Hunt for Molecules
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REMOTE SENSING OF A COMET AT MILLIMETER AND SUBMILLIMETER WAVELENGTHS FROM A COMET-ORBITING SPACECRAFT

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Abstract. This is a brief description of the ROSETTA mission, launched in 2004, which has a Rendez-Vous with Comet 67P/Churyumov- Gerasimenko, to be reached after a 10yr journey. In particular it is described how the author got involved in the MIRO instrument on ROSETTA.

Good afternoon. I want to thank the organizers of this conference for inviting me to help honor Professor Encrenaz for his role in opening the submillimeter spectral window for spectroscopy.

As mentioned in the Web Site for this symposium, the detection of H_2O and NH_3 at radio wavelengths at Hat Creek, in 1968 and H_2CO at Green Bank in 1969 triggered a frantic hunt for the detection of new molecules in the interstellar medium. In parallel, there also was an intense effort to detect spectral lines in comets, in an attempt to understand better the composition, chemistry, and physical nature of comets and ultimately their origin.

Approximately 5 years after the first detections of interstellar molecules, around 1973, the radio searches succeeded with detections of OH, CH, HCN, and CH_3CN from Comet Kohoutek and H_2O from Comet Bradfield. Dr. Bockelee-Morvan has already given a discussion of the detected molecules in comets to date, and the list is long. I don't intend to give a general discussion of cometary composition in this talk.

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Fig. 1. MIRO Investigation team

- **THIRD CORNERSTONE MISSION OF ESA-LAUNCH MARCH 2, 2004**
- **MISSION TO COMET 67P/CHURYUMOV-GERASIMENKO**
  - **LANDER WITH EIGHT INVESTIGATIONS**
  - **ORBITER WITH ELEVEN SCIENTIFIC INSTRUMENTS (17 MONTHS)**
- **OBJECTIVES**
  - **Origin of comets/relationships interstellar materials/implications for origin of solar system**
  - **Chemical, mineralogical and isotopic compositions of volatile and refractory elements in nucleus**
  - **Evolution of cometary activity with heliocentric distance**
- **FOUR PLANETARY (EMEE) GRAVITY ASSISTS**
- **TWO CLOSE ASTEROID FLYBYS (STEINS AND LUTETIA)**
- **EOM 8/31/15**

Fig. 2. Overview of the Rosetta Mission

I want jump forward twenty years from the first detection of molecules in comets- to the year 1994. At that time 4 spacecraft had successfully encountered comets as flyby missions. The GIOTTO mission was the first to produce close up images of a comet nucleus and was ESA's first deep space mission. It was designed to study Comet P/Halley and it succeeded. The mission was launched by a French Ariane rocket. Table 1 summarizes this history.

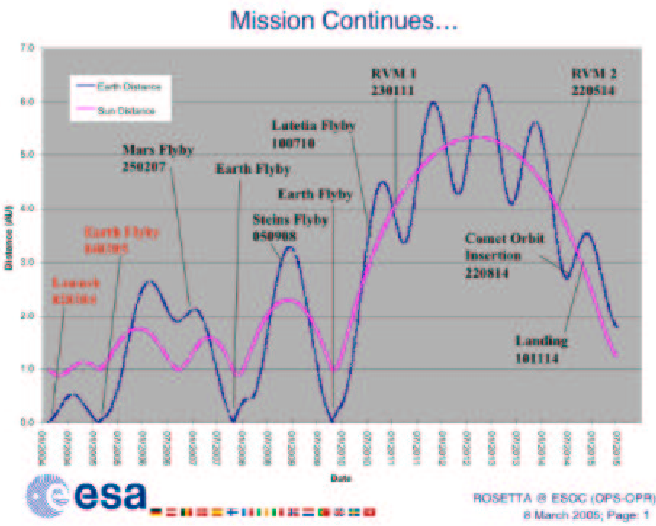

Fig. 3. Rosetta Mission Profile

I was in Paris in 1994 visiting Pierre and Therese Encrenaz. During that visit, Pierre described the ROSETTA mission to me, and told me that a microwave mapper and spectrometer instrument had been identified as a potential additional instrument on the ROSETTA orbiter payload. I believe that Jacques Crovisier, Dominique Bockelee-Morvan, Gerard Beaudin, and Therese Encrenaz all had a hand in getting this instrument concept recognized within the European community. Professor Langevin was the chairman of the ROSETTA SCIENCE TEAM.

