Feasibility study of trace gas observations in the Venusian lower atmosphere using the high-dispersion near-infrared spectrograph GARNET

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Venus is similar to Earth in size and mass, yet it possesses a dense atmosphere more than 90 times thicker than Earth's, dominated by CO_2, producing an extreme greenhouse effect and a surface temperature of ~730 K. Understanding how Venus evolved into such a drastically different environment is essential for clarifying the divergent evolution of terrestrial planets. Trace species in the atmosphere play a key role in this effort, as their abundances and spatiotemporal variations serve as tracers of photochemistry, cloud microphysics, atmospheric circulation, and surface-atmosphere interactions. In particular, the lower atmosphere more directly reflects surface conditions and the supply of gases from the planetary interior, making its composition crucial for reconstructing Venus's atmospheric evolution.

The thick global sulfuric acid cloud deck and dense CO_2 atmosphere strongly obscure the lower atmosphere of Venus. Nearly the only method to probe this region is to use near-infrared atmospheric windows, where absorption by clouds and CO_2 is relatively weak and thermal radiation from the lower atmosphere can escape to space. Absorption lines of trace species are superimposed on this transmitted radiation, enabling compositional analysis through precise spectral measurements. Previous spacecraft and ground-based spectroscopic observations have constrained several molecular abundances; however, the near-infrared windows contain numerous overlapping absorption lines from multiple species, requiring very high spectral resolution to disentangle their contributions. Although higher resolution improves molecular discrimination, it reduces photon counts per detector pixel, necessitating large telescopes. Such facilities, however, face intense competition for observing time, limiting systematic and long-term monitoring of Venus's lower atmosphere.

To address this challenge, our group is developing a compact and highly sensitive high-dispersion near-infrared spectrograph, named GARNET. By employing a germanium immersion grating and a cordierite reflective optical system, GARNET achieves a compact design adaptable to a 1-m class telescope Cassegrain focus, while maintaining a high throughput of 0.38 (without slit losses). A key feature of GARNET is its spectral resolving power of R = 200,000, several times higher than that of existing comparable instruments, enabling precise separation of densely packed absorption lines in the near-infrared windows of Venus.

To quantitatively evaluate the scientific advantages of this high resolution for trace-species observations in Venus's lower atmosphere, we conducted radiative transfer simulations using the Planetary Spectrum Generator (PSG) provided by NASA. We calculated spectra in the 2.3 μm window, where absorption lines of CO_2, CO, SO_2, H_2O, OCS, and HF coexist. By varying the spectral resolution from R = 1,000 to 200,000, we analyzed changes in sensitivity to the vertical distributions of these species. The results show that at R = 200,000, line blending is reduced, yielding enhanced sensitivity to altitudes around ~35 km. In this presentation, we will introduce the current development status of GARNET and discuss key science cases and future prospects for high-precision observations of Venus's lower atmosphere using this instrument.

Keywords: Venus atmosphere, High dispersion spectroscopy, Ground-based observations, Instrumentation