Observation of Solar-System Objects with the VLT

T. ENCRENAZ, DESPA, Observatoire de Paris, Meudon, France

As a continuation of various active ongoing programmes of ground-based planetary observations, many promising research developments can be anticipated from planetary observations with the VLT, especially in the near-infrared range. The use of adaptive optics will be essential to reach the full capabilities of the VLT, both for imaging and for spectroscopy.

Introduction

In spite of a successful space programme developed over the two last decades, there are still important questions wich remain unsolved concerning our understanding of Solar-System bodies. In fact, on many occasions, the new results coming from space data have raised new questions, dealing, in particular, with formation and evolution processes. As an example, the study of the chemical composition of planetary and cometary atmospheres has led, in several cases, to unexpected results which have been used as tests against formation and evolution models.

Ground-based observations have provided a very important contribution as a complement to space missions. In particular, our knowledge of the chemical composition of the atmospheres of the giant planets has been mostly inferred from ground-based infrared spectroscopy. Observations of stellar occultations, obtained simultaneously from several ground-based or airborne telescopes, have provided the first detection of Uranus and Neptune rings; they also have allowed the exploration of the upper atmospheres of Jupiter, Uranus, Neptune and Titan. Taking advantage of the newest technological developments, the planetary ground-based exploration programme is still very active, as illustrated by the international campaign presently organized in all observatories for monitoring Jupiter at the time of the collision of comet Shoemaker-Levy 9 with this planet, around July 20, 1994.

The Astrophysical Problems

One of the major astrophysical interests of observing Solar-System bodies is that they can provide clues about the origin of the Solar System. By studying objects in various evolutionary stages, information can be derived about formation and evolution processes involved in their history.

The most primitive bodies are found in two classes of objects: (1) the giant planets, which are massive enough to have accreted around their core the surrounding gas of the primordial nebula; (2) the comets, which are small and cold enough to have escaped any evolutionary process since their formation. In these objects, the chemical composition and the elemental and isotopic abundance ratios (such as He/H, D/H and C/H) are powerful indicators of their origin scenario and their history. Another important diagnostic is given by the study of the surface of the solid bodies (asteroids, cometary cores) and their physical and dynamical properties.

The atmospheres of the terrestrial planets have evolved significantly since their origin; indeed, a major and fascinating problem in planetology is the comparative study of the evolution of the atmospheres in the case of Venus, the Earth and Mars. Here again, the chemical and isotopic composition (in particular the D/H ratio) can provide important tools which constrain the evolutionary models of these planets.

In addition, monitoring the spatio-temporal behaviour of planetary atmospheres is a key element to address specific problems, presently poorly understood: climatology in the case of Mars and Venus, general circulation and auroral phenomena in the case of the giant planets, ices sublimation and outgassing of a comet as it approaches the Sun... In these specific cases, the planets and comets can be considered as priviledged laboratories, in which a large variety of physical and chemical processes can be investigated.

The Observations to be Performed

What are the observations which will allow us to address these questions? For determining the chemical composition of planetary and cometary atmospheres, high-resolution spectroscopy is best suited. The infrared and millimetre ranges are of special interest for the study of neutral molecules. The spectrum of a Solar-System object is composed of two components: (1) the solar component, reflected or scattered by the object, and (2) the thermal component, which peaks at longer wavelengths (15 microns in the case of Mars, 70 microns in the case of Neptune). In the reflected component, atmospheric constituents show absorption features giving information upon the column density of the absorber. In the thermal part of the spectrum, the outgoing flux refers to the atmospheric level where the optical depth approximates unity. The line can thus appear in emission or in absorption, depending upon the shape of the thermal profile and the sign of the temperature gradient. The observed lines can be used to obtain information upon the vertical distribution of the molecule. In addition to these components, Solar-System objects, and comets in particular, can show fluorescence emission lines, in the UV, the visible or the IR range.

