SUBARU/IRCS Infrared Spectroscopy of the Pluto

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ABSTRACT

We present new spectrum of the Pluto, covering the 2.8-4.1 μm wavelength range. The new data show prominent absorptions of ethane ice on surface of Pluto. Our results require the mass ratio of ethane to methane to be approximately 1:10, which is much higher than the value expected from the equilibrium condensation theory. We propose three processes to add this surplus ethane to Pluto's surface: (1) external reservoir, (2) internal reservoir, and (3) photolysis/radiolysis. Our study could provide us important implications and constraints for evolutions of the edge of the solar system, such as Pluto, Charon, and EKBOs.

Subject headings: infrared: solar system—planets and satellites: Pluto—Kuiper Belt

1. Introduction

Spectroscopic observations of Pluto at visible to 2.5 μm have showed absorption features of solid methane and carbon monoxide diluted by nitrogen ice, and recently intimated the existence of ethane ice on surface of Pluto (Grundy & Fink 1996; Douté et al. 1999; Grundy & Buie 1998; Nakamura et al. 2000; Cruikshank et al. 1997; Tholen & Buie 1997). Only a few groups obtained photometric observations of Pluto at 2.8-4.1 μm range, where they found CH_4 ice absorption bands as well as other features which were attributed to CO_2 and / or SO_2 ices (Grundy et al. 2002). However, the spectral resolution of their data was insufficient confirm the existence of ethane ice, because of difficulties deriving precise spectra at wavelengths longer than 2.5 μm with increasing telluric sky brightness. In this article, we report the additional composition of Pluto's surface from infrared spectroscopy at 2.8-4.0 μm conducted at Subaru telescope with IRCS (InfraRed Camera and Spectrograph) and AO (Adaptive Optics). We present a spectroscopic analysis of this observation as well as numerical modelling of the spectra.

2. Observations

Observations of Pluto were obtained during 2002 May 28th 08-13 UT and 29th 10-13 UT, using IRCS and AO mounted on the cassegrain focus of the Subaru telescope. We used the Grism-L mode of IRCS, which covers the L atmospheric transmission windows. On May 28th, the sub-Earth longitude on Pluto was 40-50 degree, and on may 29th, that was 90-100 degree. The respective total integration times were 5800 sec in May 28th and 4200 sec in May 29th. The slit width is 0.3 arcsec, giving the spectral resolution of $\lambda/d\lambda \sim 122$ in the L band. Charon, a satellite of Pluto, was clearly separated from Pluto on both dates with the moderate atmospheric seeing of approximately 0.3-0.4 arcsec. The absorption lines of an argon lamp were measured for the spectral wavelength calibration.

The spectrum of Pluto were reduced from the original raw data frames using NOAO IRAF (Image Reduction and Analysis Facility). First, the effect of sky was removed by the subtraction between two frames that have different positions of Pluto, and uneven of sensitivity was revised with a flat-frame. Integration of this revised two-dimensional spectrum over the spatial direction gave a one-dimensional profile. To remove an effect of telluric extinction, we measured the spectra of the solar analog stars SAO100553, SAO141540, and SAO159821, and then divided the combined spectra by their stars spectra. Through these procedures, we had the independent spectrum of Pluto.

3. Results

The spectrum of Pluto is shown in Figure 1. It shows strong absorption bands of methane, which are found in previous observations (Grundy & Fink 1996; Douté et al. 1999; Grundy & Buie 1998; Nakamura et al. 2000; Cruikshank et al. 1997; Tholen & Buie 1997; Grundy et al. 2002). And we show two model calculations as dotted and dashed curves in Figure 1 to examine the effect of ethane ice on the spectrum of Pluto. Dotted curve shows a synthetic spectrum without ethane, and dashed curve shows that with ethane. Their spectra were computed with Hapke's bidirectional reflectance model (Hapke 1993), where the mass fraction to N_2 ice is 0.01 for methane, 0.002 for carbon monoxide, and 0 or 0.001 for ethane. The optical constants are adapted from recent near-infrared studies (Quirico et al. 1999). The most prominent new features evident in this spectrum of Pluto are strong ethane ice absorptions at 3.1 μm, 3.25 μm, 3.35 μm, 3.5 μm, and 3.8 μm. Confirming these evident absorptions of ethane ice on Pluto is entirely new result.

Figure 2 shows various model calculations, from the top, the ratio of ethane to methane is 1:10000, 1:100, 1:10, and 1:1. To match our observation in Figure 1, these model spectra require ethane:methane ratio to be approximately 1:10. This mass ratio of ethane to methane is much higher than the value expected from the production by the equilibrium condensation processes within the protoplanetary disk, that processes predict the production ratio of ethane to methane is 1:10000 (Fegley & Prinn 1989).

4. Discussions

Our observation requires the way to add large amount of ethane to the surface of Pluto. We propose three scenarios.

