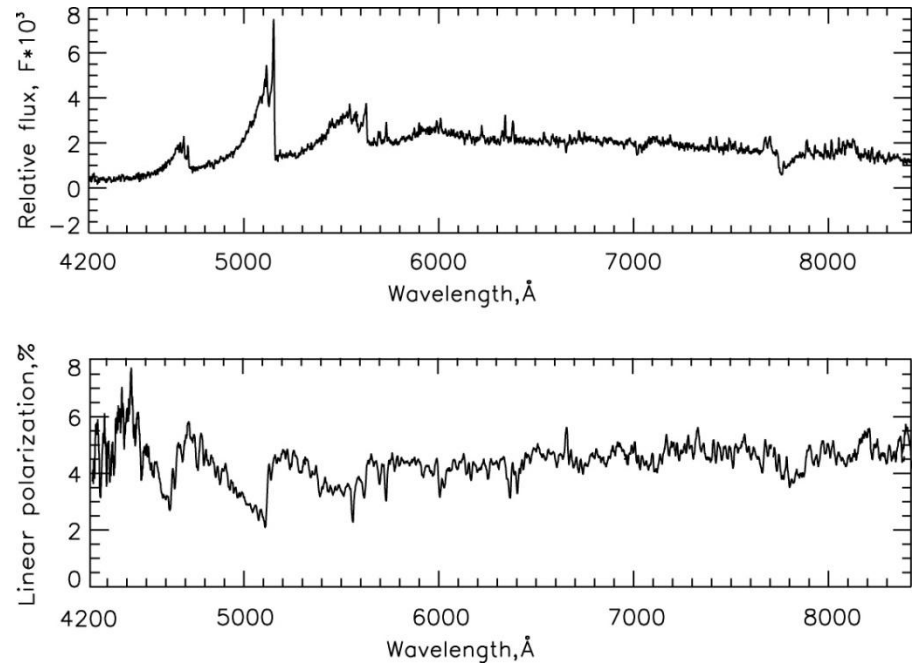


# Methods



The long-slit spectra of comet Garradd obtained at phase angle  $35.9^\circ$  on February 2.086, 2012. The top and bottom panels display the integral intensity and the degree of linear polarization as a function of wavelength in  $3 \times 10$  arcsec ( $3329 \times 11097$  km) area around the center of the comet.

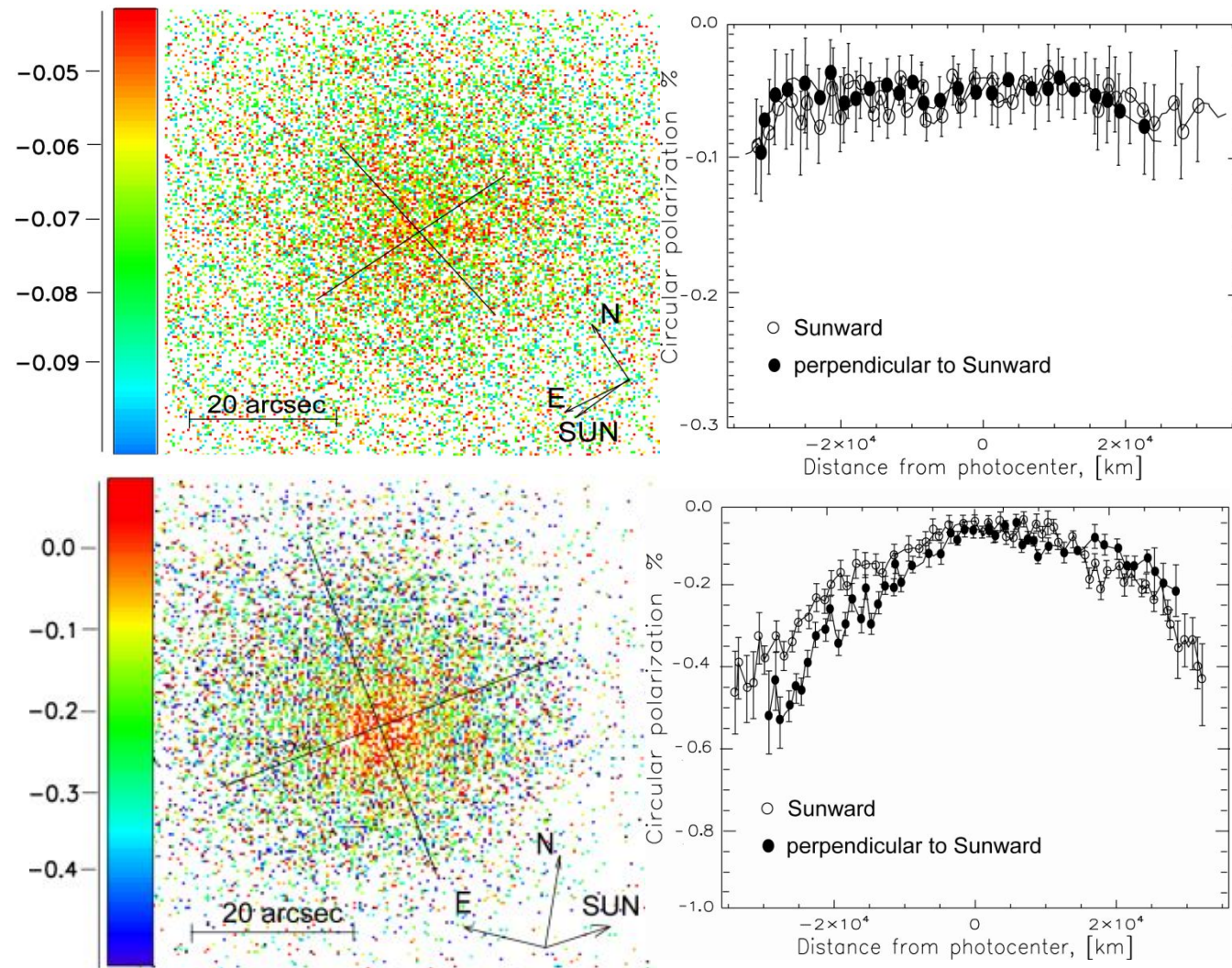
# Spectropolarimetry



The long-slit spectra of comet Garradd obtained at phase angle  $27.4^\circ$  on April 14.864, 2012. The area measured around the photocenter of the comet is  $3 \times 10$  arcsec ( $3916 \times 13055$  km). The notations are the same as in Fig. 9.



