Astronomy with Super-Precise Spectroscopic Observations

超精密分光観測による天文学

Bun’ei Sato (Science Tokyo)
佐藤文衛（東京科学大学）

1. Summary of the proposal

- Science goals and objectives
  - To clarify diversity, origin and evolution of planets in the universe
    - Determine the distribution of terrestrial and larger exoplanets orbiting various types of stars in the solar neighborhood, and reveal the properties of planetary atmospheres (chemical composition, spatial structure, motion, etc.).
  - To clarify origin and evolution of elements in the universe
    - Clarify chemical and isotopic compositions of stars, novae, interstellar matter, circum-galactic and inter-galactic matter, etc., and provide strong constraints on the nucleosynthesis processes in the universe and the chemical evolutionary history of the universe.
  - To understand stars as the basic building blocks of the universe
    - Characterize various time-scale variations of stars through spectral line profiles to establish a dynamic picture of stellar atmospheres.
  - By realizing a high dispersion spectrograph that combines super-high wavelength resolution (Super-HR; R>300,000), super-wide wavelength range (UV to NIR), super-high precision (radial-velocity (RV) measurement precision <~10 cm/s), and super-high temporal resolution (<~10 sec), push forward the above researches.
- Instrumentation and data
  - Develop a new Super-High Resolution (R~300,000) Spectrograph for Okayama 188cm telescope/Seimei 3.8m telescope and upgrade Subaru/HDS
- Cost estimation
  - A total of 960 million yen; 500 million yen for Super-HRS for Okayama 188cm/Seimei telescope, and 460 million yen for upgrade of Subaru/HDS
- Project organization
  - A total of ~30 researchers have shown interests in this project

2. Science Goals

- To clarify diversity, origin and evolution of planets in the universe
- To clarify origin and evolution of elements in the universe
- To understand stars as the basic building blocks of the universe

3. Scientific Objectives

By realizing a high dispersion spectrograph that combines super-high wavelength resolution (Super-HR; R>300,000), super-wide wavelength range (UV to NIR), super-high precision (radial-velocity (RV) measurement precision <~10 cm/s), and super-high temporal resolution (<~10 sec), push forward the following researches;

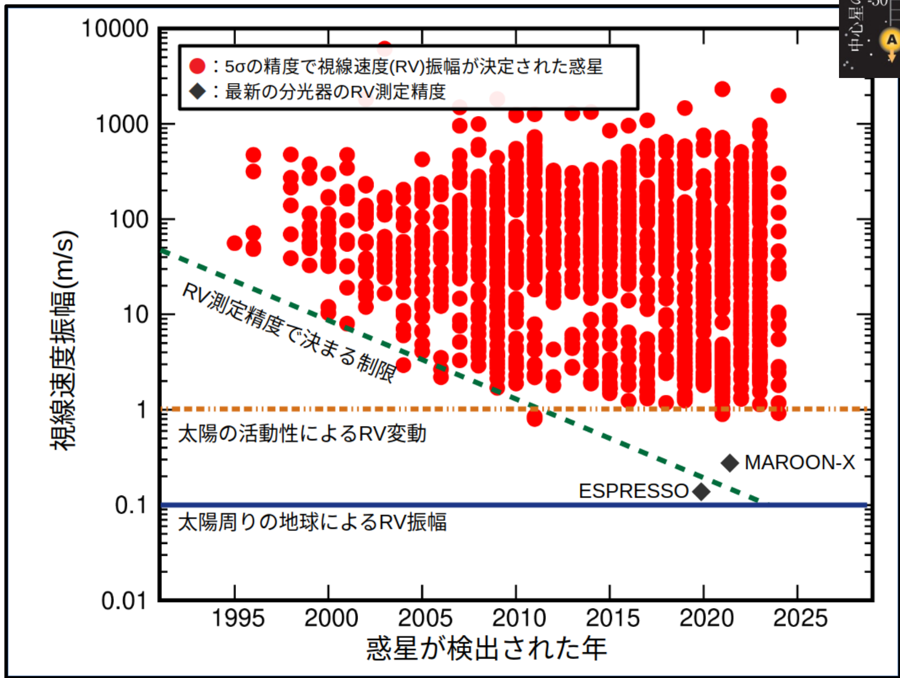
A) Determine the distribution of terrestrial and larger exoplanets orbiting various types of stars in the solar neighborhood, and reveal the properties of planetary atmospheres (chemical composition, spatial structure, motion, etc.).

