

LETTER TO THE EDITOR

Visible spectroscopy of 2003 UB₃₁₃: evidence for N₂ ice on the surface of the largest TNO?

J. Licandro^{1,2}, W. M. Grundy³, N. Pinilla-Alonso⁴, and P. Leisy^{1,2}

¹ Isaac Newton Group, PO Box 321, 38700 Santa Cruz de La Palma, Tenerife, Spain
e-mail: licandro@ing.iac.es

² Instituto de Astrofísica de Canarias, c/Vía Láctea s/n, 38205 La Laguna, Tenerife, Spain

³ Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001-4470, USA

⁴ Fundación Galileo Galilei & Telescopio Nazionale Galileo, PO Box 565, 38700 S/C de La Palma, Tenerife, Spain

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ABSTRACT

Context. The recent discovery of two large trans-Neptunian objects (TNOs) 2003 UB₃₁₃ and 2005 FY₉, with surface properties similar to those of Pluto, provides an exciting new laboratory for the study of processes considered for Pluto and Triton: volatile mixing and transport; atmospheric freeze-out and escape, ice chemistry, and nitrogen phase transitions.

Aims. We studied the surface composition of TNO 2003 UB₃₁₃, the first known TNO larger than Pluto.

Methods. We report a visible spectrum covering the 0.35–0.95 μm spectral range, obtained with the 4.2 m William Herschel Telescope at “El Roque de los Muchachos” Observatory (La Palma, Spain).

Results. The visible spectrum of this TNO presents very prominent absorptions bands formed in solid CH₄. At wavelengths shorter than 0.6 μm the spectrum is almost featureless and slightly red ($S' = 4\%$). The icy-CH₄ bands are significantly stronger than those of Pluto and slightly weaker than those observed in the spectrum of another giant TNO, 2005 FY₉, implying that methane is more abundant on its surface than in Pluto’s and close to that of the surface of 2005 FY₉. A shift of $15 \pm 3 \text{ \AA}$ relative to the position of the bands of the spectrum of laboratory CH₄ ice is observed in the bands at larger wavelengths (e.g. around 0.89 μm), but not at shorter wavelengths (the band around 0.73 μm is not shifted) this may be evidence for a vertical compositional gradient. Purer methane could have condensed first while 2003 UB₃₁₃ moved towards aphelion during the last 200 years, and as the atmosphere gradually collapsed, the composition became more nitrogen-rich as the last, most volatile components condensed, and CH₄ diluted in N₂ is present in the outer surface layers.

Key words. Kuiper Belt

1. Introduction

The spectra of three of the four largest members of the trans-neptunian belt, 2003 UB₃₁₃, Pluto, and 2005 FY₉ are dominated by strong methane ice absorption bands (Cruikshank et al. 1993; Brown et al. 2005a; Licandro et al. 2006) Pluto also presents weak but unambiguous signatures of CO and N₂-ice (e.g. Cruikshank 1998). These bands are also detected in the spectrum of Neptune’s satellite Triton (Cruikshank et al. 1993), a possibly captured ex-TNO. The presence of frozen methane on the surfaces of Pluto, Triton, 2003 UB₃₁₃ and 2005 FY₉ favors the Spencer et al. (1997) idea that surface methane is replenished from the interior, may be ubiquitous in large trans-neptunian objects. 2005 FY₉ and 2003 UB₃₁₃ provide an exciting new laboratory for the study of processes considered for Pluto and Triton: volatile mixing and transport; atmospheric freeze-out and escape, ice chemistry, and nitrogen phase transitions. In particular the abundance of volatiles like CO and N₂ is important to determine the possible presence of a bound atmosphere and constrain the formation conditions.

TNO 2005 UB₃₁₃ is the largest known object in the trans-neptunian belt, with a surface albedo higher than that of Pluto (2400 \pm 100 km or a size \sim 5% larger than Pluto, and $p_V = 86 \pm 7\%$, Brown et al. 2006). Discovered near aphelion at 97.50 AU, it will take some 2 centuries to reach its perihelion at 38.2 AU.

This huge variation in heliocentric distance causes large seasonal temperature variations that should affect the sublimation and recondensation of its surface volatiles.

In this paper we present visible spectroscopy of 2003 UB₃₁₃ and compare it with spectra of Pluto and 2005 FY₉ (Licandro et al. 2006) in order to derive mineralogical information from its surface.