In addition to spectroscopy, imaging techniques provide useful information on the surface of objects like the Moon, Mars and the giant planets Jupiter and Saturn. Multiband CCD and infrared imaging allows to map the mineralogy of surfaces, or to monitor the cloud morphology of the giant planets. This technique is being improved with the ongoing development of imaging spectroscopy, which allows, at least on the bright planets, a coupling of both spatial and spectral capabilities.

Another powerful technique is the photometric monitoring of a stellar occultation by a planet. As the planet passes in front of the star, the stellar flux is refracted by the planet's atmosphere. By studying the stellar lightcurve at the time of immersion and emersion, it is possible to derive the refractive index of the atmosphere. In addition, this method allows the detection of rings around the planets; it provided the first evidence for rings around Uranus and Neptune.

A Few Recent Results from Ground-Based Observations

High-resolution spectroscopy in the near-infrared (1–5 microns) has led to major discoveries over the past few years. A few examples are given below.

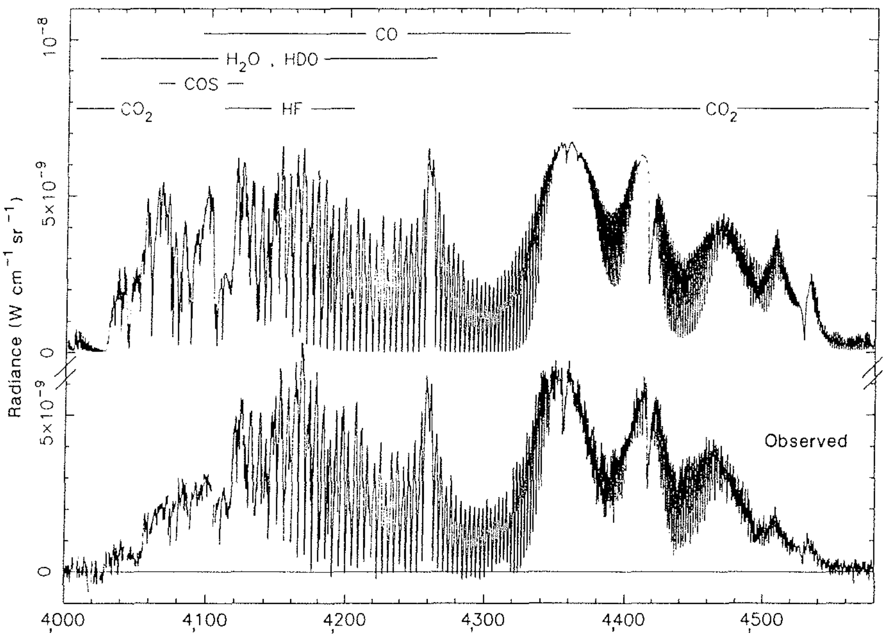

Figure 1: *The 2.3-micron spectral window in the spectrum of the dark side of Venus (FTS, CFHT). The spectral resolution is 0.23 cm^{-1}. The figure is taken from Bézard et al. (1990).*

The lower atmosphere of Venus, below 50 km, is hidden by a thick and opaque cloud which prevents it to be observed at almost all wavelengths. However, there are a few discrete near-infrared spectral windows, between the strong absorption bands of the dominant atmospheric constituent CO_2, where the thermal radiation is emitted from the lowest cloud layers. High-resolution spectroscopy of these regions (Bézard et al., 1990; Fig. 1), performed with the FT spectrometer of the 3.6-m CFH telescope at Mauna Kea (Hawaii), has led to the abundance determination of various minor constituents (H_2O, CO, COS, SO_2, HCl, HF, HDO), either from the 2.3-micron window or from the 1.8-micron window. The D/H ratio has been found equal to 120 times the terrestrial value (de Bergh et al., 1991). According to evolutionary models of the planet, this strong deuterium enrichment would imply a high abundance of water in Venus' past history.