B) Clarify chemical and isotopic compositions of stars, novae, interstellar matter, circum-galactic and inter-galactic matter, etc., and provide strong constraints on the nucleosynthesis processes in the universe and the chemical evolutionary history of the universe.

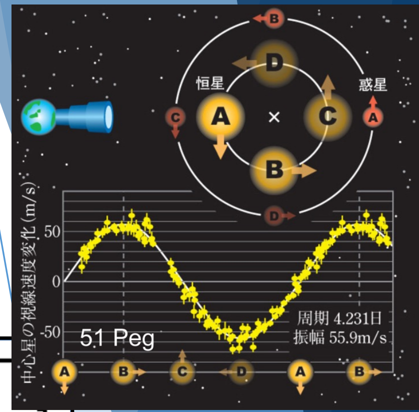
C) Characterize various time-scale variations of stars through spectral line profiles to establish a dynamic picture of stellar atmospheres.

4. Science Investigations (A)

- The latest spectrograph has achieved a precision of ~10-30 cm/s in RV measurements, so the current detection limit (~1m/s) of exoplanet-hunting is limited by the star itself, not the instrument.
- Precisely monitor the RV and spectral line-profile changes of stars with Super-HR (R>300,000) and Super-HPRV (<~10 cm/s) over short to long periods of time.
- Detect and correct for the effects of stellar activity in stellar RVs, and to determine the presence or absence of orbiting terrestrial planets.



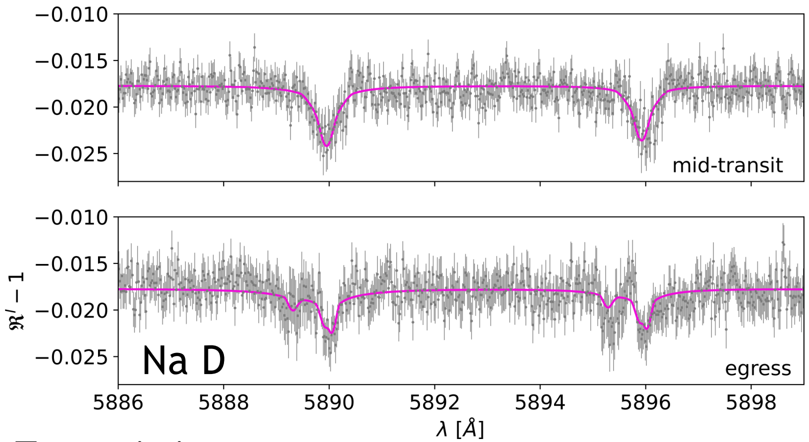
https://official.rikanenpyo.jp/posts/6129



4. Science Investigations (A)

- Detect various atoms, molecules, and ions mainly in short-period exo-planetary atmospheres and estimate their spatial and velocity distribution in planetary atmospheres with Super-HR.

WASP-121b (T_{eq}=2350 K)

