INFRARED HIGH-RESOLUTION SPECTROSCOPY OF PLUTO BY SUBARU TELESCOPE

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Here we report a infrared high-resolution spectroscopy of Pluto in the $L$ band. The spectroscopic observation was performed by the Subaru telescope with the adaptive optics system. The spectrum is dominated by the strong and broad absorption features of methane, but includes some additional features. Comparing the spectrum with model calculations, we suggest that absorption features could be an indication of nonmethane hydrocarbons on Pluto’s surface.

1. Introduction

Spectroscopic observations of Pluto at visible to 2.5 $\mu$m 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 $^{1,2}$. Only a few groups obtained photometric observations of Pluto at 2.8-4.1 $\mu$m 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 $^1$. However, the spectral resolution of their data was insufficient confirm the existence of hydrocarbons’ ice, because of difficulties deriving precise spectra at wavelengths longer than 2.5 $\mu$m with increasing telluric sky brightness. In this study, we report the additional composition of Pluto’s surface from infrared spectroscopy at 2.8-4.0 $\mu$m conducted at Subaru telescope with IRCS (InfraRed Camera and Spectrograph) $^3$ and AO (Adaptive Optics) $^4$. We present a spectroscopic analysis of this observation as well as numerical modelling of the spectra.
2. Observations and Data Reduction

A near-infrared spectroscopic observation of Pluto was performed by the 8-m Subaru telescope with IRCS in conjunction with its AO system on 2002 May 28 (UT) near the opposition (RA=17h05m33s, dec=12°39’25”). The sub-Earth longitude was 40-50 degrees and the separation from Charon was 0.9 arcsec. Spectral resolving power was approximately 400 at the $L$ band in our observation, meanwhile that was about 60 in Grundy et al. The typical psf width was 0.3-0.4 arcsec during the observation and the total on-source integration time was 2600 sec. For the cancellation of telluric absorption features, a reference star (G3V star SAO141540) was observed just after Pluto observation. The air mass differences between Pluto and the reference star were less than 0.035 throughout the observation.

We used NOAO IRAF astronomical software package to reduce near-infrared spectra obtained by IRCS. Argon lamp frames were used for the wavelength calibration. Since Pluto was clearly separated from Charon with the FWHM as sharp as 0.4 arcsec, the resulting spectrum includes no contamination from Charon.

For details refer to Sasaki et al. (2005).

3. Results

The spectrum of Pluto is shown in Figure 1 along with the previous low resolution data and synthetic spectra of simple ternary intimate mixture of $N_2$-$CH_4$-$CO$. As Nakamura et al., we employed Hapke’s bidirectional model to calculate the spectrum of a uniform half-infinite layer covering the whole surface of Pluto. It should be noted that the detailed model calculations are beyond the scope of this paper because we cannot account for the realistic solid solutions, vertically layered structure and spatially segregated patches unlike some previous approaches. Apparently, the shape of the synthetic spectra is dominated by $CH_4$ because $N_2$ and CO have no significant absorptions in the wavelength range.

Grundy et al. found a decrease of the reflectance lower than 3.2 $\mu$m and beyond 3.95 $\mu$m. They interpreted the result as the contribution from non-volatile ices, such as $H_2O$ for the former, $SO_2$ and $CO_2$ for the latter. While we cannot confirm the putative band of $SO_2$ and $CO_2$ due to the limited wavelength coverage, our spectra shortward of 3.2 $\mu$m are consistent with their results.

Our observations show lower reflectance around 3.45 $\mu$m and additional absorptions around 3.1, 3.2, 3.35 $\mu$m. In order to reproduce the features, we
incorporated some non-methane hydrocarbons, namely C$_2$H$_2$, C$_2$H$_4$, C$_2$H$_6$, and C$_3$H$_8$ into the model calculations. Assuming their mass ratio to CH$_4$ as 10 percent, we computed the model spectra in Figure 2. The optical constants were measured by Quirico et al.$^7$. Although HCN, CH$_3$OH, and H$_2$CO are also found in both interstellar and cometary ices, the optical constants for them are not available. In Figure 2, CH$_4$ is assumed to be diluted in the solid molecular nitrogen. It is found that C$_2$H$_2$, C$_2$H$_4$ and C$_2$H$_6$ would produce the 3.1 $\mu$m absorption if their relative concentration to CH$_4$ is approximately 10 weight percent. This value should be regarded as the upper limit for C$_3$H$_8$ because the absorption at 3.0 $\mu$m is not seen in the observed spectrum. Figure 2 indicates that C$_2$H$_4$ and C$_2$H$_6$ could be associated with the absorptions around 3.2 $\mu$m and 3.35 $\mu$m.

