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A Survey of Near-infrared Diffuse Interstellar Bands

Satoshi Hamano[1*], Naoto Kobayashi[2], Hideyo Kawakita[1], Yuji Ikeda[3], Sohei Kondo[1], Hiroaki Sameshima[1], Akira Arai[1], Noriyuki Matsunaga[2], Chikako Yasui[5], Misaki Mizumoto[6,4], Kei Fukue[1], Natsuko Izumi[5], Shogo Otsubo[1], Keiichi Takenaka[1]

[1] Laboratory of Infrared High-resolution Spectroscopy, Kyoto Sangyo University
[2] Kiso Observatory, Institute of Astronomy, School of Science, The University of Tokyo
[3] Photocoding
[4] Department of Astronomy, Graduate School of Science, University of Tokyo
[5] National Astronomical Observatory of Japan
[6] Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA)

Abstract: We propose a study of interstellar molecules with near-infrared (NIR) high-resolution spectroscopy as a science case for the 3.6-m Devasthal Optical Telescope (DOT). In particular, we present the results obtained on-going survey of diffuse interstellar bands (DIBs) in NIR with the newly developed NIR high-resolution spectrograph WINERED, which offers a high sensitivity in the wavelength range of 0.91-1.36 μm. Using the WINERED spectrograph attached to the 1.3-m Araki telescope in Japan, we obtained high-quality spectra of a number of early-type stars in various environments, such as diffuse interstellar clouds, dark clouds and star-forming regions, to investigate the properties of NIR DIBs and constrain their carriers. As a result, we successfully identified about 50 new NIR DIBs, where only five fairly strong DIBs had been identified previously. Also, some properties of DIBs in the NIR are discussed to constrain the carriers of DIBs.

1 Interstellar molecules with NIR spectroscopy

Recently, the number of NIR high-resolution spectrographs is rapidly increasing due to the availability of the large format infrared array. NIR high-resolution spectroscopy is a strong tool for astrophysics and astrochemistry. The progress of instruments has been producing the fruitful results in various scientific fields: stellar abundance & kinematical analysis, planet search, interstellar medium, high-redshift quasars and its absorption-line systems, etc. Therefore, NIR high-resolution spectrographs can be a good choice as second-generation instruments for the 3.6-m DOT. See Kobayashi et al. (these proceedings) for the detailed description of NIR high-resolution spectrographs.

Here, we would like to focus on the NIR spectroscopic studies of interstellar molecules. In the NIR wavelength range, we can detect the absorption bands of various large and small molecules in interstellar medium, such as DIBs, C_2, CN, CO, and H_3^+. DIBs are ubiquitous absorption bands

*E-mail: hamano@cc.kyoto-su.ac.jp

originating from interstellar clouds in the spectra of background reddened stars. The carriers of DIBs are long-standing mystery in the astronomy. They are now considered to arise from the gas-phase carbonaceous molecules, such as fullerenes and its derivatives (Omont et al. 2016), polycyclic aromatic hydrocarbons (PAHs; Salama et al. 2011), and carbon chain molecules (Maier et al. 2011). In fact, Campbell et al. 2015 obtained an excellent result to identify five DIBs in the short NIR ($\lambda \sim 0.95$ μm) as the electronic absorption bands of ionized buckminsterfullerene C_{60}^{+}. This is the first identification of the DIBs carriers. At this time, DIBs in the NIR are of great importance to study the interstellar properties and processes of fullerenes and their relations with other unidentified DIBs. On the other hand, with the spectroscopy of absorption bands originating from interstellar small molecules, we can study the fundamental chemical processes related to small carbon molecules. In addition, the rotational distribution of such small molecules can be used as "thermometer" or "densitometer" of interstellar clouds (Casu et al. 2012).

The rest of this paper will be dedicated to describe our on-going survey programs of DIBs in NIR wavelength range with the WINERED spectrograph mounted on the 1.3-m Araki telescope. The specifications of WINERED are described in Sec. 2. The distinctive feature of WINERED is the high throughput of the optics which enables us to obtain high-quality spectra of $J < 11$ mag objects even with a 1m-class telescope. Also, the high transmittance of NIR fluxes enables us to explore the DIBs in high-extinction lines of sight. Our study with a 1m-class telescope can be extended with 4m-class telescopes as the 3.6-m DOT. Most of the results presented in this paper are already published by Hamano et al. (2015, 2016).