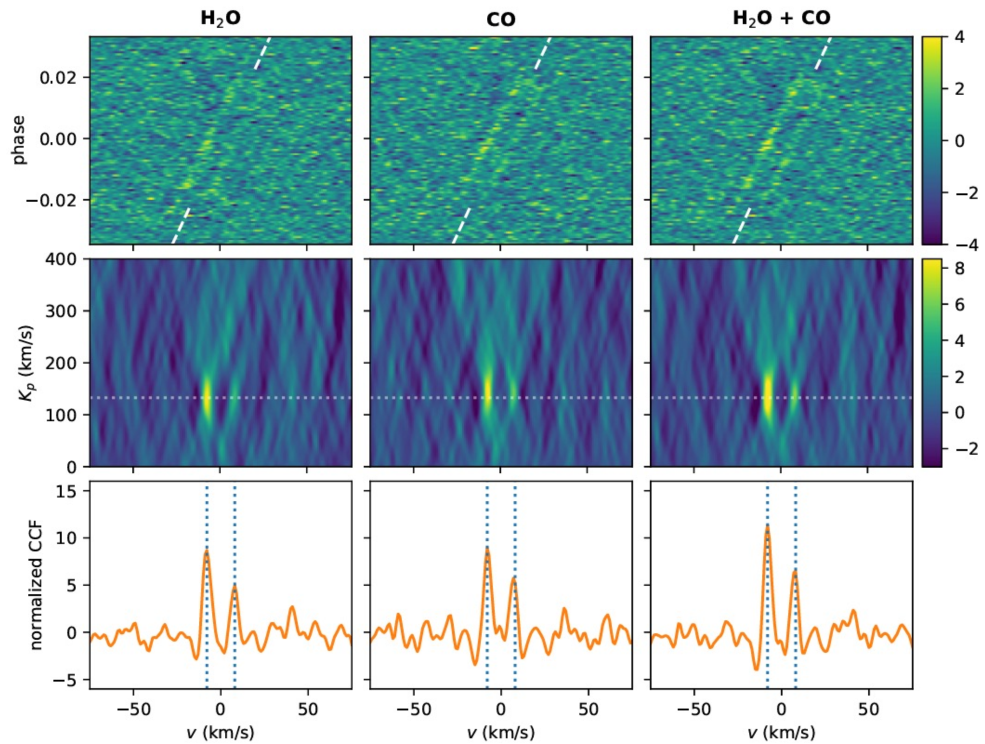


Transmission spectra

Seidel+ 2023

WASP-127b (T_{eq}=1400 K)