# Circular polarization



- The significant left-handed (negative) circular polarization was detected at distances up to  $3 \times 10^4$  km from the cometary nucleus with values from about  $-0.06\%$  to  $-0.5\%$  (with errors 0.02%) on February 14 and April 21, respectively.
- There is some systematic increase in the degree of circular polarization to the outer edge of the coma on April 21.



# “New” comets and Centaurs

The long-period comets are believed to originate from the Oort Cloud. These comets are coming to the inner Solar system for the first time.

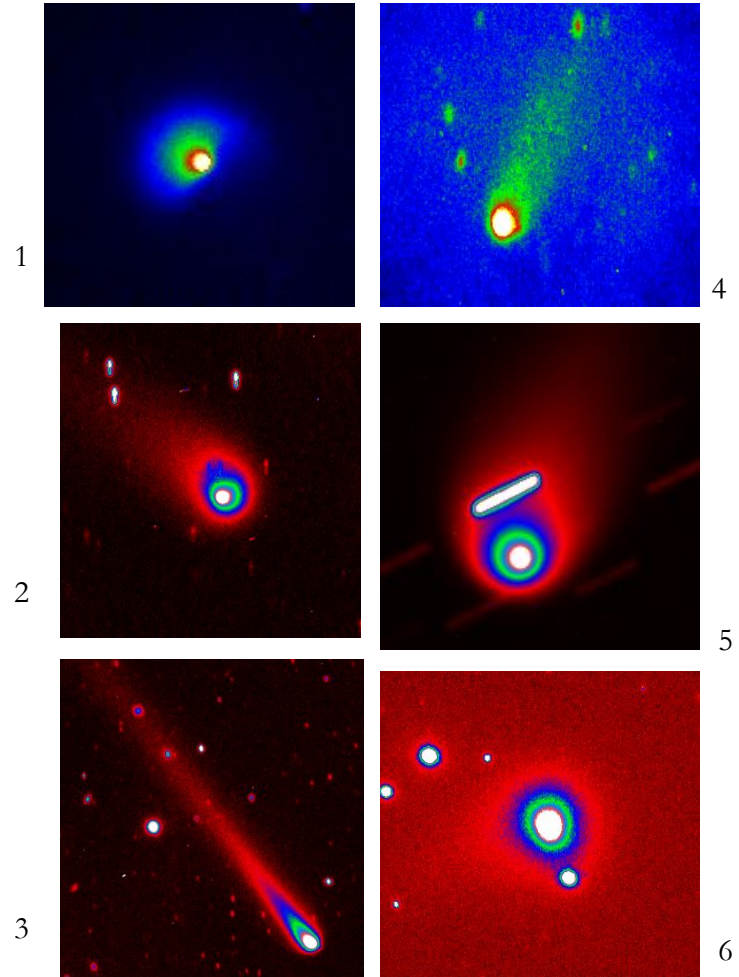
Traditional definition of a dynamically ‘new’ comet, which is the comet visiting our planetary system for the first time, is that it should have its  $1/a < 1 \times 10^{-4} \text{ AU}^{-1}$  (e.g. Oort and Schmidt, 1951).

The dynamical behavior of Centaurs is still poorly understood.

Centaurs are objects, whose orbits meet the following conditions.

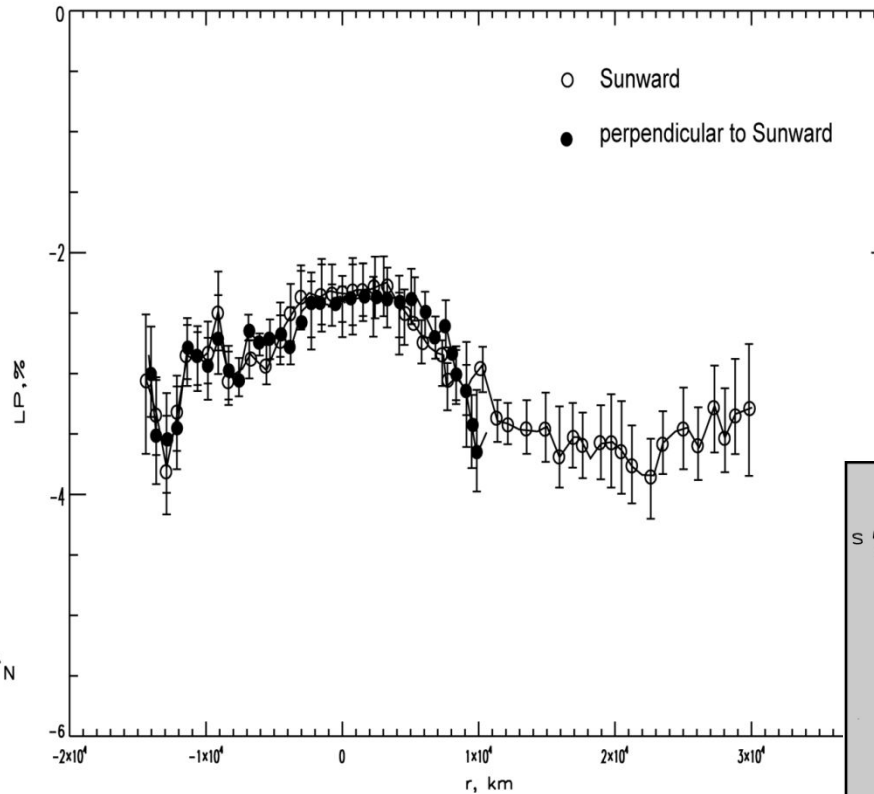
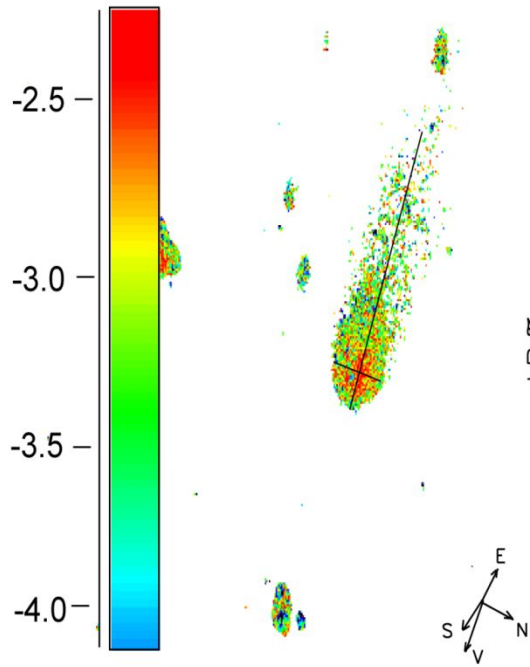
1. The perihelion distance,  $q$ , and the semimajor axis,  $a$ , satisfy

