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2004: The Annus Mirabilis of the Planetary System Exploration

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Abstract. 2004 has represented for the majority of the international scientific community involved in planetary sciences an exceptional year. Many space probes designed and developed in the last two decades reached their operational stage and started producing scientific data of unprecedented quality. The ESA's planetary probes MARS EXPRESS, ROSETTA and SMART1, the NASA-ASI-ESA mission CASSINI-HUYGENS have all started their activity last year and, in many cases, shall continue well into the next decade. The italian contribution to these missions is relevant in terms not only of scientific contribution but also in terms of hardware contribution. Since the end of the 80's the italian scientific community with the support of the Italian Space Agency (ASI) has invested a great deal of resources in the participation to planetary space missions. Many ambitious experiments have been proposed and were later mounted on board planetary probes. PFS, OMEGA and MARSIS on board MARS EXPRESS, VIMS and the RADAR for the CASSINI mission, VIRTIS on board ROSETTA and AMIE mounted on SMART1. This review shall provide an overview of the most relevant scientific results obtained by some of the abovementioned instruments.

Key words. Planets: Mars – Planets: Saturn – Saturn's Rings – Icy Satellites – Space Missions

1. Introduction

The 28th of January 2004 the ESA mission MARS EXPRESS has started its nominal operations, with the systematic observation and mapping of the surface and atmosphere of Mars from its nominal polar orbit. Over the past several years, Mars has been probed with a variety of spacecraft, robotic rovers, and telescopes. Three satellites are now in orbit about the planet, and two rovers are still engaged in exploring its surface. As a result, Mars is starting to reveal many of its secrets, including a more complicated history involving water than many expected. Fundamental to an understanding of its history is an accurate geologic map of the surface. This involves identifying specific minerals from space that compose rocks, soil, and ice, and then tying these results to outcrops and landforms, including those that are being analyzed in greater depth by the rovers. MARS EXPRESS, operated by the European Space Agency, takes its name from its rapid assembly, following the heritage of the unlucky Russian mission MARS96. MARS EXPRESS carries onboard three italian instruments for the remote sensing of the atmosphere, of the surface and for the search of water in the subsurface layers: PFS, OMEGA and MARSIS.

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The 2nd of March 2004 the ROSETTA probe has been launched from the ESA's base in the French Guyana after one year delay, and started its long journey to meet the comet Churyumov-Gerasimenko (C-G) in 2014. ROSETTA is the first ESA's planetary cornerstone, it will study Comet C-G in detail, with the prime objective of following it from large heliocentric distances (more than 3 AU) inbound, through perihelion and outbound up to almost 1 AU from the Sun. This will allow the detection of the onset of activity, as well as the determination of the composition of emitted gases. At the same time, modification of the nucleus surface will be observed and analysed. Detailed in situ analysis will be performed by Rosetta's Lander, establishing ground truth for the remote-sensing instruments. The spacecraft carries several italian scientific instruments: the dust analyser GIADA, the imaging spectrometer VIRTIS, and the Wide Angle Camera (WAC) of the imaging system OSIRIS.

The 1st of July the CASSINI-HUYGENS probe has been captured by the Saturnian gravitational field and has started its 4 years (6 years if we include the extended mission) tour which shall allow to encounter and study in detail Titan and all the icy satellites, as well as the saturnian rings and the planet Saturn itself. Moreover, the 25th of December the HUYGENS probe has been released from the CASSINI orbiter and aimed to Titan, where it landed the 14th of January 2005. CASSINI-HUYGENS is a NASA-ASI-ESA mission, the Titan probe named HUYGENS has been built by ESA, while the orbiter CASSINI carries many critical subsystem built by Italian industries. The italian contribution to this mission is highly diversified and include the visible channel of the VIMS spectrometer, the Radar, the Radio Science Instrument and the instrument HASI on board the HUYGENS probe.

Finally the 15th of November the SMART-1 probe (the first European mission to the Moon) has reached its final lunar orbit and has started its observations of the lunar surface. The mission is devoted to the test of new technologies for future missions. These new technologies includes also some scientific experiments, among which the AMIE micro-camera has been designed and built with italian contribution.