In the case of the giant planets, there is also a "spectral window", where there is no absorption by the dominant absorber CH_4. This is the 4–5-micron region, where thermal radiation comes from deep tropospheric levels (a few bars in the case of Jupiter). This range is thus best suited for searching minor atmospheric species. CH_3D, GeH_4, CO and more recently AsH_3 have been detected in both Jupiter and Saturn. Another important result has been the unexpected detection of the H_3^+ ion in an auroral spot of Jupiter at 2.1 microns and later at 4 microns (Drossart et al., 1989, 1992). These emission lines could originate from thermal emission in the hot atmosphere.

Cometary research has also benefited from near-infrared spectroscopy. This is the spectral range where parent molecules, directly outgassed from the nucleus, exhibit their strongest fluorescence emission signatures. Comet Halley provided a unique opportunity for this research. High-resolution observations with the 0.9-m telescope of the Kuiper Airborne Observatory, in the 3-micron region, provided the first observational evidence for the presence of water vapour in a comet (Mumma et al., 1986; Larson et al., 1988; Fig. 2). The same experiment was repeated later on other bright comets. The observations provided the abundance of H_2O, the temperature, the velocity field, and an estimate of the ortho-to-para ratio of water, which can provide a constraint upon the temperature at the time of the comet formation.

Another area of successful spectroscopic research is the study of fainter and fainter Solar-System objects, made possible with the development of more and more sensitive spectrometers. A remarkable example is provided with the recent detection of N_2, CH_4, CO and CO_2 ices on the surface of Neptune's satellite Triton (Cruikshank et al., 1993; Fig. 3), with the CGS4 cryogenic spectrometer at the UKIRT 3.8-m telescope (Mauna Kea, Hawaii), using moderate spectral resolution (R = 300).