2. Observations

We observed 2003 UB₃₁₃ on 2005 October 20.03 UT with the 4.2 m William Herschel telescope (WHT) at the “Roque de los Muchachos Observatory” (ORM, Canary Islands, Spain), under photometric conditions. The TNO had heliocentric distance 95.94 AU, geocentric distance 96.90 AU and phase angle 0.2°.

The visible spectrum (0.35–0.95 μm) was obtained using the low resolution gratings (R300B with a dispersion of 0.86 $\text{\AA}/\text{pixel}$, and R158R with a dispersion of 1.63 $\text{\AA}/\text{pixel}$) of the double-armed spectrograph ISIS at WHT, and a 2'' wide slit oriented at the parallactic angle to minimize the spectral effects of atmospheric dispersion. The tracking was at the TNO proper motion. Six 600 s spectra were obtained by shifting the object by 10'' in the slit to better correct the fringing. Calibration and extraction of the spectra were done using IRAF and following standard procedures (Massey et al. 1992). The six spectra of the TNO were averaged. The reflectance spectrum was obtained by

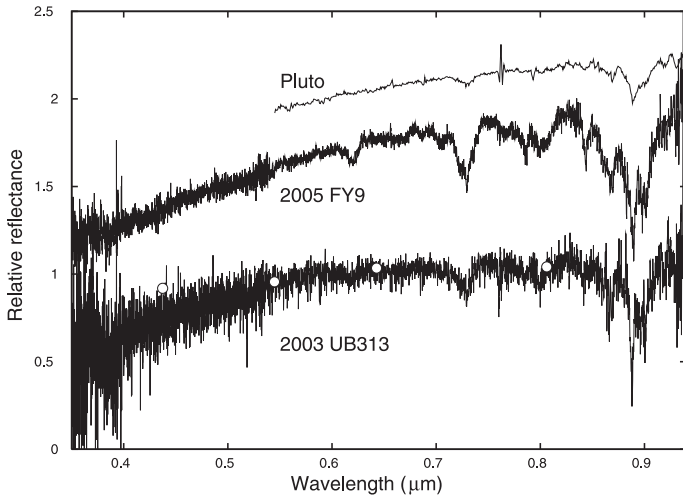


Fig. 1. Reflectance spectrum of 2003 UB₃₁₃ obtained on 2005 October 20.03 UT, normalized at 0.6 μm . The spectrum of Pluto (Grundy & Fink 1996) and the spectrum 2005 FY₉ (Licandro et al. 2006), both shifted vertically, are plotted for comparison.

dividing the spectrum of the TNO by the spectrum of the G2 star Landolt (SA) 93-101 (Landolt 1992) obtained the same night just before and after the observation of the TNO at a similar airmass.

The final reflectance spectrum, normalized at 0.6 μm is plotted in Fig. 1 together with spectra of TNOs Pluto and 2005 FY₉. The spectrum of 2003 UB₃₁₃ presents all the methane ice absorption bands in this wavelength range reported by Grundy et al. (2002), even the weaker ones, and a slightly red slope, and it is very similar to the spectra of Pluto and 2005 FY₉.

3. Discussion

The depths of CH₄ ice absorption bands depends on its abundance, texture, and/or the thickness of the methane-rich surface layer. Licandro et al. (2006) noted that the near-infrared spectrum of TNO 2005 FY₉ is very similar to the near-infrared spectrum of 2003 UB₃₁₃ reported by Brown et al. (2005b). The infrared bands in the spectrum of 2005 FY₉ are deeper than the same bands in Pluto's spectrum (Licandro et al. 2006), which suggests that either the abundance of methane ice on the surface of 2005 FY₉ is larger than on Pluto's surface, and/or the size of methane ice grains (or the thickness of the methane-rich surface layer) is larger than that in Pluto's surface. Unfortunately the low spectral resolution of the near-infrared spectrum of 2005 FY₉, and the S/N of the near-infrared spectrum of 2003 UB₃₁₃, do not permit accurate measurements of band depths and central wavelengths of the CH₄ bands. Licandro et al. (2006) also reported that the prominent bands at 0.73 μm and 0.89 μm are ~ 6 and ~ 3 times deeper respectively in the spectrum of 2005 FY₉ than in Pluto's spectrum, while bands in the near infrared spectrum are only < 2 times deeper, concluding that light reflected from 2005 FY₉ samples larger mean optical path lengths in CH₄ ice than light from Pluto does.