2. MARS EXPRESS

The instrument OMEGA (Observatoire pour la Mineralogie, l'Eau, la Glace et l'Activite) is an imaging spectrometer split in two channels one devoted to the VIS spectral range (0.35-1 μm) and the other to the IR range (0.9-5 μm); the VIS channel has been built in Italy under the responsibility of G.Bellucci, INAF-IFSI (Bibring et al. 2004). OMEGA is mapping the surface composition of Mars at a 0.3 to 5 kilometer resolution by means of visible-near-infrared hyperspectral reflectance imagery. The analysis of the NIR spectra acquired during the first year of mission reveal a large spectral variability, previously undetected, which is the proof of a diverse and complex surface mineralogy also at small spatial scales ($\sim -1km$), offering key insights into the evolution of Mars. OMEGA has identified and mapped mafic iron-bearing silicates, essentially Pyroxenes (Low Calcium, LCP, and High Calcium, HCP, species) and Olivines, on both the northern and southern hemispheres (Mustard et al., 2005), (Bibring et al. 2005). These petrologic observations allow to define a stratigraphic context representing the crust of Mars. Olivine is found as outcrops in ancient terrains but also in high concentrations in Hesperian-aged volcanics and crater floors. Thus, magma compositions capable of crystallizing Olivine have occurred throughout much of Mars history. High concentrations of LCP are found only in the ancient cratered terrains, and thus this rock type appears to have been formed only in the Noachian. HCP is found throughout the stratigraphic column, typically in combination with LCP and also with olivine in more recent Hesperian-aged volcanic flows. These volcanic compositions indicate that the source regions were strongly depleted in aluminum and calcium (Mustard et al., 2005). OMEGA observed ices and frosts with a water-ice composition on the north polar perennial cap, on the south cap water ice is covered by a thin carbon dioxide-ice veneer ((Bibring et al. 2004),(Langevin et al. 2005b)). OMEGA

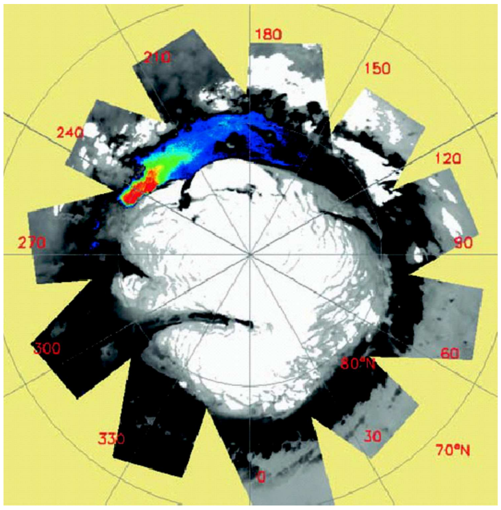

Fig. 1. OMEGA composite map of the north pole showing sulfates absorption feature at 1.927 μm. The strength of the band increase from purple to red ((Langevin et al. 2005a)

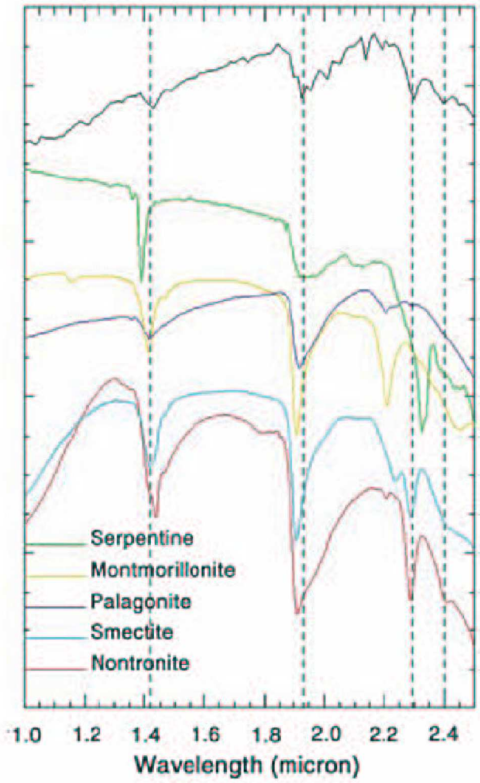

Fig. 2. OMEGA spectrum (top) compared to the spectra of several terrestrial hydrated minerals and clays; the presence of water hydration absorption band at 1.42, 1.93, 2.29 and 2.4 μm is evident (Bibring et al. 2005).

