FORMATION SCENARIOS OF ASTEROID BINARIES AND IMPLICATIONS FOR THE SCIENCE RETURN OF THE MARCOPOLO-R MISSION

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What do observations tell us about small binaries

• They represent 15% of the Near-Earth Object (NEO) population
• Most of them seem to have similar properties:
  – Rapidly rotating primaries
  – Spherical/oblate primaries
  – Close secondaries
  – Low eccentricities

1999KW4, Ostro et al.
Top Shapes and Ridges

1999 KW₄ radar model, Ostro et al. 2005

Formation model, Walsh et al. 2008

Single asteroid 1999 RQ₃₆
Howell et al. 2008, ACM

Binary 2004 DC
Taylor et al. 2008, ACM

Šteins from Rosetta Images
Added science value of a binary target for a sample return space mission

- Binary asteroids represent 15% of the NEO population

- Several formation mechanisms have been proposed, each starting from a single body which separates and forms two components (e.g. Walsh et al. 2008, Jacobson&Scheeres 2011)

- Determining the physical properties of a binary would help discriminating between the different formation scenarii

- According to some scenario, some portions of the surface would be ideal spots for a sample return space mission

- A binary is an ideal target to study the fascinating geology and surface processes in a low g environment
Formation mechanisms of small binaries

- Catastrophic disruption of a large asteroid: formation of aggregates and binaries
- Tidal encounter with a planet fragment a body into a binary system
- YORP spin-up can break a body into a binary system

However, not all 3 mechanisms form binaries with observed properties of NEO binaries, but all imply that these bodies have particular physical properties, which can be checked by a space mission.
Advantages of the binary target for a sample return mission

- maximize the scientific return of the mission,
- offer advantages for orbiter dynamics

- The presence of a satellite of the target asteroid allows having a mass determination in advance of the mission.

- Precise measurements of the mutual orbit and rotation state of both components can be used to probe higher-level harmonics of the gravitational potential, and therefore internal structure.

- A unique opportunity is offered to study the dynamical evolution driven by the YORP/Yarkovsky thermal effects and the associated fascinating geology and surface processes in a low-g environment.

- Possible migration of regolith on the primary from poles to equator reveals fresh (previously subsurface) material on the pole (good candidate site for “fresh” sample collection)

1999 KW4 (image Radar)
Cosmic Vision ESA – M3

Science Study Team (SST):
M.A. Barucci (F) Chair
P. Michel (F) Co-Chair
J. Brucato (I)
H. Böhnhardt (D)
E. Dotto (I)
P. Ehrenfreund (NL)
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(ESA - Study Scientist)

David Agnolon
(ESA- Study Manager)

Jens Romstedt
(ESA - Study Payload Manager)

Selected in Feb. 2011 for assessment study phase
Next selection step: December 2013
MarcoPolo-R addresses a wide range of objectives

**Stars**
Stellar nucleosynthesis
Nature of stellar condensate grains

**The Interstellar Medium**
IS grains, mantles & organics

**The proto-solar nebula**
Accretion disk environment, processes and timescales

**Planetary formation**
Inner Solar System Disk & planetesimal properties at the time of planet formation

**Asteroids**
Accretion history, alteration processes, impact events, regolith

**Life**
Nature of organics in NEOs

**The Earth**
Impact hazard
Evolution of life on Earth
Small bodies in our Solar System

- Several populations: Near-Earth, main belt, Kuiper belt
- Fate: impact into the Sun, on planets, ejected from the Solar System
Impacts had both beneficial and destructive effects on the evolution of planetary biospheres.

During the late phase of Earth accretion (Walsh et al. 2011) and 3.9 Gyr ago:
Late Heavy bombardment LHB
(cf. The Nice Model)
Carbon chemistry
From stars to life
## Organic compounds in Murchison

<table>
<thead>
<tr>
<th>Compound Class</th>
<th>Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>106</td>
</tr>
<tr>
<td>CO</td>
<td>0.06</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.14</td>
</tr>
<tr>
<td>NH₃</td>
<td>19</td>
</tr>
<tr>
<td>Aliphatic hydrocarbons</td>
<td>12-35</td>
</tr>
<tr>
<td>Aromatic hydrocarbons</td>
<td>15-28</td>
</tr>
<tr>
<td>Amino Acids</td>
<td>60</td>
</tr>
<tr>
<td>Monocarboxylic acids</td>
<td>332</td>
</tr>
<tr>
<td>Dicarboxylic acids</td>
<td>26</td>
</tr>
<tr>
<td>α-hydroxycarboxylic acids</td>
<td>14</td>
</tr>
<tr>
<td>Polyols (sugar-related)</td>
<td>~24</td>
</tr>
<tr>
<td>Basic N-heterocycles</td>
<td>0.05-0.5</td>
</tr>
<tr>
<td>Purines</td>
<td>1.2</td>
</tr>
<tr>
<td>Pyrimidines</td>
<td>0.06</td>
</tr>
<tr>
<td>Amines</td>
<td>8</td>
</tr>
<tr>
<td>Urea</td>
<td>25</td>
</tr>
<tr>
<td>Benzothiophenes</td>
<td>0.3</td>
</tr>
<tr>
<td>Alcohols</td>
<td>11</td>
</tr>
<tr>
<td>Aldehydes</td>
<td>11</td>
</tr>
<tr>
<td>Ketones</td>
<td>16</td>
</tr>
</tbody>
</table>