Adding C$_2$H$_4$ as the fourth component, we obtained a better agreement with the observations than the simple ternary mixture model, but there still remains discrepancy between 3.4 $\mu$m and 3.55 $\mu$m. On the other hand, C$_2$H$_6$ improves the fit in this range, although we see no clear absorption around 3.65 $\mu$m in the observed spectrum. So we plotted two synthetic spectra (ternary + C$_2$H$_6$ and ternary + C$_2$H$_6$ + C$_2$H$_2$) in Figure 3 for
Fig. 2. Modeled spectra including non-methane hydrocarbons (NMHCs) as the fourth component. The fourth components are $C_2H_2$, $C_2H_4$, $C_3H_6$, and $C_3H_8$. The model parameters of the basic ternary mixture are the same as those in Figure 1, and the mass fraction to $CH_4$ of the fourth component is 0.1.

Fig. 3. Reflectance spectrum of Pluto with the modeled spectra. The circles shows our observation as shown in Figure 1. The dashed and dotted curves represent the synthetic spectrum with $C_2H_6:CH_4 = 1:10$ and $C_2H_2:C_2H_6:CH_4$ with mass ratios 1:1:10, respectively.

the detailed comparison with the observed spectrum. In both cases, the observed absorptions around 3.2 $\mu$m and 3.35 $\mu$m shifts toward shorter
wavelengths compared with the model spectra. Quirico & Schmitt \(^8\) has shown that the dilution in solid \(N_2\) ice cause the shift of hydrocarbons’ absorptions. More laboratory experiments are needed to explore the dilution effect more quantitatively. Adding \(C_2H_2\) as the fifth component in the model calculation makes the spectrum match the observed spectrum quite well, as shown in Figure 3.

4. Discussion

In the the protoplanetary disk and the interstellar cloud that proceeded it, the gas-phase ion-molecule reactions could yield \(C_2H_2\). The reaction of \(H\) with \(C_2H_2\) on cold dust grains could produce \(C_2H_6\) more effectively than \(C_2H_4\) \(^9\). In fact, \(C_2H_2\) and \(C_2H_6\) have been found in the comas of Oort-cloud comets \(^10,11\), but the detection of \(C_2H_4\) has not been reported so far. The \(C_2H_6/CH_4\) ratio estimated from Figure 3 is consistent notonly with the Oort-cloud comets but also with a value of a short-period comet 21P/Giacobini-Zinner \(^12\) and the upper limit for interstellar materials \(^13\). Moreover, the \(C_2H_2/CH_4\) ratio approximately agrees with the values for Oort-cloud comets \(^10,14\).

Non-methane hydrocarbons could be the secondary products generated from methane. Krasnopolsky & Cruikshank \(^15\) simulated photochemical reactions in Pluto’s tenuous atmosphere and the subsequent precipitation to the surface. \(C_2H_2\) and \(C_4H_2\) have the highest precipitation rates among numerous photochemical products, but \(C_2H_2\) cannot produce the observed 3.2 and 3.35 \(\mu\)m features and we do not have the optical constants for solid \(C_4H_2\). The precipitation rates of \(C_2H_4\) and \(C_2H_6\) are smaller than those of \(C_2H_2\) and \(C_4H_2\) by an order of magnitude. If the 3.2 and 3.35 \(\mu\)m features are indication of \(C_2H_4\) and/or \(C_2H_6\) produced by the photochemical reactions, we must increase their relative concentrations to \(C_2H_2\) and \(C_4H_2\) somehow. Moore & Hudson \(^16\) conducted the systematic infrared study of proton-irradiated \(N_2\)-rich ices containing \(CH_4\) and \(CO\). They found \(C_2H_2\), \(C_2H_4\), \(C_2H_6\) and \(C_3H_8\) along with \(HCN\) and \(HNC\) in the irradiated analog materials of Pluto’s surface. It should be emphasized that they identified \(C_2H_6\) with the absorption at 3.35 \(\mu\)m but the expected absorption around 3.65 \(\mu\)m was not detected as our observation. In addition, \(HCN\) is expected to decrease the gap between the models and observation around 3.1 \(\mu\)m. Therefore, we do not rule out possibilities that observed features were associated with non-methane hydrocarbons produced by the in-situ surface reactions induced by cosmic-ray irradiation to the original ternary mixture
of N$_2$, CH$_4$ and CO. In either case, thin deposits are vulnerable to micrometeorite impact. The relative mass ratio to the parent methane, derived from our observations, could be a key to understanding the gardening process on Pluto, such as poorly known dust flux$^{17}$ and vertical mixing timescale$^{15}$.

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**References**