has also identified localized concentrations of hydrated phyllosilicates and sulfates but no carbonates, fig. 1 (Langevin et al. 2005a), (Gendrin et al. 2005). The lack of carbonates points out to an early CO_2 removal from the atmosphere. At geological time scales, the surface diversity originates from a coupled evolution of the magmatic, volcanic, and alteration history of Mars, with no major role played by CO_2 within the volatile inventory: OMEGA found no definite evidence that CO_2 sustained a long-term greenhouse effect enabling liquid H_2O to remain stable at the surface of Mars in the post-Noachian (younger) terrains. The OMEGA observations to date are consistent with an early escape of most of the Mars atmosphere, leaving the atmosphere and not the rocks as the major present CO_2 reservoir;

In summary water has been found trapped in two sinks: as ice mixed with dust within the two large perennial polar caps and as surface hydrated minerals, see Fig. 2, which seem to have been synthesized during the early evolution of Mars. If indeed the water remained essentially stable in solid and gaseous states during the past 3 billion years, with only transient episodes of liquid water brought to the surface, then the episodic evolution of the planet obliquity might have played a major role in the observed surface composition: in condensing water ice in a variety of areas determined by the atmospheric circulation in different insolation conditions, resulting in morphological and compositional (alteration) effects, that can be observed in the present surface properties of a number of areas. PFS (Planetary Fourier Spectrometer), built in Italy under the leadership of V. Formisano (INAF-IASF), is an interferometer that operates in the infrared, covering the spectral range 220 to 8190 cm^{-1} (or 1.2 to 45 μm) in two spectral channels. The spectral resolution is 1.3 cm^{-1} and the spatial resolution is about 10 km near the pericentre (Hirsch et al., 1996). PFS is optimised for atmospheric studies and can provide unique data necessary to improve our knowledge not only of the atmosphere properties but also about mineralogical composition of the surface and the surface - atmosphere interaction (Formisano et al., 2005). The major findings of PFS during 2004 are related to the study of the atmospheric structure and to the discovery of Methane emission.

The longwavelength channel (LWC) of the instrument works in the thermal IR and its data allow the simultaneous retrieval of surface temperature, integrated content of water ice and dust suspended in the atmosphere and air thermal field up to an altitude of about 50 km. The atmospheric structure is studied through the inversion of the CO_2 15 μm band to produce the vertical temperature profile which can than be used to provide 3D maps of the temperature variation (Grassi et al., 2005).

Important observations were also obtained of ice clouds and of the dust suspended in the atmosphere. Both are relevant for the understanding of the martian climate and are closely related to the water vapour, dust and CO_2 cycles. Ice clouds are of two types; those related to topographic features were observed above volcanoes Olympus and Ascraeus Mons. The second type of clouds we observed is the polar hood clouds with a sharp boundary at 481N latitude (Zasova et al., 2005).

PFS observed methane in the 3000 cm^{-1} region where the strongest fundamental band of Methane is located (Formisano et al., 2004). The global mixing ratio when the data are compared to synthetic spectra corresponds to about 10 ppbv. Moreover, the methane abundance show strong variability with location, with abundances varying from 0 to 35ppbv. This variability implies that localised sources and/or sinks of methane should be present. On Earth, the dominant sources of methane are of biogenic nature. On Mars, methane could be derived from biogenic sources such as subsurface microorganisms or nonbiogenic sources such as the slow release of methane stored in subsurface reservoirs, outgassing from volcanic/hydrothermal reservoirs, or destruction of meteoritic or cometary material during infall. The observed global average mixing ratio of 10 ppbv coupled to a methane photochemical lifetime near the surface of few hundred years (Wong et al., 2003) implies a production rate of 150 tons/year. This value is compatible with the impact of a comet of several hundred meters in size as long as 2000 years ago, which is plausible. There are also more efficient mechanisms which implies formation of methane by magmatic processes in the interior of Mars and storage in methane hydrate compounds with a later release in the atmosphere (Max & Clifford 2000) and references therein.

MARSIS the subsurface sounding radar for the detection of water ice layers in the martian interior (Picardi et al., 2004), built in Italy under the responsibility of G. Picardi (University of Rome) was not operated throughout 2004 due to mission safety concerns; only recently (June 2005) the instrument large antennas (40 meters in length) have been successfully deployed and scientific measurements were started.