$a_J < q < a_N$  and  $a_J < a < a_N$ , respectively, where  $a_J = 5.2 \text{ AU}$  is the semimajor axis of Jupiter and  $a_N = 30.0 \text{ AU}$  is the semimajor axis of Neptune.



1. 29P/SW1 2. C/2013 V4 (Catalina) 3. C/2014 A4 (SONEAR) 4. C/2010 R1 (LINEAR), 5. C/2010 S1 (LINEAR), 6. C/2012 J1 (Catalina)

# C/2010 R1 (LINEAR)



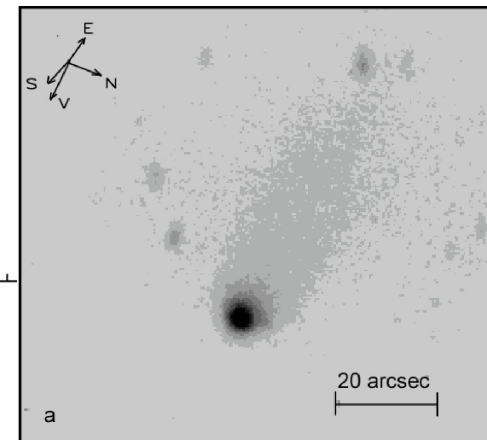
2013, Feb. 6

$r = 5.9$  AU

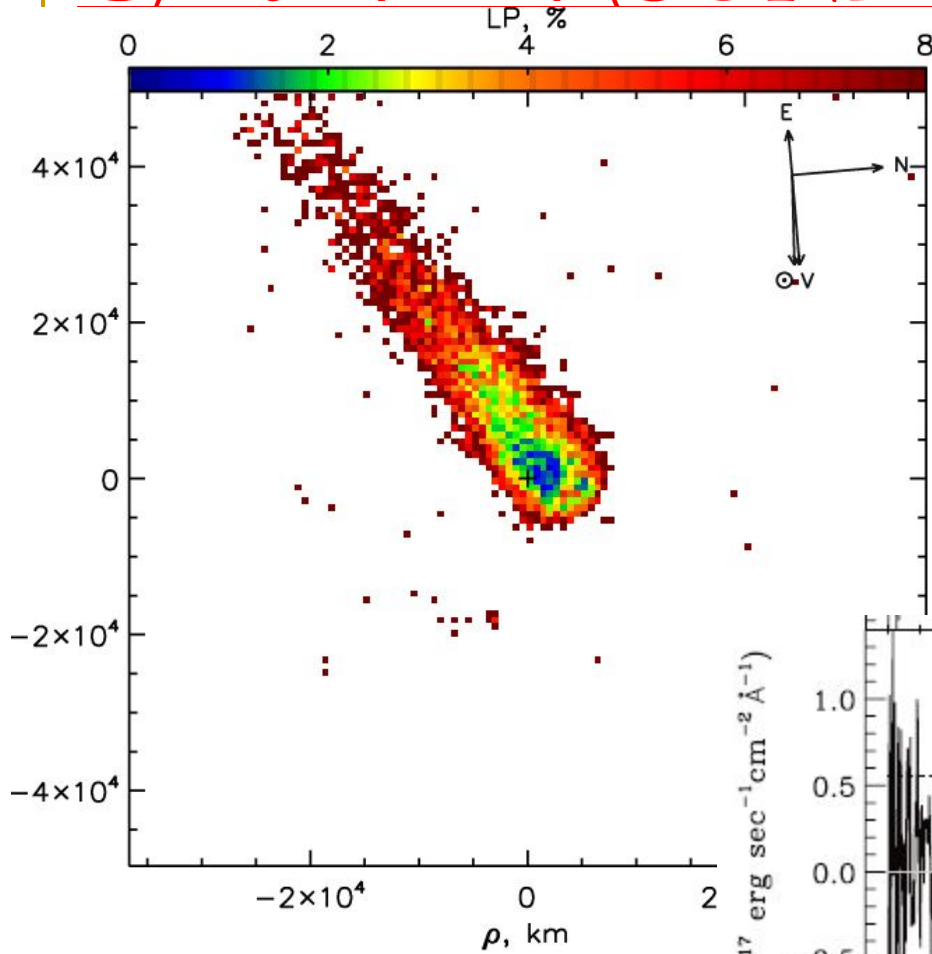
$\Delta = 5.6$  AU

$\alpha = 9.2^\circ$

Filter R



# C/2014 A4 (SONEAR)



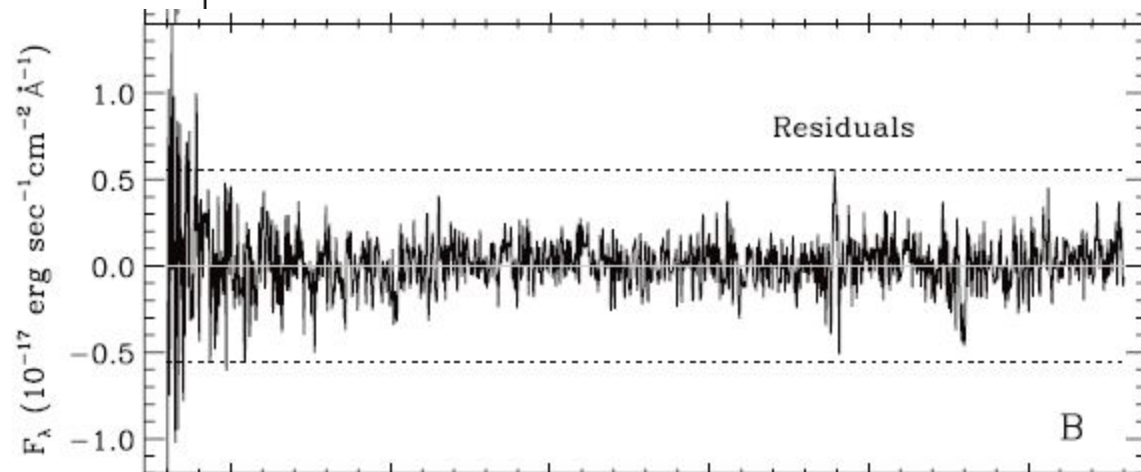
2015, Nov. 5

$r = 4.21 \text{ AU}$

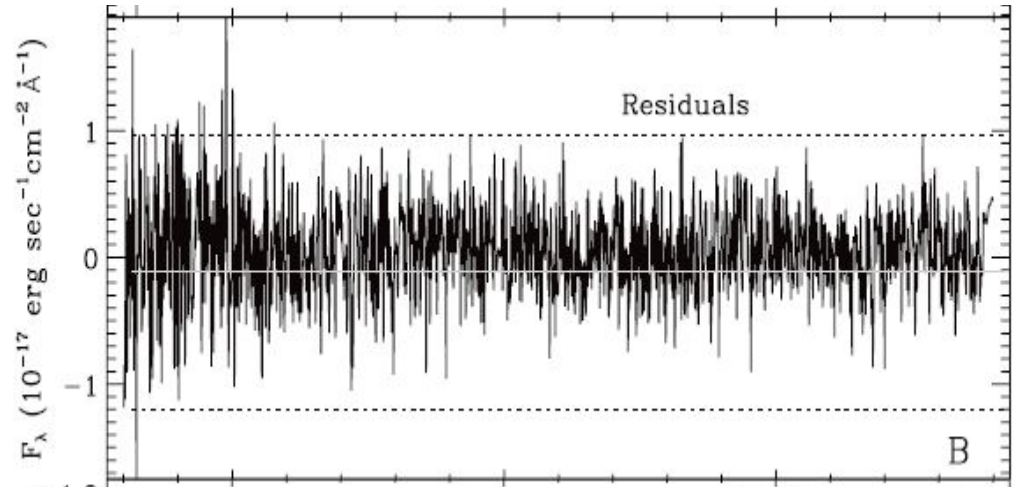
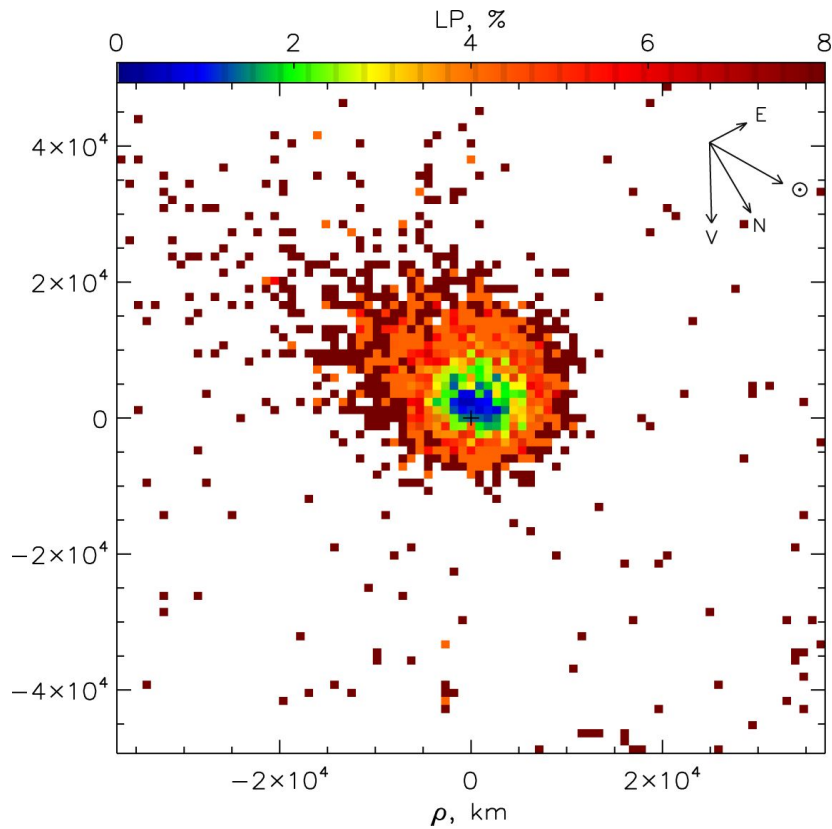
$\Delta = 3.28 \text{ AU}$