Because infrared observations re-

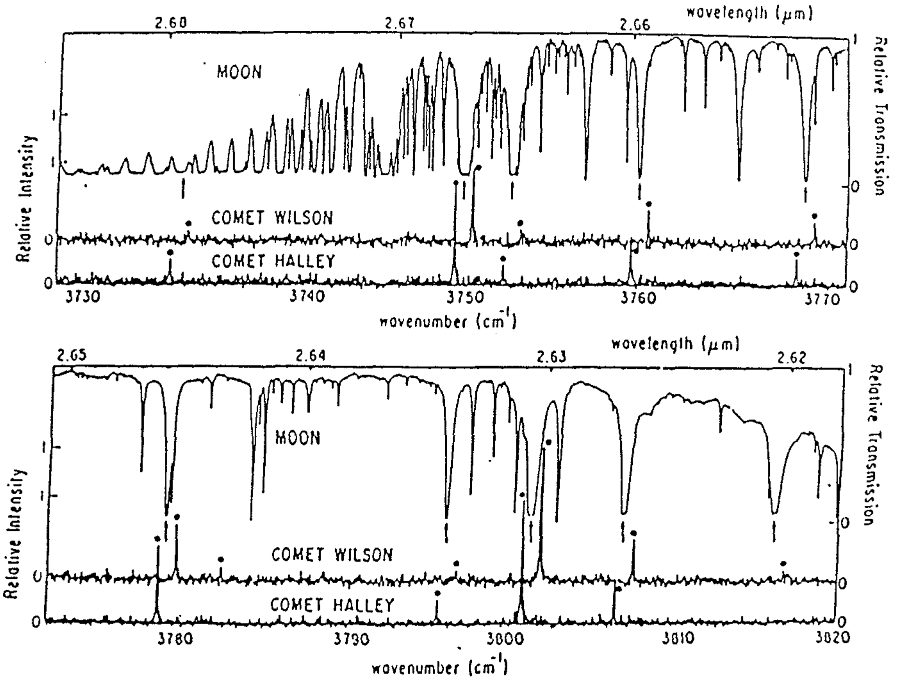

Figure 2: *The high-resolution spectrum of the 2.7-micron H_2O band recorded with the FTS of the Kuiper Airborne Observatory in comets Halley and Wilson. The resolving power is 100,000. Upper curve: Moon (atmospheric transmission); lower curves: Wilson and Halley. The absolute Doppler shift is in the range 0.4–0.5 cm^{-1}, and is sufficient to separate the terrestrial water lines (shown in absorption in the lunar spectrum) from the cometary emissions. Both cometary spectra are uncorrected from atmospheric transmission and instrumental response, but the lunar spectrum is used to calibrate the relative intensities. The figure is taken from Larson et al. (1988).*

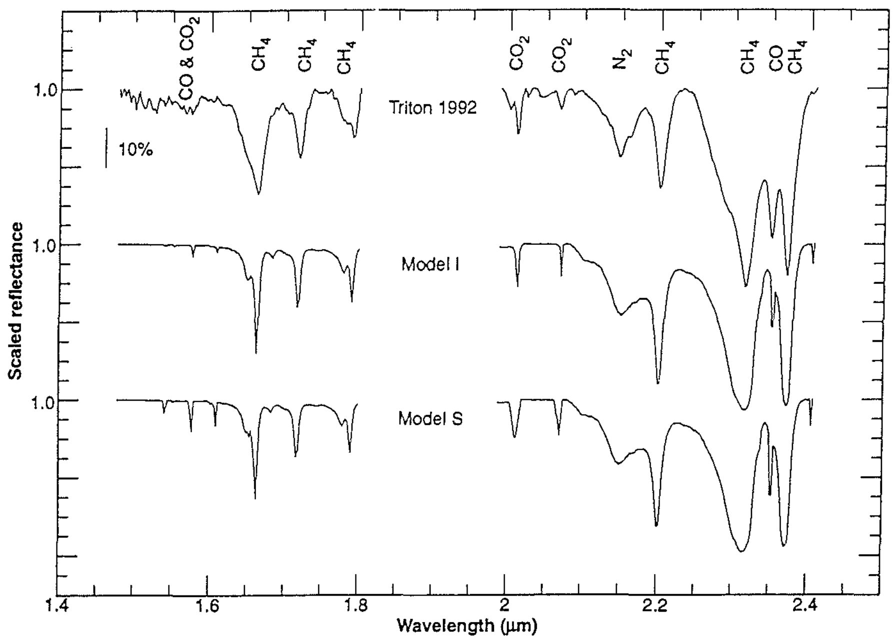

Figure 3: *The infrared spectrum of Triton in the near-infrared range. Upper curve: observations; lower curves: scattering models including ices of N_2, CO, CO_2 and CH_4, with two abundances of CO_2 (0.10% in Model I, 10% in Model S). The figure is taken from Cruikshank et al. (1993).*

quest a very dry terrestrial atmosphere, most of the results mentioned above have been obtained in high-altitude sites or even from aircraft. However, in the visible and near IR (below 2.5 microns), the amount of terrestrial water vapour is less critical. Two very significant results have been obtained in planetary physics using the 3.6-m ESO telescope on La Silla: the first one is the detection of rings around Uranus (Sicardy et al., 1982) and Neptune (Hubbard et al., 1986), using the stellar occultation technique; the second is the first imaging of Solar-System objects (Titan, Pallas and Ceres) at the diffraction limit in the near-infrared, using the adaptive optics instrument (COME-ON) at the 3.6-m ESO telescope (Saint-Pé et al., 1993; Fig. 4). The latter results open a new field of Solar-System imaging observations, which is likely to develop in the forthcoming years.

Solar-System Observations with the VLT

With respect to a 4-m-class telescope, the use of the VLT is going to provide a double advantage: a factor 2 gain in spatial resolution, and a factor 4 in collecting flux (for unresolved sources, or for a constant aperture in the case of extended sources); the latter advantage implies, for photon-limited observations, a factor 4 in observing time.