3. ROSETTA

The grains impact analyser GIADA is one of the three instruments built in Italy and mounted on board the ROSETTA spacecraft, the PI is L. Colangeli (INAF-OAC). GIADA is designed to measure the physical and dynamical properties of grains emitted by the nucleus, and is an event driven instrument: continuous operation is required to accumulate statistically relevant amount of events during comet evolution. GIADA during 2004 performed functional tests and calibrations which demonstrate its full operability, but no direct measurements were taken.

The WAC (Wide Angle Camera) part of the imaging system OSIRIS and built under the responsibility of C. Barbieri (INAF-OAC) performed several measurements during the early months in space, which gave confidence in the capabilities of the instrument. The WAC is a two mirror off axis designed to optimise stray light rejection, has a 12.1x12.7 FOV on a 2048x2048 pixels detector; additionally hosts filters for CS. OH, OI,NH, CN, NH_2, Na plus dust continuum (bandwidth 4nm), and Green

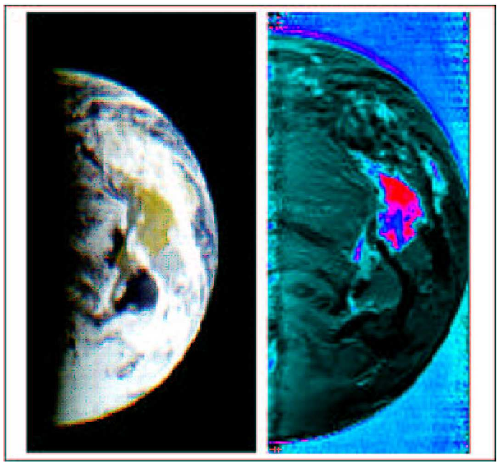

Fig. 3. VIRTIS observations of the Earth. Left, Earth in true colors; Right, vegetation abundance map

and Red broad band. Observation of the asteroid 16 Psyche allowed the team to position the detection limit at the 14th magnitude with a 60s integration time. Capability to observe in the various filters (CS, OH, OI, NH, CN and NH_2) has been experimented with comets 2002T7 Linear and C/2004 Q Macholz. The instrument VIRTIS (Visible and Infrared Thermal Imaging Spectrometer), It has been built under the leadership (PI) of A. Coradini (INAF-IFSI), and is in fact an hyperspectral imager capable of producing 864 monochromatic images with a field of view of 64x64 mrad^2. Its full spectral range extends from the UV (250nm) with a spectral resolution of 2nm, up to the thermal infrared (5000nm) where the resolution is 9nm. Best data taken so far by VIRTIS are those acquired on 5 March, during the first gravitational swing-by with the Earth, from a distance of 250 000 kilometres. The data have pointed out the full capabilities of the instrument which can produce compositional maps correlating the spatial distribution of mineral and atmospheric compounds with their abundances. As a single example of VIRTIS capabilities in figure 3 are reported a standard RGB image, obtained using the bands at 400, 550 and 700nm, which shows the Earth in real colors, and the map of the distribution of the vegetation obtained by ratioing reflectances at 780 nm and 685 nm (the first band correspond to the continuum while the second band is located at the deepest clorophyll absorption region). It is evident the association of the most vegetated areas with the land, while cloudy areas hiding the surface are shown in black. Same exercises can be done also in the IR where there is an additional contribution due to the Earth thermal emission starting at around 3000nm.

4. CASSINI

CASSINI was launched in 1997, and all the experiment provided interesting data already during the cruise phase to Saturn. For instance, the Radio Science experiment (RSS) started to fulfill its scientific objectives already in 2003 when a confirmation of the General Relativity with an accuracy 100 times better than previous measurements was obtained by italian scientists (Bertotti, Iess, &Tortora 2003). Another example is the radiometric calibration of VIMS performed in flight using the lunar observations (Mccord et al. 2004). However, the great bulk of scientific data started to flow down from the spacecraft immediately after the insertion in the Saturn orbit, the 1st of July last year. The CASSINI mission so far has demonstrated extremely successfull and even trying to convey in the limited space provided by this review a partial list of the achievements obtained also with the italian contribution is a formidable task. In the first months of observations, until the end of 2004, objects as diverse as Saturn, its ring systems, Titan, Phoebe and other icy satellites, have been studied with unprecedented instrumental capabilities. I will limit to a couple of examples, namely the unique fly-by of Phoebe, the outermost Saturn satellite, and the first results from the RADAR at Titan.