First, an external reservoir: Small EKBOs (Edgeworth-Kuiper Belt Objects), the precursor of short period comets, could deliver the primordial volatiles such as ethane to the surface of Pluto. Some Comets actually showed ethane in this gas phase was comparable abundance to methane (Mumma et al. 1996; Kawakita et al. 2003). The high C_2H_6/CH_4 ratio is consistent with kinetically controlled production process in icy grain mantles in the natal cloud (Mumma et al. 1996). The key point in this scenario is whether the impact velocities of these comets are slow enough to add their ethane to Pluto's surface without thermal metamorphism or shock decomposition. It is desired to investigate the effects of comet impact and chemical reactions in the impact plume on the surface of Pluto to verify this hypothesis.

Second, an internal reservoir: Internal ethane could seep to surface of Pluto, whose ethane was the composition of the primitive materials of Pluto or the production by the differentiation processes interior of Pluto. In the region of Pluto, where the semimajor axis is about 40 AU, it is likely that

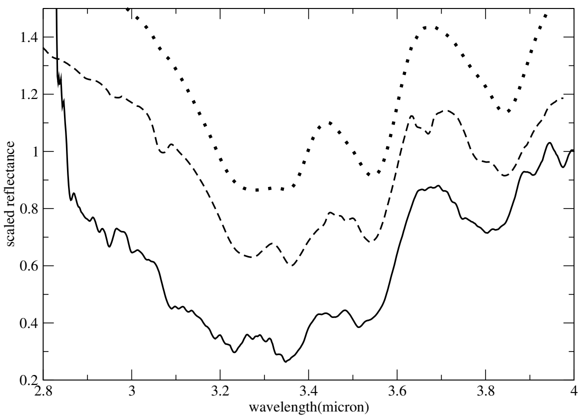

Fig. 1.— Reflectance spectrum of Pluto compared with modelled spectra. The solid line of observations shows the smoothed curve resulted from the Savitzky-Golay Smoothing filters of 21 pixels. Model spectra show absorptions of mixture of N_2 : CH_4 : CO with the mass ratio 1 : 0.01 : 0.002, dotted curve is 'without ethane' and dashed curve is 'with ethane'.

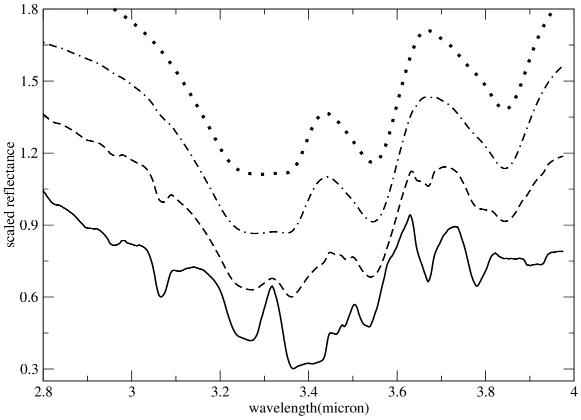

Fig. 2.— Various model calculations of Pluto at L band. Mass ratio of the mixture is the same as that in Figure 1. The ratio of ethane to methane is 1:10000, 1:100, 1:10, and 1:1 from top to bottom.

the equilibrium condensation process had not occurred, and ethane/methane ratio of the materials of Pluto was maintained high enough. Pluto could have some primitive ethane surviving through decomposition during accretion processes. Even if the primitive ethane has not surviving, it is possible that ethane was produced by a differentiation during evolution processes interior of Pluto. Recent observations of Charon provide us with the spectra of this satellite, and they show several absorptions of water ice and ammonia ice, which are entirely different from the futures of Pluto (Roush et al. 1996; Brown & Calvin 2000). If this scenario is correct, the difference between surface composition of Pluto and Charon could be explained by the difference of evolution and differentiation processes.

Third, photolysis/radiolysis: Ethane could be produced via photolysis or radiolysis of atmospheric CH_4. Titan, a satellite of Saturn, had actually experienced this photochemical reaction (Lunine et al. 1989). The fundamental driving force in the long-term evolution of Titan's atmosphere is the photolysis of methane to form higher hydrocarbons such as ethane (Lunine et al. 1989). Then it is subject to enrichment in ethane due to the long-term photolysis of methane. However, considering the fact that atmosphere of Pluto may exist only when Pluto is near its perihelion, it is not certain whether these chemical reactions is sufficient to produce enough abundance of ethane on surface of Pluto. On the other hand, the study of irradiated water-ice mixtures with hydrocarbons showed that C_2H_6 yielded from C_2H_2 due to H-addition reactions (Moore & Hudson 1998). However, because CH_4 is not a source of C_2H_2, the existence of acetylene on Pluto is required to produce ethane by radiolysis (Moore & Hudson 1998). Further observations of the Pluto's atmosphere could present us some evidence for supporting this scenario.

5. Conclusion

We present new spectum of Pluto at 2.8-4.1 μm, and confirm the absorptions of ethane ice on surface of Pluto. Recently, Pluto has been considered the one of the members of EKBOs as well as its satellite, Charon, and Neptune's satellite, Triton have been. However, their surface compositions are different each other (Roush et al. 1996; Brown & Calvin 2000; Cruikshank et al. 2000; Brown et al. 1995; Yelle et al. 1995). These differences could show the difference of their sizes, evolution processes, tidal heating (Shock & McKinnon 1993), and chemical reactions for their histories. Our result, evident absorptions of large amount of ethane on Pluto's surface, provides us several important implications and constraints for consideration of these subjects.

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