2 NIR DIBs survey with WINERED

WINERED (Fig. 1) is a PI-type NIR high-resolution echelle spectrograph mounted on the F/10 Nasmyth focus of the 1.3-m Araki telescope at the Koyama Astronomical Observatory, Kyoto Sangyo University, Japan (Kondo et al. 2015). WINERED uses a 1.7 μm cutoff 2048$\times$2048 HAWAII-2RG infrared array with a pixel scale of 0.8$''$ pixel^{-1} covering the wavelength range 0.91-1.36 μm. We used a slit of length 48$''$ and width 1.6$''$ (2 pixels). This slit width corresponds to a spectral resolving power of $R \equiv \lambda/\Delta\lambda =$ 28,000 or $\Delta v = 11$ km s^{-1}.

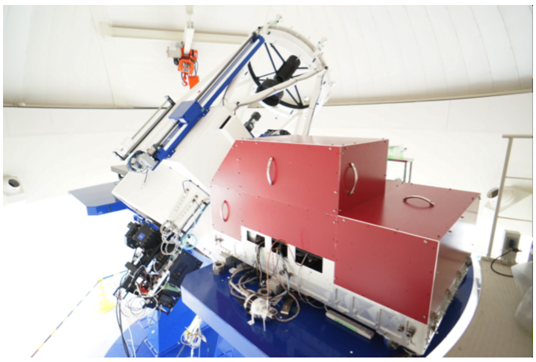

Figure 1: The picture of the NIR high-resolution spectrograph, WINERED (the red box).

We have obtained NIR spectra of more than 100 reddened early-type stars for our DIBs survey program. The obtained raw images are semi-automatically reduced to one-dimensional spectra with our data reduction pipeline based on PyRAF.

3 New DIBs in NIR

From the obtained spectra, we searched for the new DIBs in $0.91 < \lambda < 1.36$ μm. The telluric lines are removed by dividing the target spectra with the spectra of A0V telluric standard stars obtained at similar airmasses as the targets during the observations. Fig. 2 shows the comparison of spectra of a star without reddening and a star with heavy interstellar extinction. The signal-to-noise ratio of the spectra reached about 500, which is quite high for NIR high-resolution spectra. We discern the stellar and interstellar features from the comparison and searched for DIBs, which are the broad interstellar absorption features detected at the velocities of interstellar clouds. As a result, we could detect about 50 new DIBs with equivalent widths (EWs) greater than 10 mÅ in $0.91 < \lambda < 1.36$ μm, where only 5 DIBs were reported previously (Hamano et al. 2015). Figure 3 shows the EW distribution.