The depths of the CH₄ bands at 0.73 μm and 0.89 μm in the spectrum of 2003 UB₃₁₃ are also greater than the same bands in the spectrum of Pluto (see Fig. 2), but slightly weaker than those in the spectrum of 2005 FY₉. The 0.73 μm and 0.89 μm bands are 1.9 and 1.1 times deeper, respectively, in the spectrum of 2005 FY₉ than in the spectrum of 2003 UB₃₁₃. We conclude that light reflected from 2003 UB₃₁₃ requires mean optical path

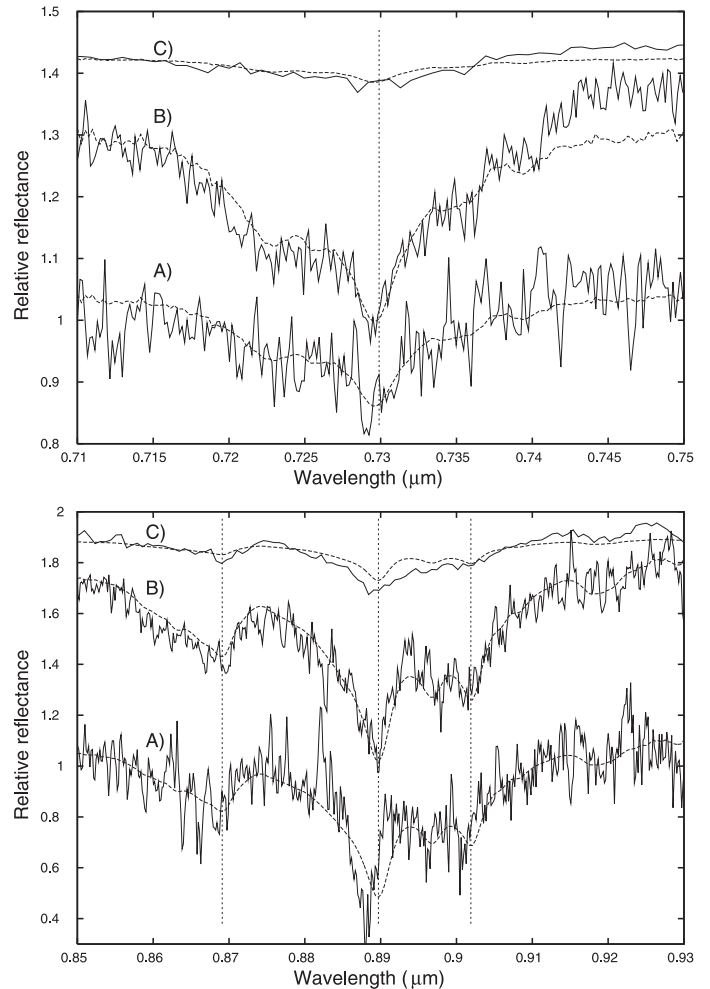


Fig. 2. Reflectance spectra of TNOs 2003 UB₃₁₃, 2005 FY₉, and Pluto shifted vertically, in the two wavelength regions of the most prominent CH₄ ice absorption bands. *Upper:* (A) is the spectrum of 2003 UB₃₁₃ and overplotted (dashed lines) is the spectrum of pure methane ice grains of 1.5 cm diameter; (B) is the spectrum of 2005 FY₉ and overplotted (dashed lines) the spectrum of pure methane ice grains of 4.5 cm diameter; (C) is the spectrum of Pluto and overplotted (dashed lines) the spectrum of pure methane ice grains of 500 μm diameter; vertical dashed lines indicate the central position of pure methane ice bands (Grundy et al. 2002). *Lower:* (A) same as in upper figure; (B) is the spectrum of 2005 FY₉ and overplotted (dashed lines) the spectrum of pure methane ice grains of 2.5 cm diameter; (C) as in upper figure.

lengths in CH₄ ice somewhere between the values for Pluto and for 2005 FY₉. Compared with Pluto, larger grain sizes on the surface of 2003 UB₃₁₃ and 2005 FY₉ would accomplish this, as would higher CH₄ concentrations dissolved in nitrogen ice. Broader geographic distribution of CH₄ ice on 2003 UB₃₁₃ and 2005 FY₉ could contribute as well, since Pluto's CH₄ ice is inhomogeneously distributed (Grundy & Buie 2001). Also the grain size and concentration of CH₄ seems to be larger in 2005 FY₉ than in 2003 UB₃₁₃.