$\alpha = 4.9^\circ$

Filter R



# C/2013 V4 (Catalina)



2015, Nov. 6

$r = 5.19$  AU

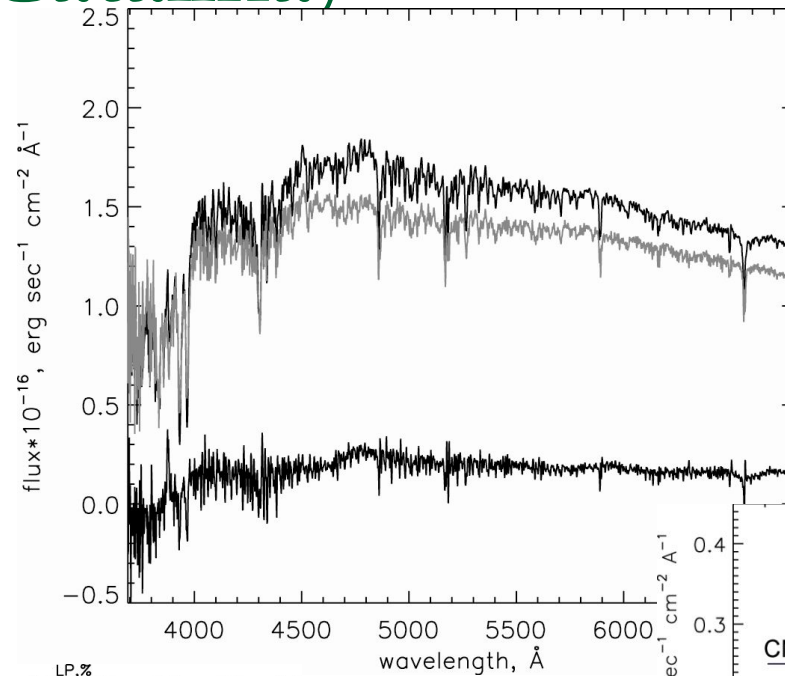
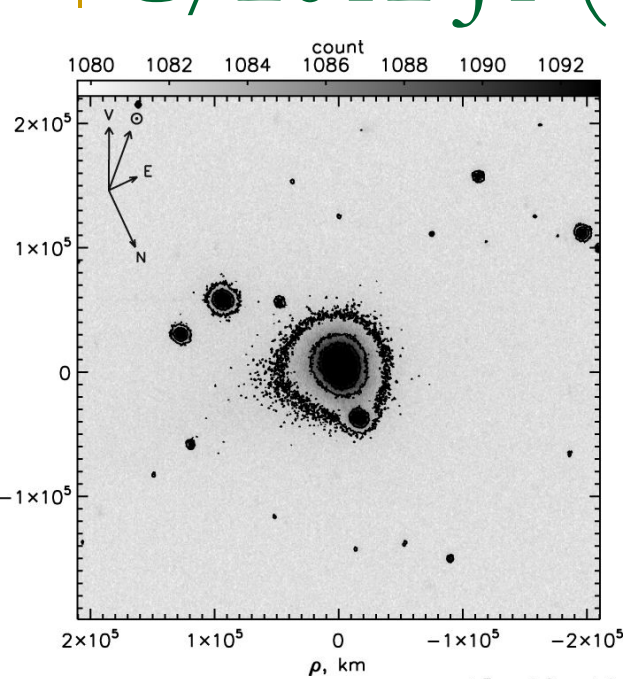
$\Delta = 4.96$  AU

$\alpha = 9.4^\circ$

Filter R



# C/2012 J1 (Catalina)

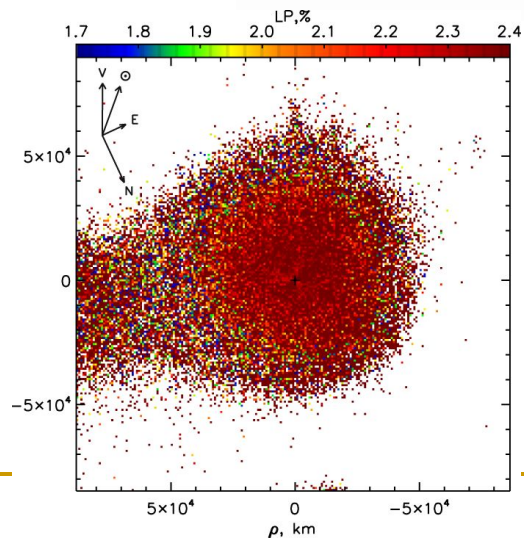
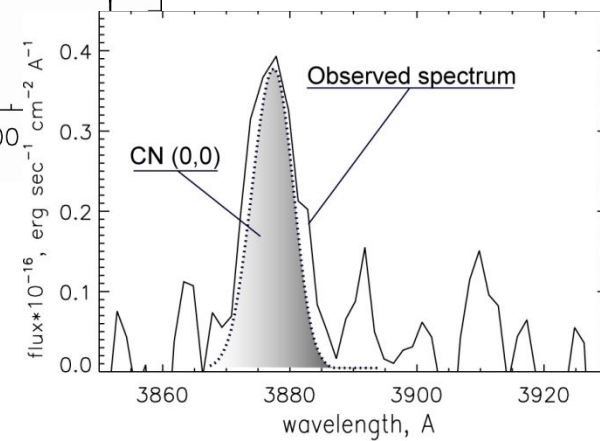