Professor Pierre Encrenaz suggested to me that I consider proposing an instrument from the U.S. After a number of discussions with Pierre and Jacques Crovisier, we decided to submit a proposal to NASA which if accepted could be forwarded to ESA for consideration as part of the ROSETTA orbiter payload. The experiment was named MIRO, for Microwave Instrument for the ROSETTA Orbiter. The MIRO experiment

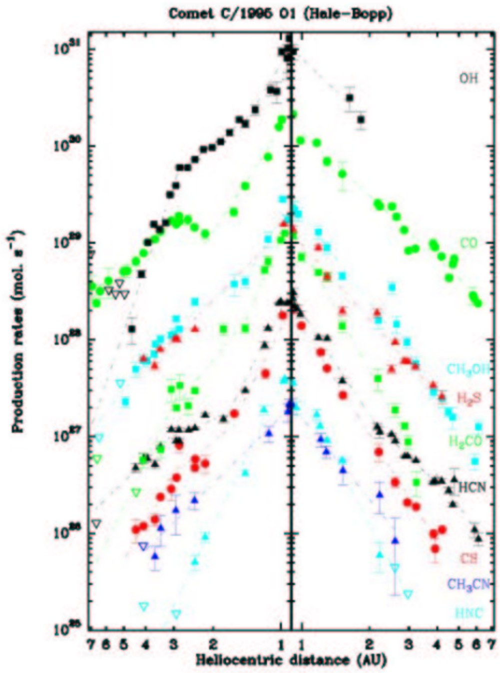

Fig. 4. Production rates of various molecules as a function of helio-centric distance, for Comet Hale-Bopp (Biver et al 2002)

team is shown in the Figure 1. Ultimately, MIRO was proposed and accepted by NASA in 1996, and then forwarded to ESA. It was accepted and became a part of the official payload in 1997.

For those of you not familiar with the ROSETTA mission, let me take a minute to mention just a few of its characteristics. Figure 2 provides an overview of the Rosetta Mission. Figure 3 provides a timeline of the mission expressed as a function of the Rosetta distance from Earth and Sun.

The ROSETTA mission is dramatically different than all previous comet missions. With the exception of Deep Impact, previous missions have all been flyby missions with the comet near 1 AU from the sun at closest approach. Table 1 provides a list of previous spacecraft missions to comets.

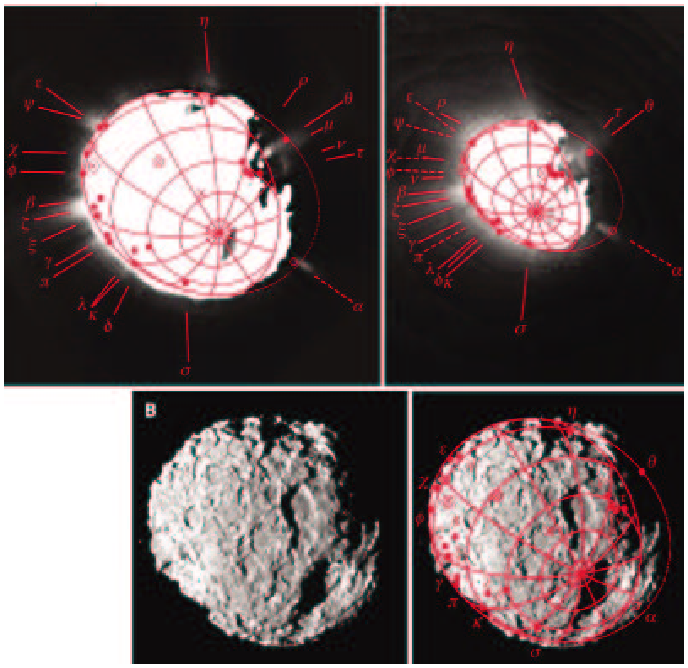

Fig. 5. Results from Stardust at Comet Wild 2. (From Sekanina et al. 2004, Science 304). Straight red lines indicate positions of numerous jects. Dust lies on conical sheets emanating from point like regions. Jets originate from illuminated and dark regions on nucleus.

ROSETTA was planned to be a comet Rendezvous Mission with the orbiter staying in close proximity to the nucleus for an extended period of time. A few key characteristics of the Rosetta mission are:

- 1) Rosetta will encounter Comet 67P/Churyumov-Gerasimenko at a heliocentric distance near 3.5 AU and follow the Comet to a heliocentric distance 1.2 AU;
- 2) The Rosetta S/C will orbit the comet and collect data for 18 months or more;
- 3) The Rosetta S/C carries a surface science probe that will make a

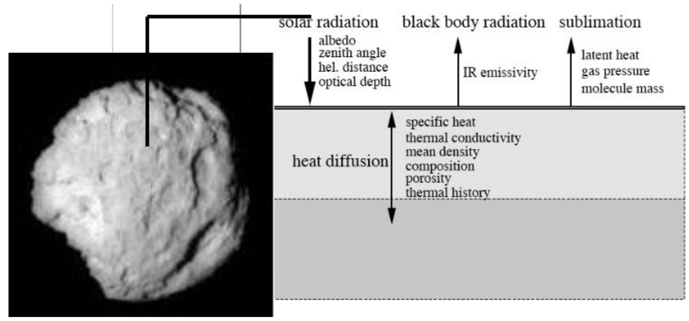

Fig. 6. Energy balance at surface of cometary nucleus (after Voertzen 2003)

soft landing on the comet surface; and

- 4) There are many complementary instruments on the orbiter and probe.