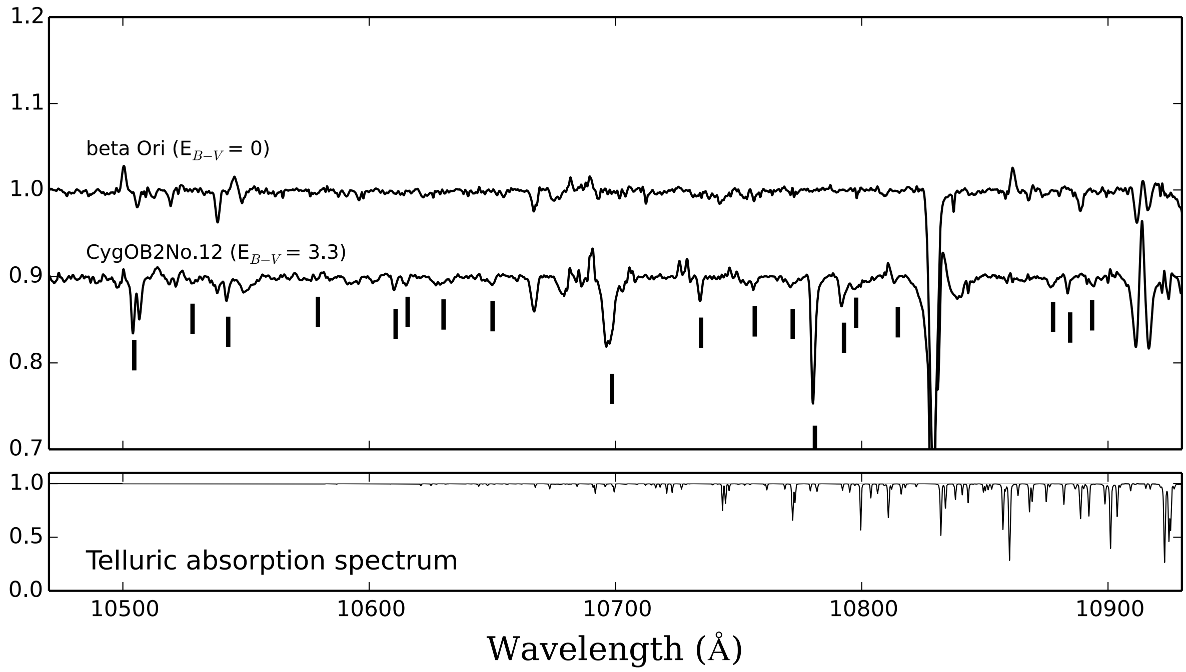

Figure 2: *Upper panel:* The typical WINERED spectra of β Ori, reference star without interstellar reddening, and Cyg OB2 No.12, which is veiled with heavy interstellar extinction (E_{B-V} = 3.3). Common features are stellar lines. Absorption bands detected only in Cyg OB2 No.12 are DIBs originating from intervening interstellar clouds (marked with lines). *Lower panel:* The transmittance of the Earth's atmosphere.

4 Discussion

We discuss the properties of newly detected DIBs in this section. We examined the correlations among strong DIBs in NIR. It is found that a group of 5 DIBs (DIB 10780, 10792, 11797, 12623, and 13175) are correlated well with each other, so-called "family". Figure 4 shows the correlation plots. The black and red points show the EWs of field stars and the stars in the Cyg OB2 association (Cyg OB2), which is a massive star-forming region. Because the gas clouds in Cyg OB2 are considered to be illuminated with strong UV flux from numerous OB stars in the region, the black and red points in Fig. 4 trace the DIBs in quite different environments. The tight correlations common in different environments suggest that these DIBs originate from molecules with similar properties, such as the

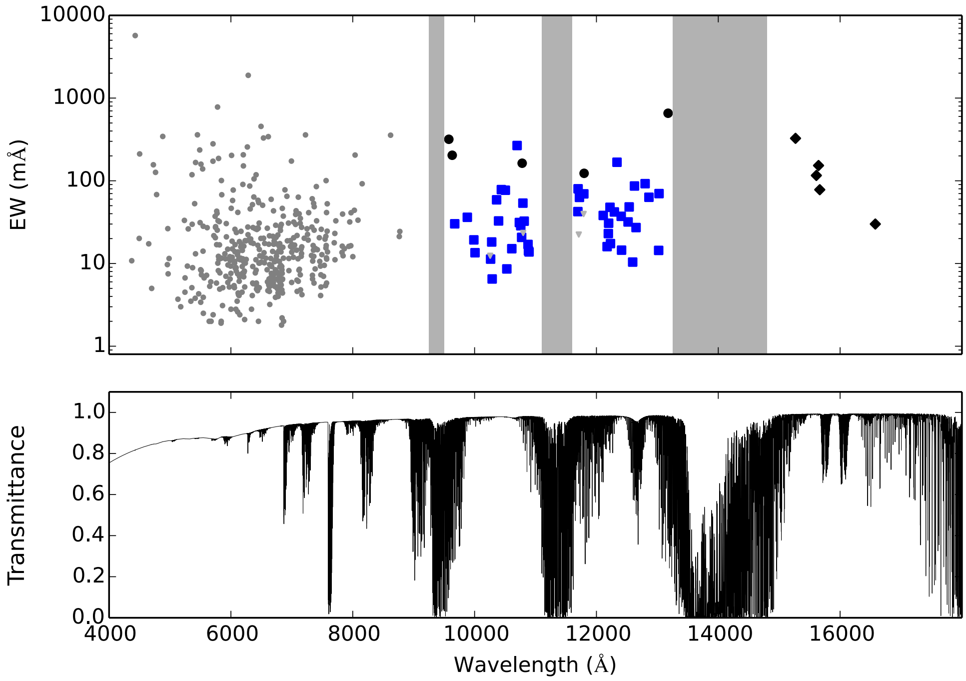

Figure 3: *Upper panel:* The EW distribution of DIBs toward HD183143 (E_{B-V} = 1.27) from the optical to the $H-$band. Blue squares show the EWs of DIBs newly detected in this survey while black circles show the EWs of DIBs previously detected in $0.91 < \lambda < 1.36$ μm. Gray circles and black diamonds show the EWs of DIBs adopted from Hobbs et al. (2009) and Cox et al. (2014), respectively. The gray areas show the regions with heavy telluric absorption. *Lower panel:* The transmittance of the Earth's atmosphere.