2012, Nov. 15

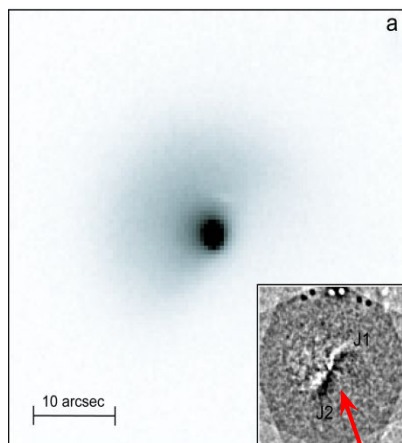
$r = 3.17 \text{ AU}$

$\Delta = 2.45 \text{ AU}$

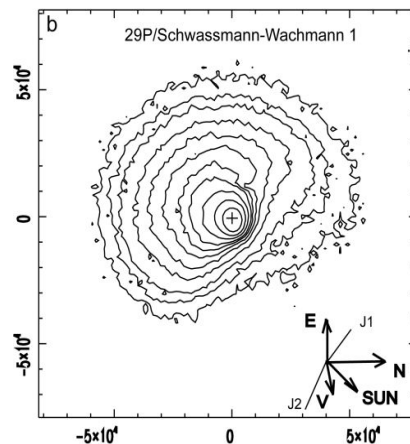
$\alpha = 14.02$



# 29P/Schwassmann-Wachmann 1



Intensity



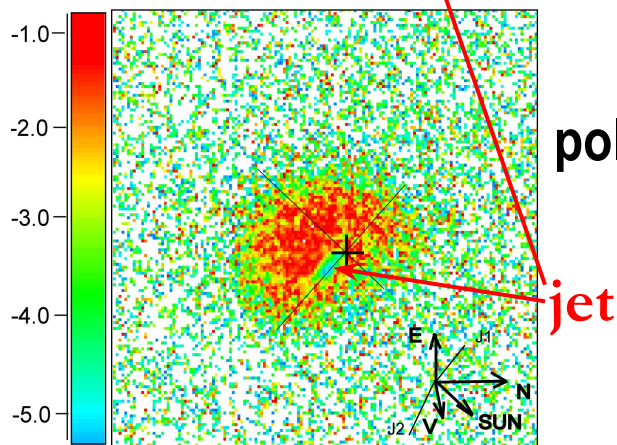
2012, Feb 14

$r = 6.26$  AU

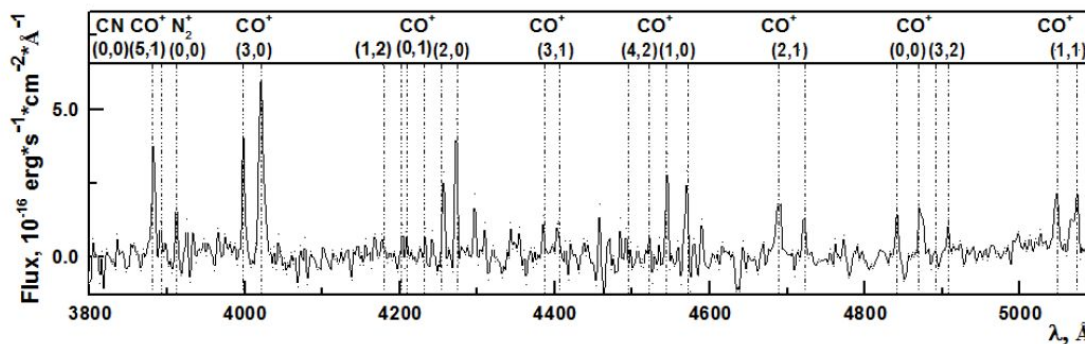
$\Delta = 5.51$  AU

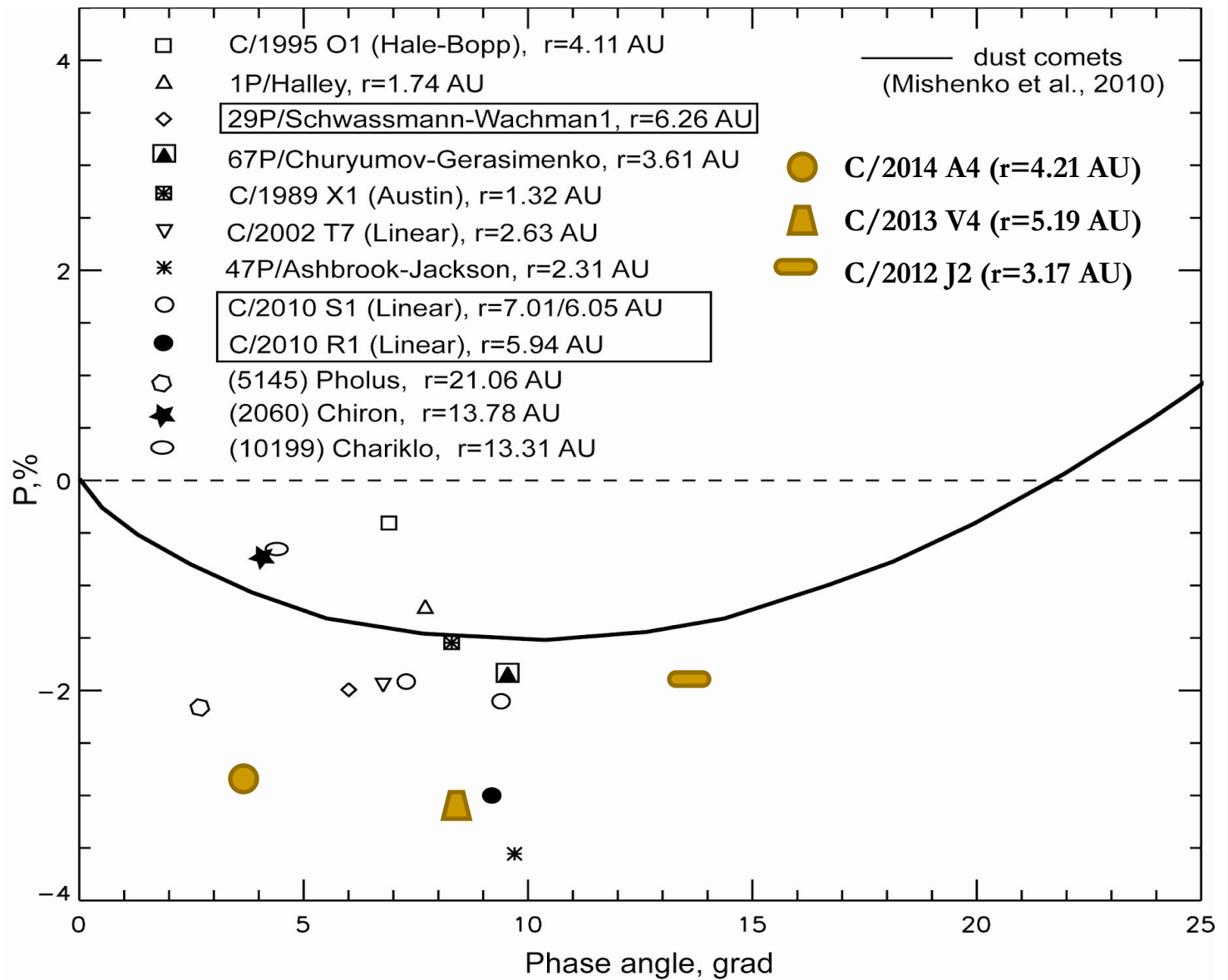
$\alpha = 6.3^\circ$

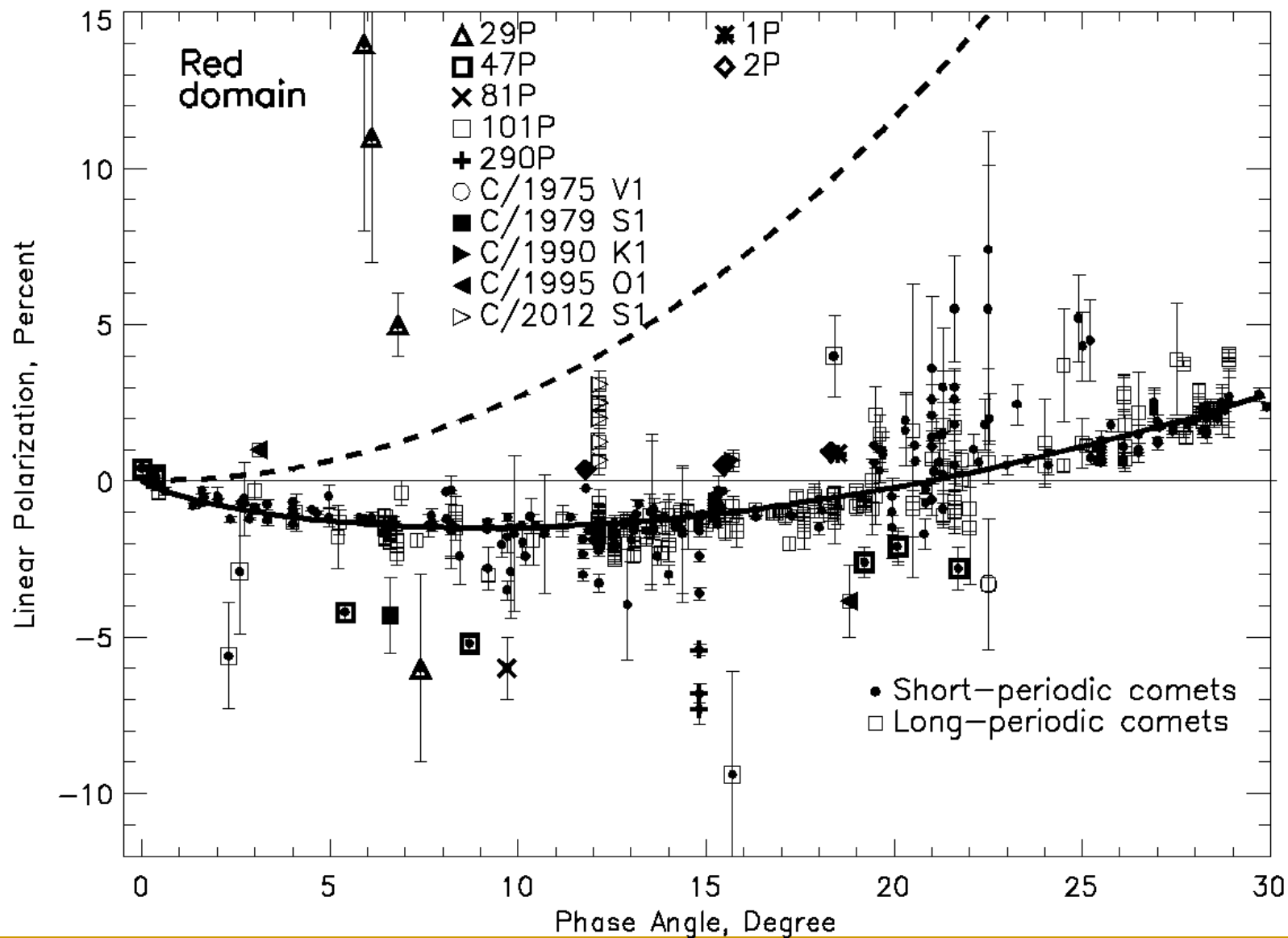
Filter 6840 Å



Linear polarization

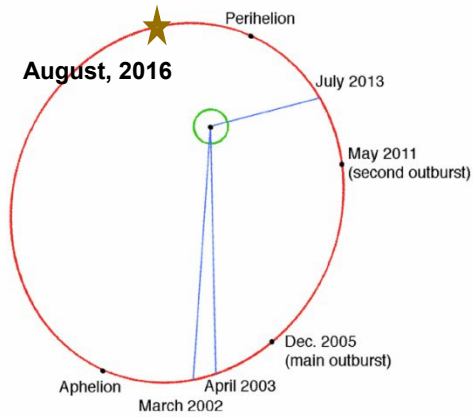






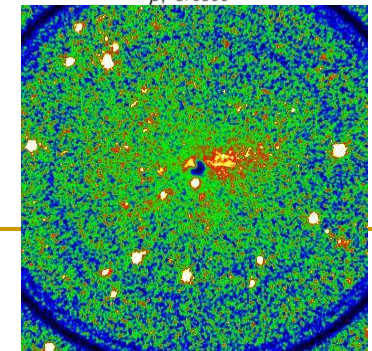
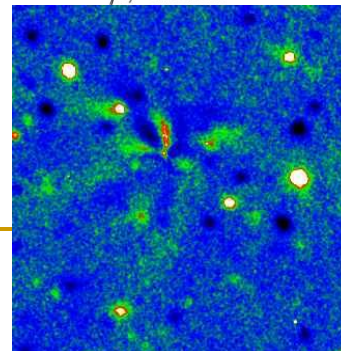
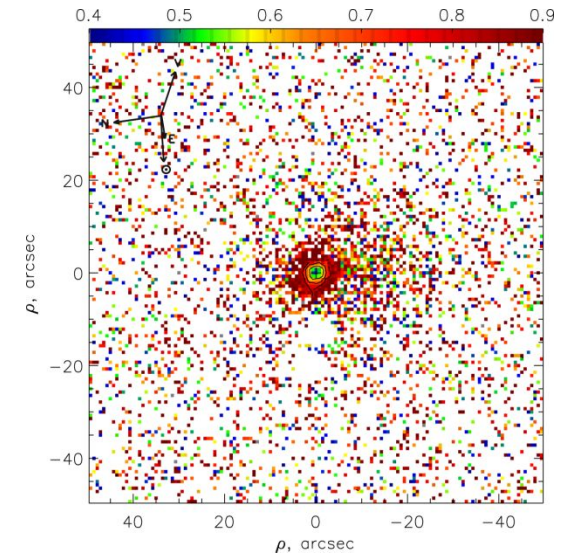
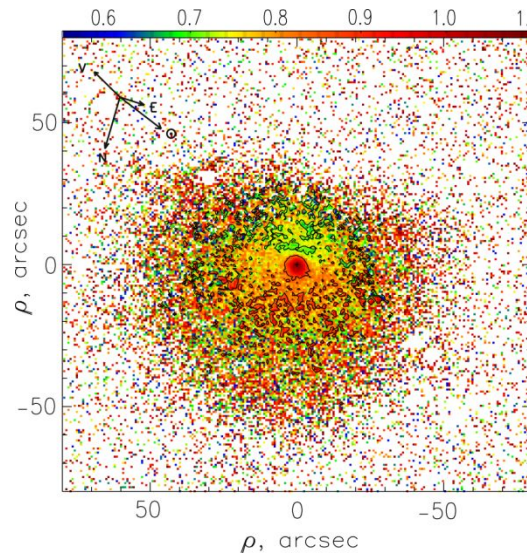