In order to illustrate and give support to the previous discussion, spectra of methane ice grains of different size were produced using the one-dimensional geometrical-optics formulation by Shkuratov et al. (1999) and the optical constants of CH₄ ice from Grundy et al. (2002), and compared with the spectra of 2003 UB₃₁₃, 2005 FY₉, and Pluto around the 0.73 and 0.89 μm spectral bands (see Fig. 2). The 0.73 μm band of 2003 UB₃₁₃, 2005 FY₉, and Pluto can be reproduced using 1.5, 4.5, and

Table 1. Position of the prominent methane lines in the spectra of 2003 UB₃₁₃, 2005 FY₉, and Pluto. Laboratory data from Grundy et al. (2002), Pluto data (with uncertainties ~ 10 Å) from Grundy & Fink (1996), 2005 FY₉ data (with uncertainties ~ 4 Å) from Licandro et al. (2006).

band	methane	2003 UB ₃₁₃	2005 FY ₉	Pluto
	(Å)	(Å)	(Å)	(Å)
$3\nu_1 + 4\nu_4$	7299	7296	7296	7290
$2\nu_1 + \nu_3 + 2\nu_4$	8897	8881	8891	8885

0.5 cm grains, respectively. The 0.89 μm band of 2003 UB₃₁₃, 2005 FY₉ and Pluto is better fitted with 1.5, 2.5 and 0.5 cm grains respectively. As expected, larger grains are needed to reproduce the bands observed in the spectrum of 2005 FY₉ than in the spectrum of 2003 UB₃₁₃ and both are larger than the grains used to reproduce the spectrum of Pluto. In the case of 2005 FY₉, smaller grains are needed to reproduce the 0.89 μm band than the 0.73 μm band. Licandro et al. (2006) found that the weaker CH₄ bands at shorter wavelengths require very large path lengths in CH₄ ice, since absorption by those bands is much weaker than the stronger, near-infrared bands, which require relatively little CH₄ to produce deep absorption bands. Consequently, the shorter wavelengths are particularly sensitive to regions having the most abundant CH₄ ice. Different grain sizes are not used to reproduce the 0.73 μm and 0.89 μm bands observed in the spectrum of 2003 UB₃₁₃, but notice that the fit of the 0.89 μm band is not as good as that of the 0.73 μm one. In particular, the center of the 0.89 μm band is clearly shifted to shorter wavelengths relative to the modeled pure CH₄ ice spectrum.

The shift of the CH₄ ice absorption bands relative to the wavelengths of pure methane ice absorption bands is indicative of dilution of CH₄ in N₂ ice. Pluto's CH₄ bands are seen to be partially shifted to shorter wavelengths relative to the wavelengths of pure methane ice absorption bands, indicating that at least some of the methane ice on Pluto's surface is diluted in N₂ (Quirico et al. 1997; Schmitt et al. 1998; Douté et al. 1999).

Central wavelengths of the two deeper methane ice bands in the visible spectrum of 2003 UB₃₁₃ were obtained by fitting a Gaussian around the bands, and are presented in Table 1. While the $3\nu_1 + 4\nu_4$ band is centered at 7296 Å, very close to the laboratory data, the $2\nu_1 + \nu_3 + 2\nu_4$ is at 8881 Å shifted by 16 Å from the position of pure methane ice. To verify the wavelength calibration of the spectrum, we measured the position of the bright sky lines, and the uncertainties are smaller than 1 Å. As the method used to determine the central wavelengths by fitting gaussians depends on the spectral region considered around the minimum, we also obtained the shifts by an auto-correlation against the model spectrum of pure CH₄ in the spectral regions shown in Fig. 2. Shifts of -1 and 15 ± 3 Å were obtained in the case of 2003 UB₃₁₃ for the 0.73 and 0.89 μm bands respectively, while shifts of 2 and 5 ± 5 were obtained for 2005 FY₉.

The band at 0.89 μm presents another characteristic that supports the detection of CH₄ diluted in N₂ ice. In Fig. 3 we present the spectrum around the band and the spectrum of pure CH₄ shifted by 15 pixels. Notice that the width of the band in the spectrum of 2003 UB₃₁₃ is smaller than the width of the band in the spectrum of pure CH₄ ice. This is what happens if the absorption is due to the monomer of CH₄ (Quirico & Schmitt 1997) as in dilutions of CH₄ on N₂ at low concentrations. Brown et al. (2005b) measured the central wavelengths of several bands in their near-infrared spectrum of 2003 UB₃₁₃ and compared them to the position of pure methane at 30 K and methane diluted in N₂ ice from Quirico & Schmitt (1997) laboratory measurements.