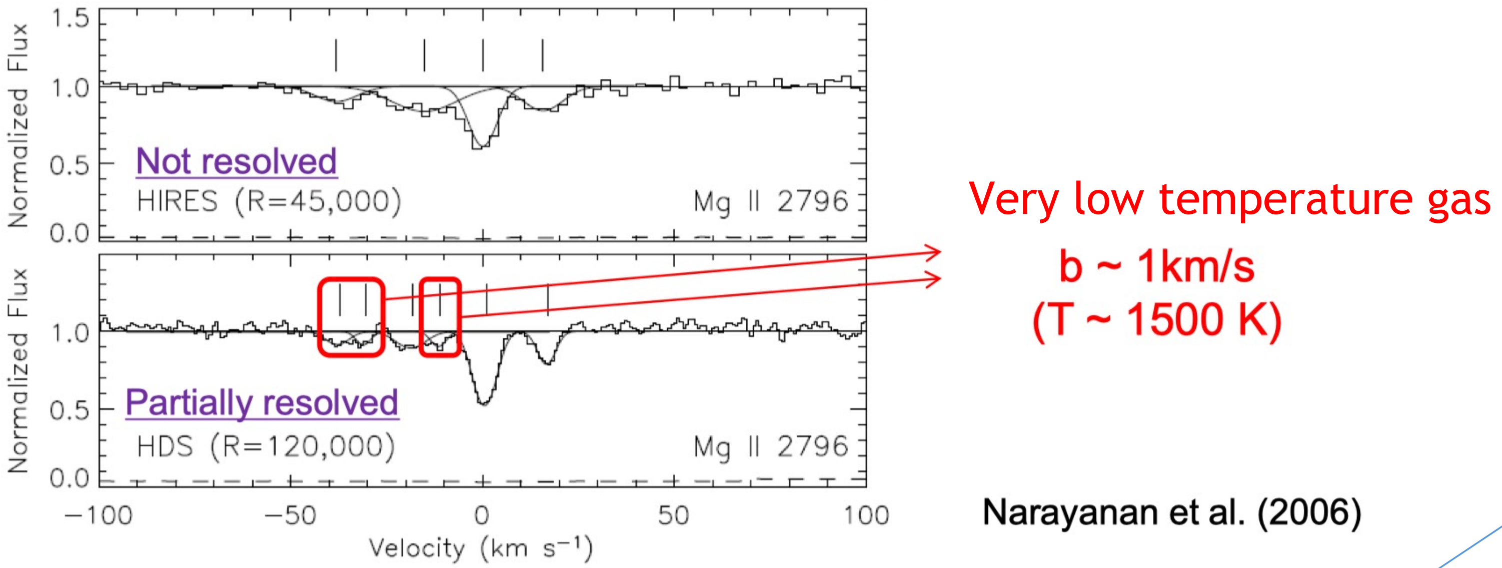
Emission spectra



Nortmann+ 2024

4. Science Investigations (B)

- Observe quasar absorption line systems to detect intergalactic very low temperature gas and isotopes, as well as material around galaxies with Super-HR.



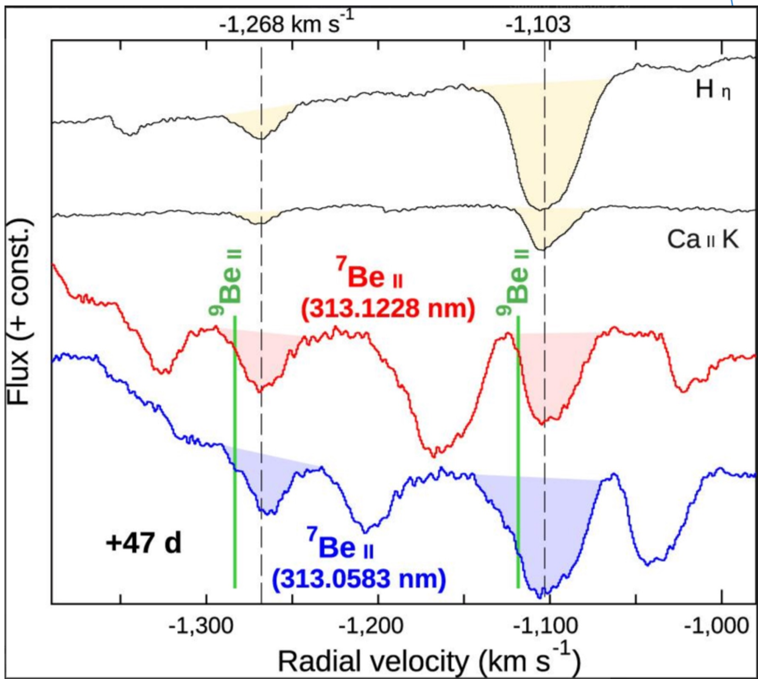
Narayanan et al. (2006)

Slide from Toru Misawa

4. Scientific Investigations (B)

- Measure beryllium isotope absorption lines in the near-UV region to accurately determine the abundance of elements that are synthesized in nova explosions and decay into lithium in a short period of time by electron capture.
- Measure the r-process element abundances in the near-UV region in a number of metal-poor stars and investigate their abundance patterns.
- Determine isotopic abundance ratios of lithium and heavy elements in stellar and interstellar matter using the slight line splitting caused by isotopes appearing in atomic spectral lines with Super-HR.