The diffraction limit of an 8-m telescope is about 0.06 arcsec at 2 microns or 0.3 arcsec at 10 microns. Table 1 summarizes the maximum sizes of the brightest Solar-System objects, with the number of pixels of each object over the central meridian, at 2 microns and 10 microns respectively.

Assuming a seeing of 0.3 arcsec in the best cases, one can see that the factor 2 advantage in spatial resolution is achieved above a wavelength of 10 microns. At lower wavelengths, an adaptive optics system is needed. Based upon the present experience of the COME-ON+ instrument now operating at La Silla, we will assume, in what follows, that the VLT 8-m telescopes will be equipped with an adaptive optics system which reaches the diffraction limit for wavelengths higher than 1 micron. This high spatial resolution capability will be useful for direct imaging, but also for high-resolution spectroscopy (Encrenaz et al. 1992), as it will be possible to concentrate the whole flux of a weak object on the narrow (less than 0.5″) entry slit of a cryo-echelle grating spectrometer (R > 50,000).

Table 1 shows that a large number of Solar-System bodies will be spatially resolved at two microns. Two types of observations will benefit from the VLT: (1) high-resolution imaging spectroscopy of extended objects; (2) photometry and spectro-photometry of weak objects.

1. High-resolution imaging spectroscopy of extended objects

The expected performances are a spatial resolution of 0.06 arcsec and a spectral resolving power of 100,000 at 2 microns. The first targets to be studied are the bright extended planets: Venus, Mars, Jupiter and Saturn. A few specific examples are given below.

Imaging spectroscopy in the near-infrared has already been achieved, at moderate spatial resolution, to investigate the lower atmosphere of Venus on the night side of the planet. This has been achieved by coupling the FT spectrometer of CFHT with a bidimensional camera, providing the full spectral resolving power (40,000) and a spatial resolution of 0.5 arcsec (about 100 km on the surface of the Venus disk). In the future, the use of adaptive optics on a 4-m telescope will improve the spatial resolution by a factor about 5, which will correspond to the spatial resolution achieved by the Galileo probe at the time of its Venus flyby (Carlson et al., 1991). The use of the VLT will improve again this limit by a factor 2, allowing to investigate in more depth both the atmospheric composition and the complex cloud structure which was revealed by the Galileo data.

TABLE 1.

Solar-System object	Size (arcsec)	Number of pixels	
		2 microns	10 microns
Venus	60.0	1000	200
Mars	18.0	300	60
Jupiter	47.0	780	157
Saturn	19.0	317	63
Uranus	4.0	67	13
Neptune	2.3	38	7
Io	1.2	20	4
Europe	1.0	16	3
Ganymede	1.7	28	5
Callisto	1.6	26	5
Titan	0.8	13	2
Ceres	0.7	11	2
Pallas	0.4	6	1
Vesta	0.5	8	1