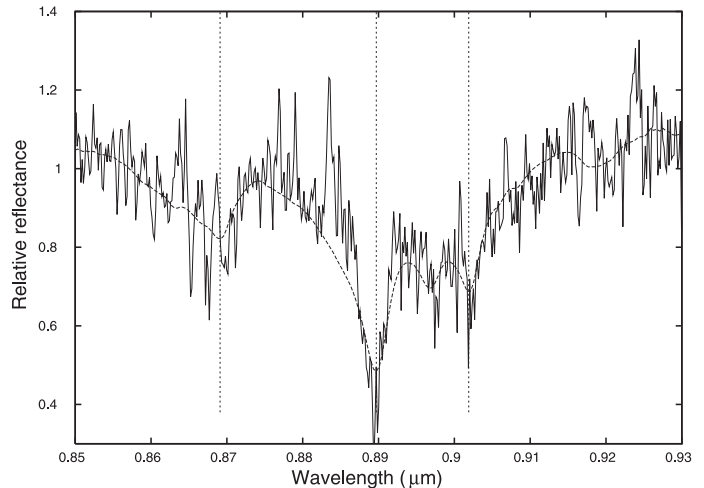


Fig. 3. Reflectance spectrum of TNOs 2003 UB₃₁₃ (solid line) and the spectrum of pure methane ice grains of 1.5 cm diameter shifted by 15 Å (dashed line).

They obtained a mean shift of the four better defined methane bands of 15 ± 5 Å and concluded that while a small amount of dissolved methane may be present, the band positions suggest that the majority of methane is in essentially pure form. In the case of Pluto, Rudy et al. (2003) reported shifts in the near-infrared that are very similar to that in the 0.89 μm band. Considering the uncertainties, the shifts reported by Brown et al. (2005b) are not necessarily discrepant with our measurements. An unshifted methane band can correspond either to pure methane ice or CH₄ diluted in N₂ ice at a relatively high concentration (Quirico & Schmitt 1997).

The shift observed at larger wavelengths, but not at shorter wavelengths, observed in the spectrum of 2003 UB₃₁₃, could be evidence for a vertical compositional gradient. The weaker bands are formed on average more deeply within the surface than the cores of the stronger bands are. If the weak bands look unshifted and the strong bands look shifted, that could indicate that purer methane condensed first, and, as the atmosphere gradually collapsed while 2003 UB₃₁₃ moved towards aphelion during the last two centuries, the composition became more nitrogen-rich as the last, most volatile components condensed. N₂ is much more volatile than CH₄ and so should survive in gaseous state to lower temperatures than CH₄ would as 2003 UB₃₁₃ moves away from perihelion and cools.

CO and N₂ ices were indisputably detected in Pluto's spectrum (Owen et al. 1993). The hexagonal β phase of N₂ ice was detected by means of its 2.15 μm absorption band and CO ice was detected by means of a pair of narrow bands at 2.35 and 1.58 μm . The spectral S/N of the spectrum of 2003 UB₃₁₃ (Brown et al. 2005b) is not sufficient to see the CO absorptions. The N₂ band would also be difficult to detect, even if N₂ were a major component of the surface of 2003 UB₃₁₃, because the nitrogen absorption has about a factor of a thousand smaller peak absorption coefficient than that of the nearby CH₄ band at 2.2 μm , which dominates that spectral region. It is also possible that surface temperatures on 2003 UB₃₁₃ might be below the 35.6 K transition temperature between the warmer β phase of N₂ ice, and the colder, cubic α phase of N₂ ice, which has an extremely narrow 2.15 μm absorption, which would be unresolved in Brown et al. (2005b) data (e.g., Grundy et al. 1993). Future, higher spectral resolution observations will put more constraints on the presence of N₂ and CO ice on the surface of 2003 UB₃₁₃.

A final important characteristic of the spectrum is its colour. The surface of 2003 UB₃₁₃ is slightly red. To compare with Pluto we computed the ratio of the reflectance spectrum at 0.825 and 0.590 μm as in Grundy & Fink (1996). The value of this ratio is 1.10, and corresponds to a spectral slope $S' = 4\%/1000 \text{ \AA}$. Pluto and 2005 FY₉ present a slightly redder spectrum, with a ratio of 1.20 and 1.21 respectively ($S' = 8.8$ and $8.9\%/1000 \text{ \AA}$, Licandro et al. 2006). The most accepted hypothesis to explain the red colour of Pluto is the existence of complex organics molecules (tholins) formed from simple organics by photolysis (e.g. Khare et al. 1984). Thus tholins should be less abundant on 2003 UB₃₁₃ than on Pluto and 2005 FY₉.