Nova Delphini 2013 (=V339 Del)

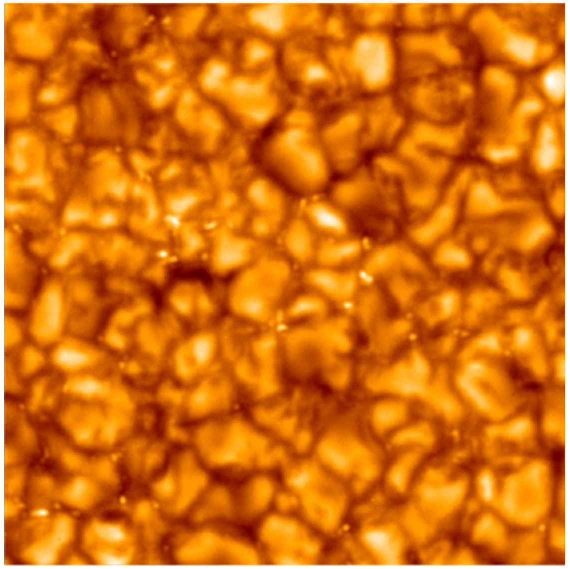


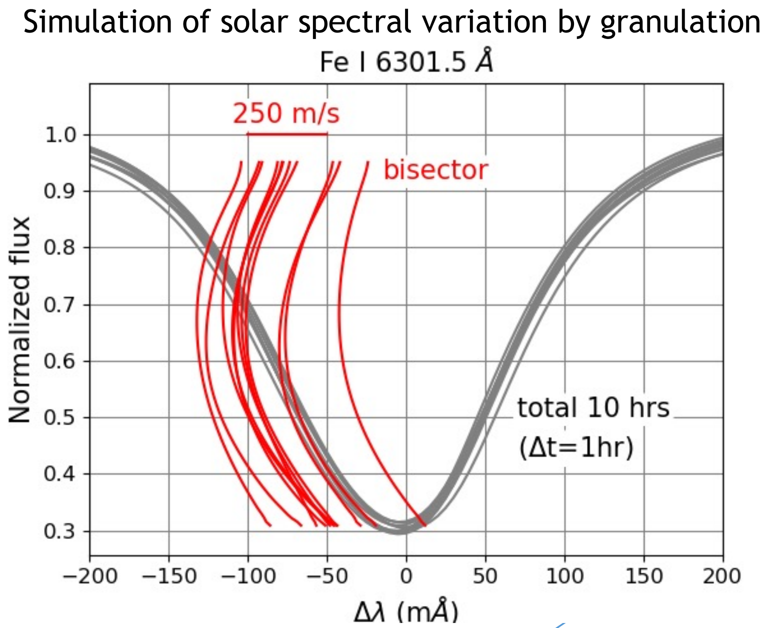
https://subarutelescope.org/en/results/2015/02/18/2280.html

Tajitsu et al. 2015

4. Scientific Investigations (C)

- Precisely measure the spectral line shapes of various stars and their variability with Super-HR and super-high-temporal resolution, investigate their relation to stellar activity, and validate dynamic stellar atmosphere models.





5. Instruments and data to be returned (1)

- Develop a new Super-High Resolution (R~300,000) Spectrograph for Okayama 188cm telescope/Seimei 3.8m telescope