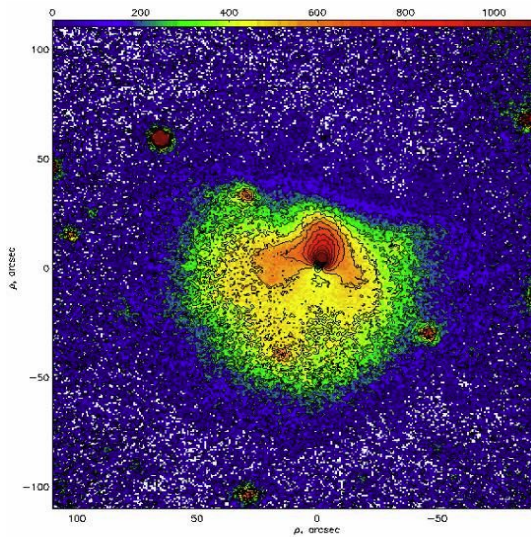


# 174P/Echeclus

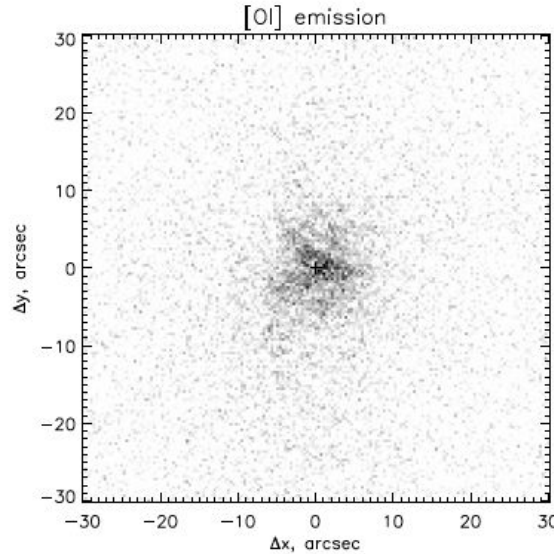
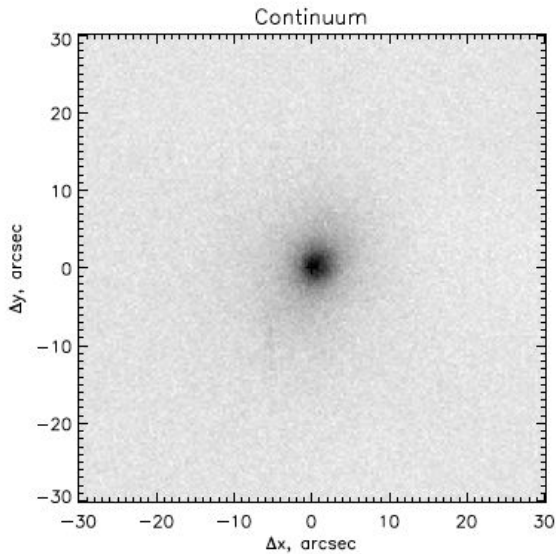


We obtained new observations of an outburst of Centaur 174P/Echeclus at a heliocentric distance of 6.2 au and determined dust production rates and dust colors. We found changes in the dust productivity and morphology of the coma compared to the last outburst. Based on photometrical data, we analyzed the color slope using the model of agglomerated debris particles.

*Article in preparation*



# PRODUCTION RATE $Q(O^1D)$



Radial velocity:

From observations:  $9.3 \pm 0.3$  km/s

From Ephemeris: 9.5 km/s

$$Q(O^1D) = \frac{4}{3} 4\pi \Delta^2 I_{tot} / h\lambda;$$

Table 2.  $Q(O^1D)$  production rate for comets

Comet	Date, UT	r, au	$Q(O^1D)$ , atom/s
Bennet 1970 II <sup>1</sup>	Apr 18, 1970	0.841	$2.8 \cdot 10^{28}$
1P/Halley <sup>2</sup>	Jan 16, 1986	0.790	$2.9 \cdot 10^{30}$
C/1990 V (Austin) <sup>3</sup>	May 16, 1990	1.035	$1.2 \cdot 10^{28}$
C/1995 O1 (Halle-Bopp) <sup>4</sup>	Mar 5, 1997	1.029	$3.21 \cdot 10^{30}$
252P/(LINEAR) <sup>5</sup>	Apr 5, 2016	1.030	$6.1 \cdot 10^{25}$

$$I_{tot} = 8.4 \cdot 10^{-12} \text{ erg s}^{-1} \text{ cm}^2$$

$$Q(O^1D) = 6.1 \cdot 10^{25} \text{ atom/s}$$

<sup>1</sup>Delseme and Combi, 1976; <sup>3</sup>Schultz et al., 1993; <sup>4</sup>Morgenthaler et al., 2001;

<sup>5</sup>This work

Thank you!