Comet	Mission	Date	Distance	Velocity
21P/Giacobini-Zinner	ICE	11 Sept 1985	7800 km	21 km/s
1P/Halley	VEGA 1	6 Mar 1986	8890 km	79 km/s
1P/Halley	Suisei	8 Mar 1986	150,000 km	
1P/Halley	VEGA 2	9 Mar 1986	8030 km	77 km/s
1 P/Halley	Sakigake	11 Mar 1986	7,000,000 km	
1P/Halley	Giotto	14 Mar 1986	596 km	68 km/s
26P Grigg-Skjelleroup	Giotto	10 Jul 1992	200 km	14 km/s
19P/Borrelly	Deep Space 1	22 Sep 2001	2170 km	17 km/s
81P/Wild 2	Stardust	2 Jan 2004	237 km	6 km/s
9P/Tempel 1	Deep Impact	4 Jul 2005	500 km (+ impactor)	11 km/s

Table 1. Spacecraft Missions to Comets

The importance of measuring the outgassing over a wide range of heliocentric distances and with high spatial resolution is illustrated in the next few figures. Figure 4 shows ground based data compiled by Nicolas Biver and his colleagues that illustrates how the production rate of various molecules in Hale-Bopp depends on heliocentric distance. Figure 5 shows a photograph and sketch of Comet Wild 2 showing the complexity of jet

- **Need Gas and Dust Tracers**
- **Continuum temperature maps and temperature gradients**
- **Sufficient Angular Resolution to resolve nucleus**
  - **At 1 AU - 3 km diam comet subtends 2 x 10^{-8} radians (4 milli arc sec)**
  - **Two serious consequences of not resolving the nucleus are:**
    - **Surface features and including jets cannot be observed, and**
    - **The coma is observed in its entirety with gases streaming both towards and away from the the observer-for an isotropic outflow velocity of 1 km/sec, the effect of not resolving the coma is to broaden a spectral line at submillimeter wavelengths to several Mhz.**
- **There is a need to get close to the nucleus**

Fig. 7. Requirements for understanding sublimation from cometary nucleus

structure from the surface of the comet. Figure 6 shows a schematic of the energy balance that takes place at the surface of a cometary nucleus.

Understanding the energy balance that takes place at the surface of the comet nucleus is a major objective for an mm and submillimeter experiment on Rosetta. Figure 7 gives some broad requirements for a science instrument. These include measurements of the nucleus surface and subsurface temperature, and production rates of major sublimating gases.

In the few minutes remaining, I would like to turn my attention to the MIRO instrument. At the time that MIRO was proposed there had been numerous earth orbiting microwave instruments however there had never been a deep space planetary instrument. Limited mass and power were perceived as engineering drivers. Our design goals were to keep the mass under 20 kg and to size the telescope at 30 cm diameter.

Table 2 shows the molecules and spectral lines chosen to use as tracers for the outgassing. The molecules were chosen because they have submil-

- **30 cm offset parabolic telescope**
- **mm wave continuum receiver**
- **smm wave continuum receiver**
- **4096 channel high resolution(44 kHz) spectrometer interfaced with smm heterodyne receiver (resolving power = 10^7)**
- **Internal hot and cold load calibration targets**
- **Fixed tuned to observe simultaneously H2O(isotopes 16,17,&18), CO, CH3OH(3 lines),NH3**
- **Frequency switched to improve gain stability**
- **Ultra stable oscillator for frequency control**
- **Mass less than 20 kg**