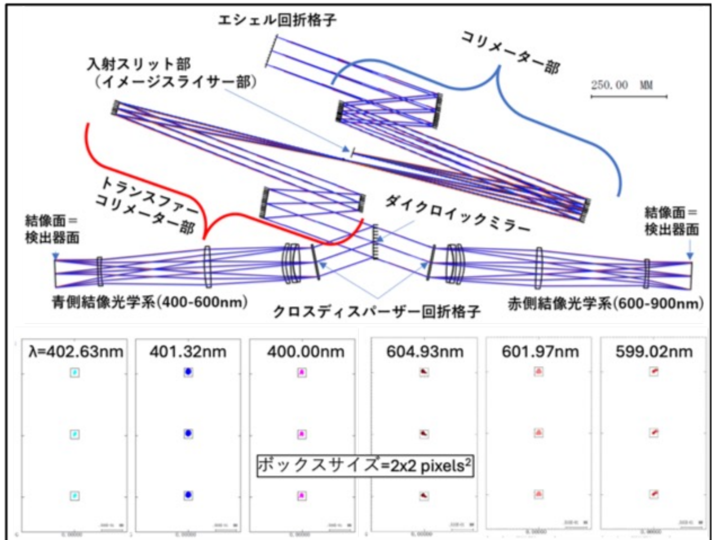
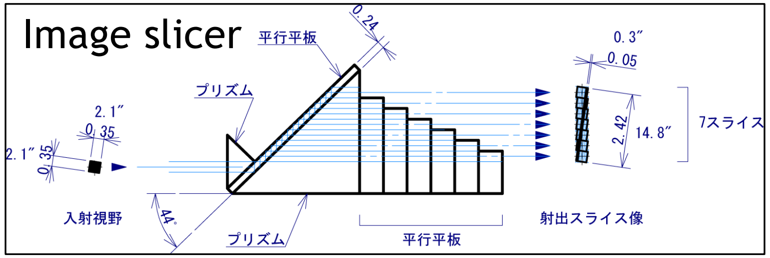
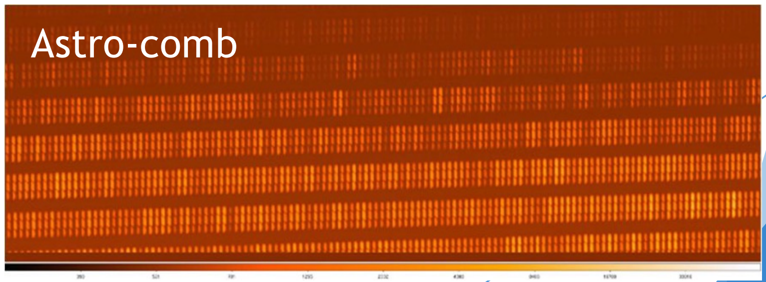
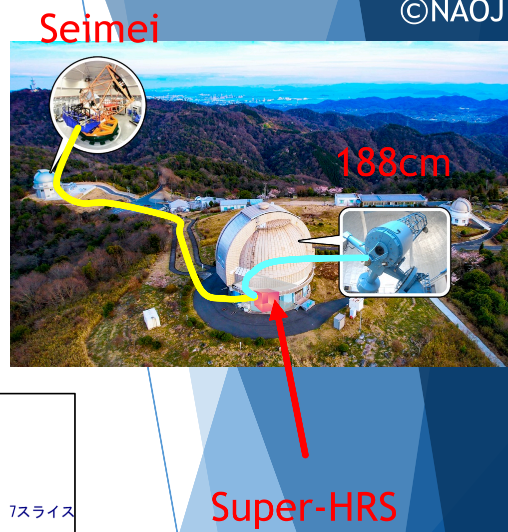


図3: (上図) 分光器光学系設計例. (下図) 光学系スポット図.縦の並びは各波長での入射スリット長2.8mm(0,±1.4mm)に沿った入射点







- R>~300,000
- σ_{RV}<~10 cm/s
- Δλ=400-900 nm
- t<~10 sec
- 150+50-60 nights

5 Supers

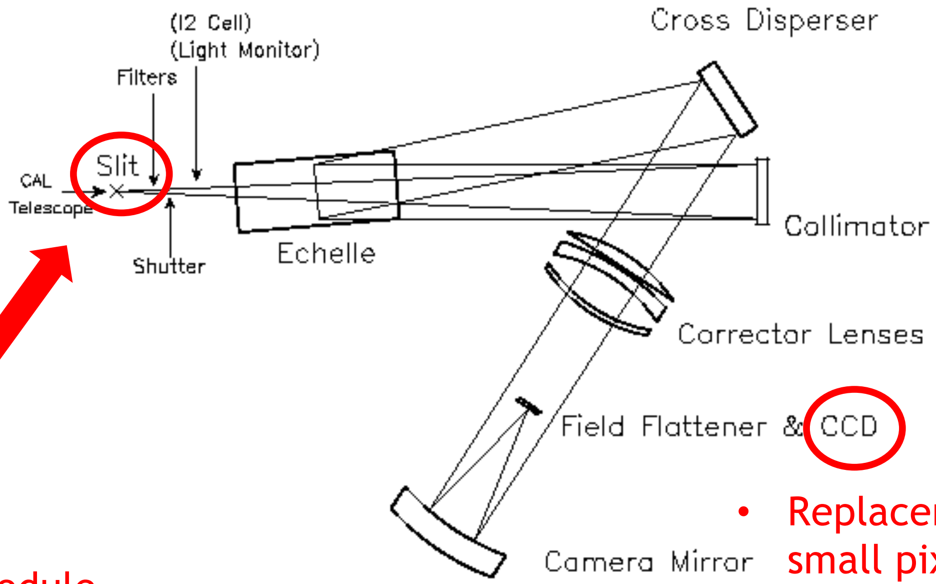
5. Instruments and data to be returned (2)