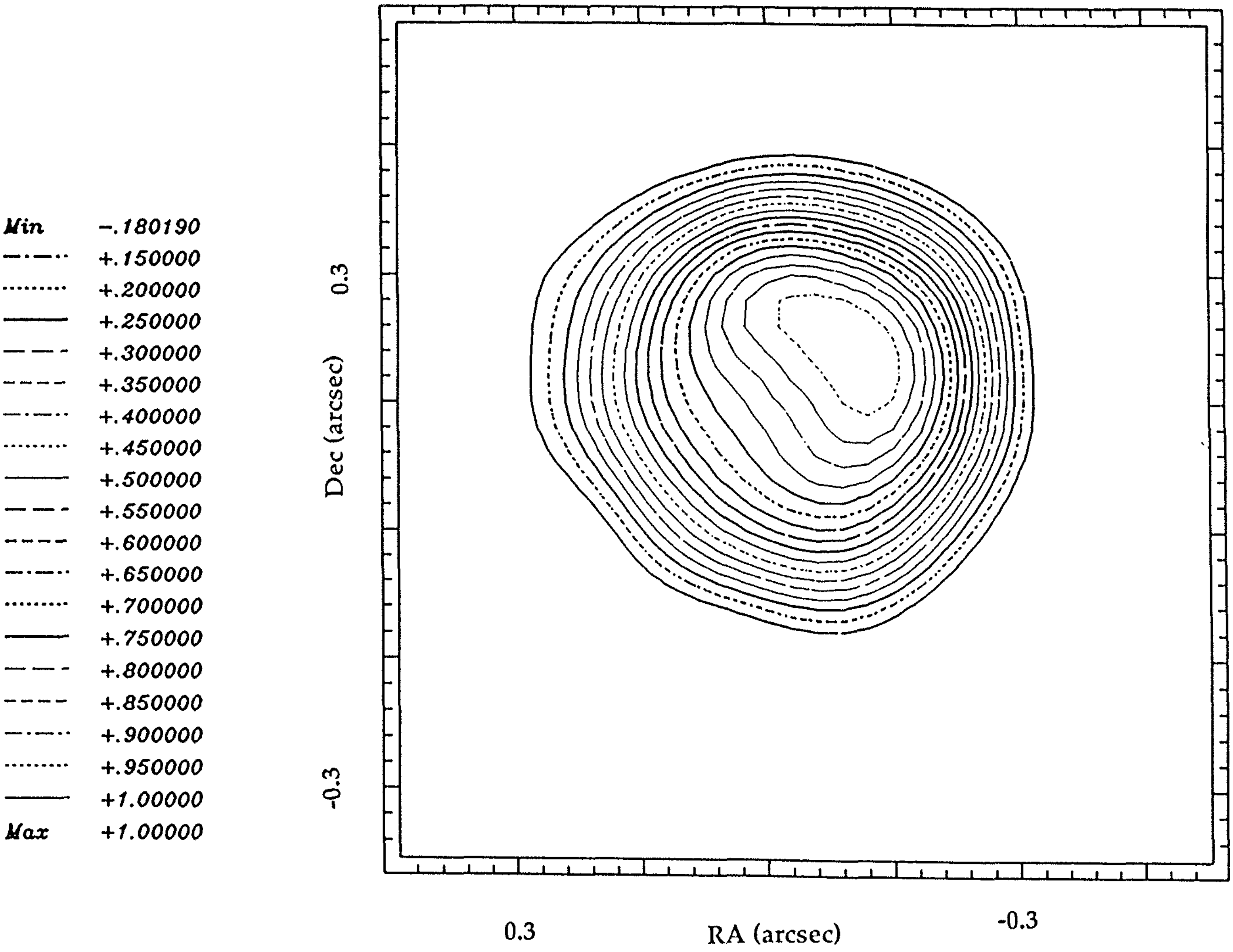

Figure 4: *Isophotes of Ceres in L'band. The image was recorded with the adaptive optics system COME-ON at the ESO 3.6-m telescope at La Silla, in May 1991. The spatial resolution is 0.25 arcsec, corresponding to the diffraction limit at 3.5 microns: The maximum level is normalized to 1 and two levels are separated by 5 % in flux. The figure is taken from Saint-Pé et al. (1993).*

The study of the Martian atmosphere is also going to benefit from the use of high-resolution imaging spectroscopy. The distribution of minor atmospheric species, and especially CO, over the disk of Mars has been the subject of a large debate and is not yet fully understood. Combining high spatial and spectral resolution will allow to resolve the individual lines of the CO (2-0) band at 2.3 microns, and to study their spatio-temporal variation. At opposition, a spatial resolution of 25 km (0.06 arcsec) will be reached with the VLT, comparable to the resolution achieved with space orbiters like the PHOBOS spacecraft (Rosenqvist et al., 1992).