4. Conclusions

We present a new 0.35–0.94 μm spectrum of the TNO 2003 UB₃₁₃. The spectrum is very similar to that of Pluto, with prominent CH₄ ice absorptions bands. At wavelengths $<0.6 \mu\text{m}$ the spectrum is almost featureless and slightly red ($S' = 4 \pm 1\%/1000 \text{ \AA}$) supporting the existence of complex organics molecules (tholins) on its surface. The visible spectrum of 2003 UB₃₁₃ is not as red as spectra of Pluto and 2005 FY₉ ($S' = 8.8$ and $8.9\%/1000 \text{ \AA}$ respectively), thus complex organics should be less abundant on the surface of 2003 UB₃₁₃ than on the surfaces of Pluto and 2005 FY₉.

The CH₄ ice bands in this new giant TNO are significantly stronger than those of Pluto, but weaker than those observed in the spectrum of 2005 FY₉ (Licandro et al. 2006). Methane is more abundant and/or the methane ice grain particles (or the thickness of the surface ice layer) are larger on its surface than on the surface of Pluto, and less abundant or composed of smaller grains than on the surface of 2005 FY₉.

A 15 \AA shift of the central wavelength of the 0.89 μm band relative to the pure methane band observed in the laboratory is observed. This shift is indicative of the presence of methane

diluted in N₂. On the other hand, the 0.73 μm band is not significantly shifted. This could be evidence for a vertical compositional gradient consistent with purer methane condensing first, with the composition becoming more nitrogen-rich as the last, most volatile components of the atmosphere condensed. Such a compositional gradient could also arise via the solar gardening mechanism discussed by Grundy & Stansberry (2000).

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References

- Brown, M. E., Trujillo, C. A., Rabinowitz, D., & Marsden, B. G. 2005a, MPEC, 2005-O42
- Brown, M. E., Trujillo, C. A., & Rabinowitz, D. 2005b, ApJ, 635, L97
- Brown, M., Schaller, E., Roe, H., Rabinowitz, D., & Trujillo, C. 2006, ApJ, 643, 61
- Cruikshank, D., 1998, in Solar System Ices, ed. B. Schmitt, et al. (Kluwer), 655
- Cruikshank, D., Roush, T., Owem, T., et al. 1993, Science, 261, 742
- Douté, S., Schmitt, B., Quirico, E., et al. 1999, Icarus, 142, 421
- Grundy, W., & Fink, U. 1996, Icarus, 124, 329
- Grundy, W. M., & Stansberry, J. 2000, Icarus, 148, 340
- Grundy, W. M., & Buie, M. W. 2001, Icarus, 153, 248
- Grundy, W. M., Schmitt, B., & Quirico, E. 1993, Icarus, 105, 254
- Grundy, W., Schmitt, B., & Quirico, E. 2002, Icarus, 155, 486
- Khare, B., Sagan, C., Arakawa, E., et al. 1984, Icarus, 60, 127
- Landolt, A. 1992, AJ, 104, 340
- Licandro, J., Pinilla-Alonso, N., Pedani, M., et al. 2006, A&A 445, 35
- Massey, P., Valdes, F., & Barnes, J. 1992, in A User's Guide to Reducing Slit Spectra with IRAF, <http://iraf.noao.edu/iraf/ftp/iraf/docs/spect.ps.Z>
- Owen, T., Roush, T., Cruikshank, D., et al. 1993, Science, 261, 745
- Quirico, E., & Schmitt, B. 1997, Icarus, 127, 354
- Rudy, R., Venturini, C., Lynch, D., et al. 2003, PASP, 115, 484
- Schmitt, B., Quirico, E., Trotta, F., & Grundy, W. M. 1998, in Solar System Ices, ed. B. Schmitt et al. (Kluwer Academic Publishers)
- Shkuratov, Y., Starukhina, L., Hoffmann, H., & Arnold, G. 1999, Icarus, 137, 235
- Spencer, J., Stansberry, J., Trafton, L., et al. 1997, in Pluto and Charon, Stern A. & ed. Tholen, D. (U. Arizona Press), 435