The origin of Phoebe, which is the outermost large satellite of Saturn, is of particular interest because its inclined, retrograde orbit suggests that it was gravitationally captured by Saturn, having accreted outside the region of the solar nebula in which Saturn formed (Johnson & Lunine 2005). By contrast, Saturns regular satellites (with prograde, low-

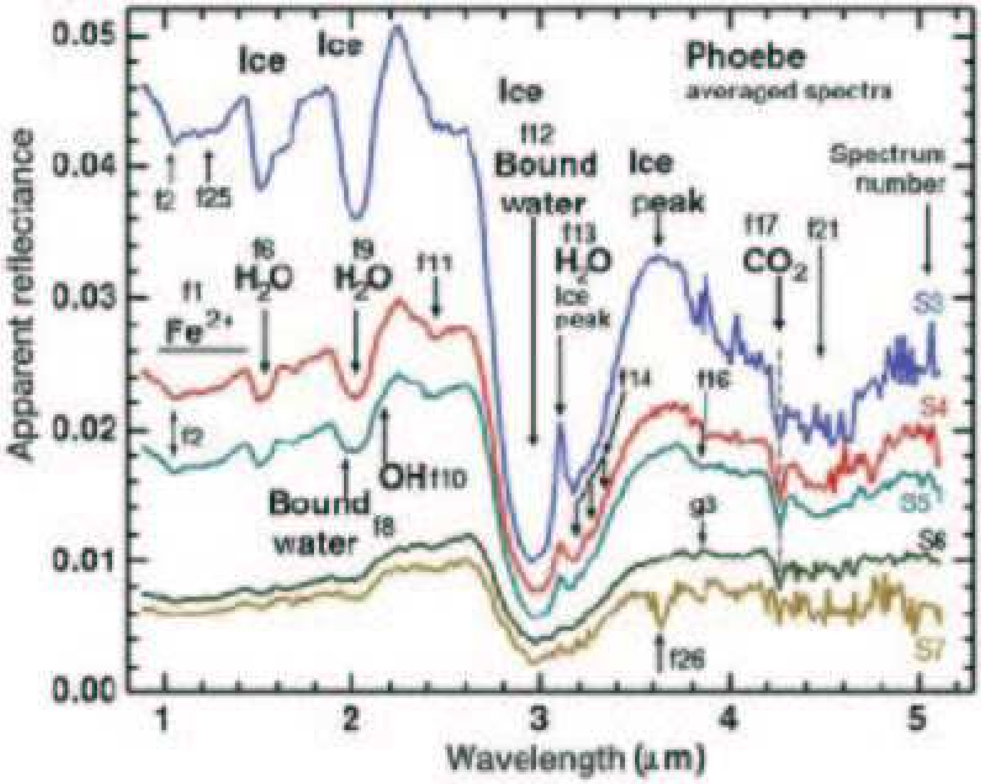

Fig. 4. Spectra of Phoebe show the presence of numerous compounds. Illustration of the spectral diversity of Phoebes surface. These spectra are averages from multiple small locations on Phoebes surface, obtained from unprojected data (Clark et al. 2005).

inclination, circular orbits) probably accreted within the sub-nebula in which Saturn itself formed. VIMS identified and mapped over the surface a large amount of compounds (fig 4). Spectra of Phoebe display a wealth of information, indicating a surface containing distinct locations of ferrous-iron-bearing minerals, bound water, trapped CO_2, probable phyllosilicates, organics, nitriles and cyanide compounds (Clark et al. 2005). The only body imaged to date in the Solar System that is more compositionally diverse is Earth. Phoebe's organic and cyanide compositions are unlike any surface yet observed in the inner Solar System. Phoebes generally dark surface closely resembles that of C-type asteroids and small outer Solar System bodies such as Chiron and Pholus that are thought to have originated in the Kuiper belt (Cruikshank et al. 1998), and thus probably Phoebe represents a unique sample of the most primitive bodies of the Solar System.