Sephton 2002
Asteroids: a wide variety of physical & compositional properties

We do not have yet a detailed image of a primitive Near-Earth Asteroid. We need several missions to obtain a comprehensive knowledge of primitive materials.
Understanding primitive materials: an international objective

**MarcoPolo-R**: selected for the assessment study phase of M3-class missions of the Programme Cosmic Vision 2015-2025 of ESA in Feb. 2011

**On-going selected projects:**

**Hayabusa 2**: phase B at JAXA, launch in 2014

**OSIRIS-Rex**: selected in NASA New Frontiers, launch in 2016

**Common objectives:**

Origin and evolution of the Solar System, origin of life, Hazard

Require several missions to understand the diversity and to have a comprehensive knowledge of primitive materials
Baseline MP-R Target: (175706) 1996FG3
Dynamical properties

- Class: C-type binary
- Orbit: 0.69 to 1.42 AU from Sun
- Inclination: 1.99 deg
- Eccentricity: 0.3498
- Orbital period: 1.08 years
Radar Observations Log
Close Approach Distance = 0.101 AU on 2011 Nov. 23

**Arecibo**
Nov. 6, 17, 18, 20, 21, and 22
Dec. 14 and 17
CW echo power spectra, ranging, & 75 m-resolution images

**Goldstone**
Nov. 20, 21, 22, and 25
CW echo power spectra and 150 m-resolution images
Baseline MP-R Target: (175706) 1996FG3
Evidence for an equatorial ridge

1996 FG3: 2011 Nov. 22

Doppler frequency (0.24 Hz/column) -->

1999 KW4
Ostro et al. (2005)

L. Benner Courtesy
Dimensions

Primary Diameter  ~ 1.9 km
Secondary Diameter  ~ 0.5 km

Radar cross section:  0.45 km² +- 35% (X-band)
Radar albedo:  0.16 +- at least 35%

L. Benner Courtesy
More *Preliminary* Results

Maximum separation = 2.55 km (on Nov. 22)
Subradar latitude = 16 deg
-> Mass ~ 3 E12 kg
-> Density ~ 0.9 g/cm$^3$

CAVEATS:
1. Ignores the mass of secondary
2. Assumes the primary is a sphere with D = 1.9 km
3. Assumes the orbit is circular
4. Uncertainties could easily be >30%

Future Work:
Shape modeling
Orbital parameter and mass estimation
Gravitational slopes

L. Benner Courtesy
Other Selected Physical Properties

Absolute mag.  $H = 18.005$  JPL/Horizons
$H = 17.76 \pm 0.03$  Pravec et al. 2006

Spectral class: C  Bus and Binzel 2002

Albedo  $p_v = 0.029 \pm 0.012$  Mueller et al. 2011

Binary system: (Pravec et al. 2006)

Primary Period  $P = 3.5942 \pm 0.0001 \text{ h}$

Secondary orbital period  $P = 16.14 \text{ h}$  synchronous
1996FG3 in the 3-μm region

- Only second NEO found with a 3-μm band
- 6 Dec data best
  - 20 Nov data too high phase for this thermal model
  - 24 Dec data consistent but rattier

- Band of ~5-10%, consistent with band shapes in meteorites, Pallas-types
  - Band depth dependent upon exact thermal correction

- Interpreted as hydrated/hydroxylated

From A. Rivkin et al.
MarcoPolo-R will provide insights…
### MarcoPolo-R Science

## Baseline Science Payload

<table>
<thead>
<tr>
<th></th>
<th>Wide Angle Camera (WAC)</th>
<th>Narrow Angle Camera (NAC)</th>
<th>Close-Up Camera (CUC)</th>
<th>Visible Near Infrared spectro. (VisNIR)</th>
<th>Mid-Infrared spectro. (MidIR)</th>
<th>Radio Science Experiment (RSE)</th>
<th>Neutral Particle Analyser (NPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass [kg]</strong></td>
<td>2.0</td>
<td>8.92</td>
<td>0.82</td>
<td>3.6</td>
<td>3.0</td>
<td>Contained in the resources of the radio subsystem</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Volume [mm]</strong></td>
<td>237x172x115</td>
<td>520x380x197</td>
<td>364x78x68</td>
<td>270x110x90</td>
<td>160x220x370</td>
<td>Contained in the resources of the radio subsystem</td>
<td>200x200x100</td>
</tr>
<tr>
<td><strong>Power [W] average</strong></td>
<td>11.5</td>
<td>13.5</td>
<td>12.5</td>
<td>18</td>
<td>2</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td><strong>Data volume single measur.</strong></td>
<td>67 Mbit</td>
<td>67 Mbit</td>
<td>67 Mbit</td>
<td>0.45 Mbit</td>
<td>360 Mbit</td>
<td>Data recorded in the ground station in real time</td>
<td>0.72 kbit</td>
</tr>
</tbody>
</table>