ionization potential, size, and chemical compositions. In addition, we found that the "family" NIR DIBs are correlated well with DIB 5780, which has been suggested to be a cation molecule because of its higher EW in UV-irradiated regions. Therefore, we suggest that the carriers of these "family" DIBs are ionized fullerenes and PAHs, which would be resilient in the harsh environment as Cyg OB2 (Hamano et al. 2016). If a high-sensitivity, high-resolution spectrograph as WINERED is attached to the 3.6-m DOT, it will become possible to observe DIBs in various environments such as other galaxies and quasar absorption line systems, which will give us further constraints on the molecular properties of DIBs carriers.

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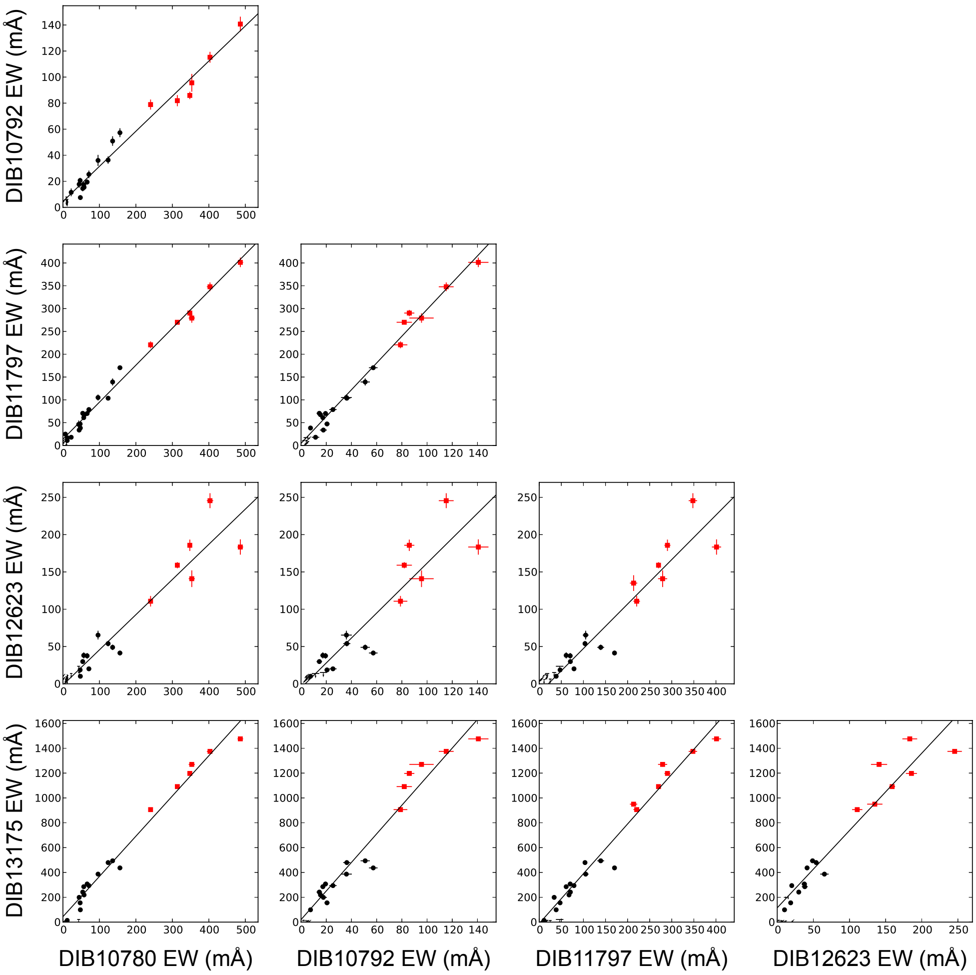

Figure 4: The correlations of the "family" DIBs in the NIR. See text for the notation.

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