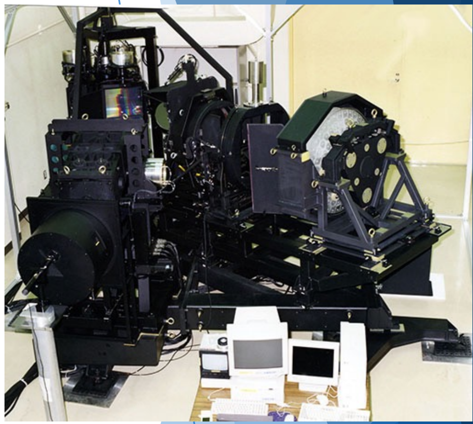
- Upgrade Subaru/HDS

  - R<165,000➔R>300,000
  - RV precision <~10cm/s
  - Improve UV efficiency
  - Add NIR
  - Time resolution <~10sec

©NAOJ

HDS optical layout





- ADC for UV
- Image slicer
  - for UV
  - for S-HR
- Astro-comb
- Fiber injection module
- AO at Nasmyth focus

- Replacement with chips having small pixel size and large format (CMOS)
- Addition of UV and NIR

6. Originality and international competitiveness

- Although there are two ultra-high wavelength resolution spectrographs (R~250,000) in operation in the world, our project has an advantage in that it will be equipped with an ultra-precise wavelength reference (astro-comb), and it will cover a wide wavelength range (near-UV to NIR) and achievable time resolution (<10 arcsec).
- Only Subaru/HDS in the northern sky and VLT/UVES in the southern sky can observe in the near-ultraviolet region (>300 nm), so this project is the only one that can observe metal-poor stars, novae, and quasar-absorption line systems with the wavelength range in the northern sky.
- The data from Subaru/HDS may be used as initial data for long-term monitoring in preparation for the TMT, taking advantage of the same site.
- Our project will enable ultra-precise spectroscopic observations with three telescopes of different apertures (Subaru, Seimei, and 188cm). This will make it possible to conduct ultra-precise spectroscopic observations for objects of various brightness at various timescales, and will lead the research field.

7. Current Status in the fields

- In the detection of exoplanets by the radial-velocity method, it has become clear that stellar activity has a non-negligible effect at the level of 1 m/s or less, and the need for detailed investigation of line-profile variations for each absorption line by ultra-high wavelength resolution observations is being recognized.
- The non-uniformity of the spatial distribution and motion in exoplanet atmospheres is beginning to be observed, and the need for observations with a velocity resolution sufficiently smaller than the planetary rotation velocity (~1 km/s; R~300,000) for various absorption lines is being recognized.

Science (A)

- The absorption lines required to validate photoionization models of circum-galactic materials are distributed over a wide wavelength range, including the ultraviolet region, which is limited by the capability of existing high-dispersion spectrometers.
- Since there are only a few observations of novae and very metal-poor stars that require observations with high wavelength resolution in the UV region, more data are needed to investigate their statistical properties and to validate the models.
- Isotopic abundance ratio measurements have very few examples compared to elemental abundance measurements. The large aperture telescope is required to obtain high signal-to-noise ratio as well as wavelength resolution, and an instrument with a wavelength resolution of more than 200,000 on an 8-10 m class telescope is required.