Fig. 8. Characteristics of MIRO instrument

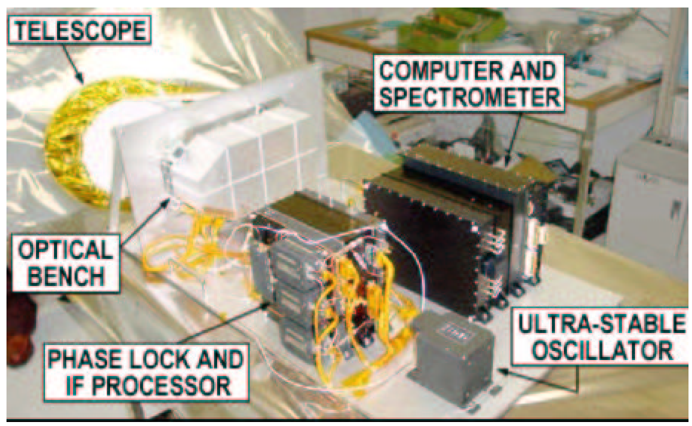

Fig. 9. Photo of the MIRO Instrument

limeter transitions and because their importance in cometary comas. Figure 8 provides an overview of the MIRO instrument. Figure 9 shows a photo of

SPECIES	FREQUENCY(MHz)	TRANSITION
WATER		
$H_2{}^{16}O$	556936.002	1(1,0)-1(0,1)
$H_2{}^{17}O$	552020.960	1(1,0)-1(0,1)
$H_2{}^{18}O$	547676.440	1(1,0)-1(0,1)
CARBON MONIXIDE CO	576267.9305	J(5-4)
AMMONIA NH_3	572498.3784	J(1-0)
METHANOL		
CH_3OH	553146.296	8 (1)–7 (0) E
CH_3OH	568566.054	3 (-2)–2)-1 E
CH_3OH	579151.005	12 (-1)--11(-1) E

Table 2. Molecules and eight transition frequencies observed by MIRO

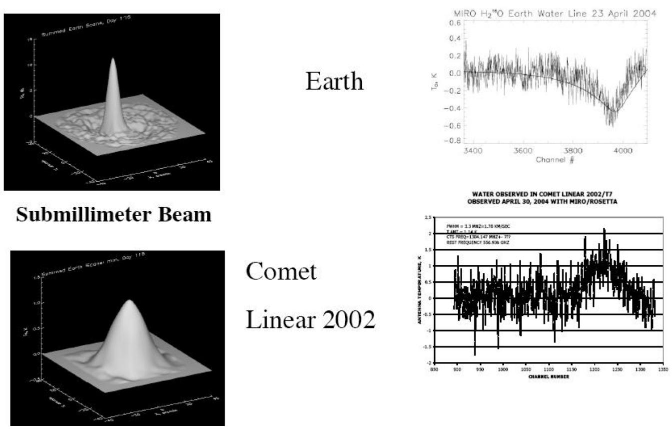

Fig. 10. Shows inflight measured beam patterns (submm at top, and mm at bottom left) and spectra of earth and Comet Linear 2002, for the 556.936 GHz water line.

the instrument.

The Rosetta spacecraft was launched successfully on March 2, 2004. During early commissioning measurements, the antenna patterns were measured using the earth as a source. These are shown in Figure 10. A frequency switched water line in the Earth's atmosphere is shown in Figure 11. Table 3 gives performance parameters measured during the commissioning period.

	Millimeter	Submillimeter
Telescope		
Diameter	30 cm	30 cm
Beam-Width(FWHM)	23.8 arc min	7.5 arc min
Foot-Print (@ 2 km)	15 m	5 m
Spectral Characteristics		
Frequency	188.5-191.5 GHz	547.5 – 580 GHz
IF Continuum Bandwidth	550 MHz	1100 Mhz
Spectral Resolution		44 KHz
Spectral Bandwidth		180 MHz
No. Channels		4096
Radiometer		
DSB Noise Temp	800 K	3800 K
Data Rates	Combined with submillimeter	0.1 – 1.92 kbps

Table 3. Performance Parameters of MIRO Instrument

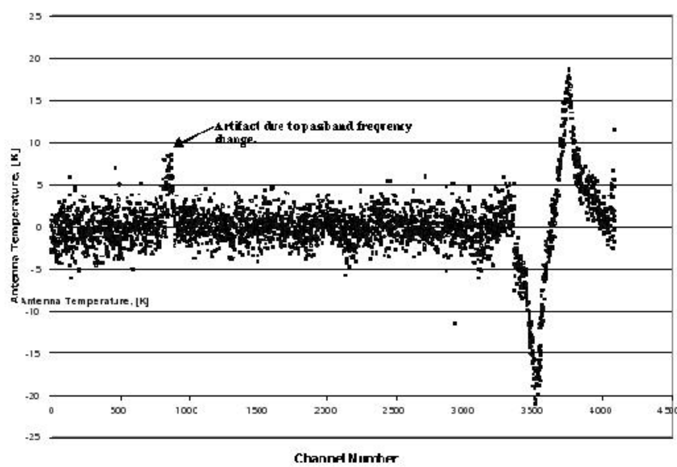

Fig. 11. Frequency switched spectrum of water appears near channel 3500