A third example is provided by the observation of H_3^+ in the auroral regions of Jupiter. Using an 8-m telescope with a diffraction limit of 0.06 arcsec actually achieved, it will be possible to reach both a spectroscopic resolving power of 100,000 and a spatial resolution of 200 km on the Jovian disk. The detectability of the Doppler-broadened H_3^+ lines should be increased by a factor larger than 10 with respect to the present data, and the improved spatial resolution will allow us to better define the contours of the existing aurorae and to identify hot spots. The same search could be attempted on other giant planets also, with the limitation of the available flux.

In the near-infrared range, the VLT will also allow us to map smaller objects, presently too small to be resolved both spatially and spectrally. The first exciting target is Io, which is known to have a stable, but apparently patchy, SO_2 atmosphere (Lellouch et al., 1992). Here again, observing the Doppler-broadened SO_2 line, at 4 microns requires maximum spectral resolution. Io will be fully resolved, with 10 pixels along the central meridian and a K-magnitude of about 10 per pixel, allowing a complete mapping of the atmosphere in correlation with the volcanic activity. Another promising target is Titan. First diffraction-limited images of Titan have been obtained in the near-infrared range, with the ESO 3.6-m telescope, equipped with adaptive optics. Titan's K-magnitude within a 0.06 arcsec pixel will be about 12, easily detectable with the VLT. Infrared spectroscopy will be needed to isolate the near-infrared windows, free from methane absorption, in order to probe the surface of Titan. The gain in sensitivity and spatial resolution provided by the VLT will be of extreme interest in preparation to the Cassini-Huygens mission, designed to explore Titan's atmosphere and surface in 2004–2008.

Another promising field of research is the observation of comets with the VLT. As mentioned above, the near-infrared range is very well suited for studying the Doppler-broadened fluorescence emissions of the parent molecules. Determining the spatial distribution of parent molecules in comets will be essential for

TABLE 2.

PLANET Satellite	Angular size	K-magnitude
JUPITER		
Amalthea	0.08	12.8
SATURN		
Mimas	0.06	11.5
Enceladus	0.08	10.3
Tethys	0.16	8.8
Dione	0.16	9.0
Rhea	0.24	8.35
lapetus	0.23	9.7
URANUS		
Ariel	0.09	13.0
Titania	0.12	12.6
Oberon	0.12	12.8
NEPTUNE		
Triton	0.19	12.3
PLUTO	0.14	12.5

understanding the thermodynamics of the coma. The use of the VLT will improve the sensitivity limit and/or increase the spatial and spectral resolution of the observations. For a comet located at 0.3 AU from the Earth, a spatial resolution of 0.06 arcsec corresponds to a diameter of 15 km, comparable to the size of a cometary nucleus; even for a more distant comet, it will be possible to probe the inner coma in detail. In addition, if the resolving power reaches 300,000, the Doppler lines can be resolved, providing a determination of the velocity field.

Finally, a special mention should be made about imaging spectroscopy of planets and comets in the thermal infrared range, in the 10-micron and 20-micron atmospheric spectral windows (Drossart, 1993). In particular, the giant planets and Titan show, in the 7–14-micron range, emission lines due to hydrocarbons which allow to probe the thermal structure of their upper atmospheres, to study the density distributions of these hydrocarbons and to monitor their spatio-temporal variations. Another exciting study could be the search for oscillations on Jupiter and Saturn, which should benefit from an improved spatial resolution for discriminating the various oscillation modes.

2. Photometry and spectrophotometry of weak objects

The use of the VLT will offer a factor 4 improvement in terms of collected signal, which translates, for photon-limited observations, into a factor 4 gain in observation time. A new class of faint objects, the bare satellites of the outer Solar System, can be observed with near-infrared spectrophotometry, for a determination of their mineralogic properties. Table 2 lists the angular size and the K-magnitude of some of them, too small to be imaged, but bright enough for spectrophotometric observations.