Science (B)

- Theoretical studies of dynamical stellar atmospheric models have been progressing, but the targets that can be validated by observation are almost exclusively limited to the Sun. For general validation by other stars, an ultra-high wavelength resolution and ultra-high time resolution spectrometer for stellar observations is required.

Science (C)

8. Cost assessments, budget line and status

Yealy Plan	2025(R7)	2026(R8)	2027(R9)	2028(R10)	2029(R11)	2030(R12)	2031(R13)	2032(R14)	2033(R15)	2034(R16)
188cm・Seimei Telescope	Observation with the high dispersion spectrograph HIDES-F									
	Installation of super-high wavelength resolution and super-high time resolution modes into HIDES-F					Ongoing (KAKENHI, TMT fund)				
	Development of super-high wavelength resolution spectrograph		Applying for KAKENHI	Intensive observation with super-high wavelength resolution spectrograph		Super-stabilization of super-high wavelength resolution spectrograph, technology transfer to large telescopes, consideration and development of next generation instruments				
Subaru Telescope	Installation of Astro-Comb into High Dispersion Spectrograph, HDS		Ongoing (KAKENHI)							
	Improvement of the ultraviolet efficiency of the high dispersion spectrograph, HDS (installation of a new ADC + image slicer)									
	Installation of super-high wavelength resolution and super-high time resolution mode to high dispersion spectrograph, HDS									
		Super wide wavelength range (detector replacement) and high stability of high dispersion spectrograph, HDS								
		Installation of AO at Optical Nasmyth								
		Scientific observation with the current (+ partially upgraded) HDS and consideration of the next instrument					Scientific observation with upgraded HDS, study and development of next-generation instruments			

960 Total (million yen)

500 Super-HRS for 188cm and Seimei Telescope

10 Image slicer for HDS
100 Detectors in the UV and IR regions for HDS
20 Detector support mechanics for HDS
50 Astro-comb for HDS
20 Enclosure improvement for HDS
40 Temperature and air pressure control for HDS
100 Visible adaptive optics
120 Personnel cost for HDS [(7/person+5/person) x person x 10 years]

We expect ~200M yen from NAOJ

9. Collaborators (Project Organization)

- NAOJ/ABC
- A. Tajitsu, H. Izumiura, W. Aoki, A. Arai, H. Harakawa, Y. Moritani, J. Nishikawa, E. Kambe, Y. Minowa, Y. Ono, Y. Takagi, M. Omiya (ABC), T. Hirano (ABC), T. Kotani (ABC), T. Takarada (ABC)

- Others
- N. Ebizuka (RIKEN), S. Honda (Hyogo U.), H. Inaba (AIST), H. Kawahara (JAXA), K. Masuda (Osaka U.), T. Misawa (Shinshu U.), S. Miyazaki (JAXA), M. Otsuka (Kyoto U.), T. Suda (TUT), M. Takada-Hidai, M. Yamashita (JAXA), S. Okubo (AIST), H. Hotta (Nagoya U.), R. Ishikawa (NIFS)

10. Why NAOJ?

- Optical high-dispersion spectroscopy in Japan, which is the basis of this project, has been developed and operated mainly by NAOJ (Okayama HIDES-F and Subaru HDS), and the experience accumulated by NAOJ in the development, operation, and observation of these instruments is essential for this project.
- This project is to develop and upgrade spectrographs to be connected to three telescopes (188cm telescope, Seimei telescope, and Subaru telescope) owned or closely related to NAOJ, and since these telescopes have common technical development elements, it would be very effective and efficient if development activities could be conducted in collaboration with NAOJ.
- This project will also greatly improve the capabilities of HDS, one of the Subaru Telescope's open-use instruments, and thus enhance the competitiveness and uniqueness of Subaru Telescope in the TMT era, and will also lead to the development of new instruments for the TMT.