Titan is an unique object in our solar system, with a surface pressure 1.5 times as high as that at the surface of Earth and near-surface atmospheric temperatures below 100 K and a size bigger than the planet Mercury. The Cassini mission's Titan Radar Mapper observed about 1 per cent of Titan's surface in SAR mode at a resolution of approximately 0.5 kilometer during the first fly-by. The image reveal a complex surface, with areas of low relief and a variety of geologic features suggestive of dome-like volcanic constructs, flows, and sinuous channels (Elachi et al. 2005). The surface appears to be young, with few impact craters. Scattering and dielectric proper-

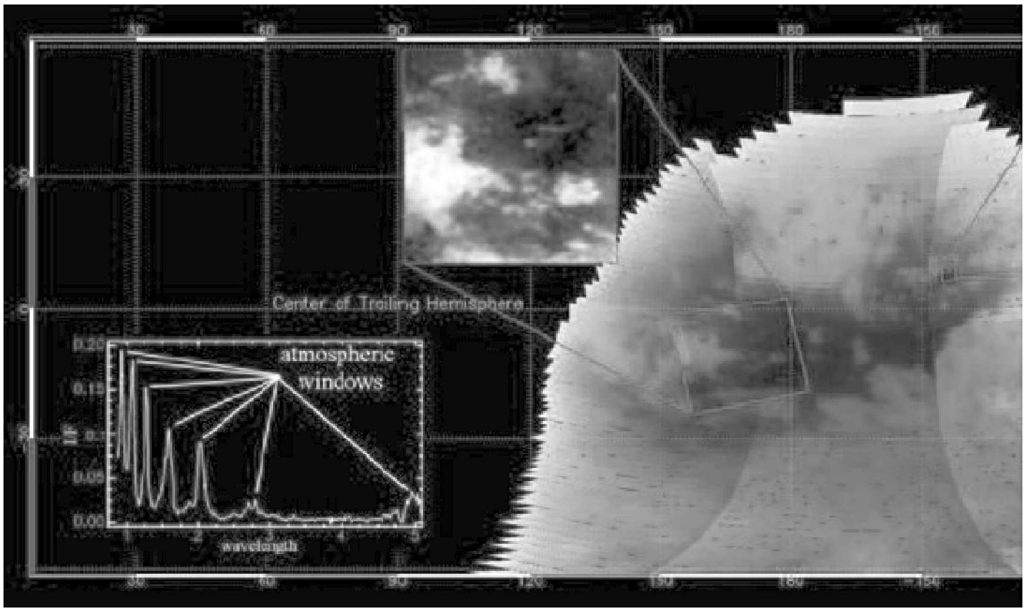

Fig. 5. Titan seen by VIMS at 2030 nm. Different sets of images with increasing spatial resolution have been used to realize this map. Observations are centered around the anti-Saturn point and cover a latitude range of 60 degrees. The High-Res image on the left is taken where the Huygens probe is supposed to fall into Titan atmosphere (Sotin et al. 2005).

ties are consistent with porous ice or organics. Dark patches in the radar images show high brightness temperatures and high emissivity and are consistent with frozen hydrocarbons. These results are consistent with data taken from VIMS in the few methane transmittance windows available in its spectral range; scattering by haze particles in Titans atmosphere and numerous methane absorptions make observation of Titans surface in the visible very difficult, though it can be studied in some narrow infrared windows (Meier et al., 2000). In fig 5 is reported a mosaic of VIMS images with spatial resolutions ranging from 5 km/pixel to 2 km/pixel. Also on the larger scale of the figure, variegation of the surface, in terms of compositional differences is confirmed as well as the absence of large impact structures. Clouds have been reported in the southern hemisphere by VIMS and ISS, and the dynamic of the atmosphere has been studied during subsequent fly-bys (Griffith et al., 2005).

5. Future Prospects

The italian planetary sciences community is deeply involved in many future endeavours. Some of the missions have already reached their final development stages like Venus Express an ESA mission to be launched end of October 2005 and planned to start the scientific activities at Venus in April 2006, which has on board the spare models of VIRTIS (lead by G. Piccioni INAF-IASF) and PFS (lead by V. Formisano INAF-IFSI), or the NASA discovery mission Dawn, carrying towards the asteroids Vesta and Ceres the imaging spectrometer VIR (Lead by A. Coradini INAF-IASF) and to be launched in june 2006; the arrival at Vesta is for 2011 and at Ceres in 2015. Some other projects have a farther horizon, like the Aurora project for the european exploration of Mars, or the Planetary cornerstone mission BepiColombo to Mercury where Italy is taking the largest share of the science with the complete set of remote sensing instruments (high resolution camera, stereocamera, hyperspectral imager combined in SIMBIO-SYS), the Radio Science experiment (MORE and ISA), and SERENA the set of instruments for the analisi of energetic neutral atoms.

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