We can use as a comparator the recent observation of Triton, on a 3.8-m telescope, with a resolving power of about 300 and 4 nights of integration (Cruikshank et al., 1993). The same observation could be made in one single night with the VLT. Uranus' satellites could be observed at wavelengths up to 2.5 microns, with the same spectral resolution, in a few nights of integration time. It will also be possible to resolve a few pixels on the disk of Triton, as well as on the surfaces of Saturn's largest bare satellites.

Finally, a last programme to be mentioned is the photometric study of bare cometary nuclei. Comet Halley was monitored at the 3.6-m ESO telescope up to very large heliocentric distances, where some signs of activity were still detectable. A systematic search for activity on many distant comets will provide interesting constraints upon the nature of the volatiles outgassed at large distances from the Sun.

Observations of Solar-System Bodies with the VLTI

We have seen that the near-infrared range is well suited for the study of faint and cold Solar-System objects. The use of the VLTI will allow systematic studies on point-like objects such as asteroids and bare cometary nuclei. At a distance of 3 AU from the Earth, a diameter of 7 km (typical of a cometary nucleus) corresponds to an angular diameter of 10 milliarcsec, and could be resolved with the VLTI. Measuring the diameters, the shapes, the rotation period, the mineralogy and the thermal properties of a large number of samples will provide a statistical information which will be very important for constraining the dynamical models of these objects, and could open a new field of research. The use of VLTI might also allow to accurately localize hot spots on larger objects, like volcanoes on Io or auroral spots on the giant planets. At Jupiter's opposition, a 10-km volcanoe on Io would have an angular size of 10 milliarcsec and could thus be resolved, and a temporal monitoring of volcanic activity could be possible.

Conclusion

Many promising research programmes are expected to be performed on Solar-System objects with the VLT, using either the 8-m telescopes or the VLTI mode. An essential factor will be the availability of an adaptive optics system at the 8-m telescope foci, in order to take full advantage of the large size of the mirrors, both for imaging and spectroscopic observing programmes.

References

Bézard B., de Bergh C., Crisp D. and Maillard J.P., *Nature* **345**, 508 (1990).

Carlson R.W. et al., *Science* **253**, 1541 (1991).

Cruikshank D.P. et al., *Science* **261**, 742 (1993).

de Bergh C., Bézard B., Owen T., Crisp D., Maillard J.P. and Lutz B.L. *Science* **251**, 547 (1991).

Drossart P. et al., *Nature* **340**, 539 (1989).

Drossart P., Compte Rendu du Forum "L'exploitation astrophysique des fenêtres 10 et 20 microns avec le VLT", Institut d'Astrophysique de Paris, Oct. 1, 1993, D. Alloin and P.O. Lagage eds., p. 51 (1993).

Drossart P., Prangé R. and Maillard J.P., *Icarus* **97**, 10 (1992).

Encrenaz T., Combes M. and Saint-Pé O., Proceedings of the ESO Workshop on High-Resolution Spectroscopy with the VLT, 1992, M.-H. Ulrich ed., ESO Conf. Proc. No. 40, p. 115.

Hubbard W.B. et al., *Nature* **319**, 636 (1986).

Larson H.P., Weaver H.A., Mumma M.J. and Drapatz S., *Astrophys.J.* **338**, 1106 (1988).

Lellouch E., Belton M., de Pater I., Paubert G., Gulkis S. and Encrenaz T., *Icarus* **98**, 271 (1992).

Mumma M.J., Weaver H.A., Larson H.P. and Davis D.S., *Science* **232**, 1523 (1986).

Rosenqvist J. et al., *Icarus* **98**, 254 (1992).

Saint-Pé O., Combes M., Rigaut F., Tomasko M. and Fulchignoni M., *Icarus*, in press (1993).

Saint-Pé O., Combes M. and Rigaut F., *Icarus*, in press (1993).

Sicardy B. et al., *Icarus* **52**, 454 (1982).