**Optional payloads:** lander with payloads, laser altimeter, seismic experiment
Lander Deployment: very easy on the secondary!
Laboratory investigation of returned samples

High spatial resolution and analytical precision are needed:

- High precision analyses - including trace element abundances to ppb levels and isotopic ratios approaching ppm levels of precision
- High spatial resolution - a few microns or less
- Requires large, complex instruments – e.g. high mass resolution instruments (large magnets, high voltage), bright sources (e.g. Synchrotron) and usually requires multi-approach studies
Baseline mission

Target: 1996 FG3, several months stay time
Launch window: 2021/2023 and sample return in 2029
Soyuz Fregat launcher, electric propulsion, direct interplanetary Escape; industrial studies started in Feb. 2012 until summer 2013

Single primary spacecraft, carrying:
• Earth Re-rentry Capsule (ERC)
• Sample acquisition and transfer system (SAS)

Touch and go sampling mechanisms (non-exhaustive list):
• Brush or cutting wheels
• Corers
• Gaseous transport devices

Sample device should collect a minimum of 100 g sample (dedicated study starting in July 2012)
Sampling - technology

1. SENER company + Comet Nucleus Sample Return (CNSR) activities in the 90’s → corer works!!
   a. Systematically collected over 50 grams
   b. Forces and torques within the specifications
   c. Very simple system

2. Other activity by Astrium internal R&D: looked at a different concept

3. For touch and go:
   a. “Sampling tool mechanism for low-gravity bodies”, activity funded by MREP, 700k€, split into two phases. Phase 2 will test sampling tool in microgravity, i.e. parabolic flight
   b. Same environment requirements as for MP-R → will be updated after the Science Study Team feedback on soil properties
   c. The activity is very open right now
   d. Study Kick-Off in July 2012
In summary

• The different models of binary formation imply different internal and surface structures of the components: MarcoPolo-R will allow us to discriminate between these models!

• All scenarii imply that the progenitor is low-strength and not perfectly monolithic: MarcoPolo-R will allow us to check this (mechanical properties of the sample, bulk density and gravitational potential of the primary)!

• A mission to a binary allows investigating the fascinating geology and surface processes at work in a low-g environment!

• The space investigation of a binary allows the deployment of a lander on the secondary with minimal effort and risk!

A sample return from a binary, in addition to the science of primitive materials, will allow us to test these scenarios and their implications on the physical properties of small bodies.
MarcoPolo-R will use a combination of in situ and laboratory measurements to:

- provide a unique window into the distant past
- allow scientists to unravel mysteries surrounding the birth and evolution of the solar system
- involve a large community, in a wide range of disciplines
- Planetology
  - Nucleosynthesis
- Astrobiology
  - Cosmochemistry
- retain samples for future advances through a Curation and Distribution Facility
- demonstrate key capabilities for any sample return mission
- generate tremendous public interest

David Hardy
An easy case for outreach

MARCO POLO R #3
I need to be ready for my long interplanetary trip on 2020-21.

To make my electronic senses at high level performances.

To find the best way to come back safely to the Earth.

To teach me how to communicate: to far from and to speak to the Earth...

They have to take care of my weight to minimize the launch cost.

I put 2 industries in competition: Astrum Ind and Thales Alenia Space Ind.

Industries are studying to provide me with all the necessary resources.

Scenario: A. Barucci - Dessin/Couleur: S. Caujade 04.12

MARCO POLO R #6: THE SHOPPING LIST

OK guys, now it's the time for you to give me my shopping list.

So you want preferentially organic matter?

Any material having its original composition, just like raw food.

Look also for some water: it's a vital element.

This material is more precious than gold: between 3 kg and 3 kg, and of various sizes.

Isn't there a price/kg?

It's a flat rate... to make it cheaper, take as much as you can.

Our planetary system is like an omelette! We want to look at the ingredients of this omelette.

I see! I have to shop in a planetary building shop! That's awesome.

It may also contain the ingredients that served to start life on Earth!

Why is this so precious?

Sparkling or still?

Sparkling? Interesting idea... volatile... hmp! Take what's available.

Ok, how much of this should I bring back?

Story: P. Michel - Dessin: S. Caujade
European Community Supporters:
577 scientists (May 2012), 25 countries
Join us!!

International collaboration is open

Next Workshop and Symposium:

• Paris (CNES HQ), Dec. 17-18, 2012: Cosmochemistry Workshop

• Barcelona (Spain), Jan. 16-17 2013: 4th MarcoPolo-R Symposium

MarcoPolo-R is on Facebook:
http://www.facebook.com/pages/MarcoPolo-R-Space-Mission/40232049502