Achievement in Solar Astronomy

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The Sun is only a star that can be studied with detailed temporal-spatial resolution.

Common mechanism are working in many objects

- Solar-stellar wind
- Corona-chromosphere heating
- Energy transfer
- Generation of NT energy by turbulent convection

Examples:
- Red dwarfs
- Proxima Centauri
- Red giants
- Betelgeuse
- Protoplanetary disk
- TW Hydrae
Measurement of magnetic fields to understand active atmosphere

Dynamical phenomena responsible for energy transfer and dissipation.
• Jets, shocks, MHD wave and its mode conversion.

Imaging obs of the chromosphere by HINODE

Frontier in solar–stelllear obs

Spectro and polari obs to get quantitative information (B, T, v,,) at the site

\[ E \approx 10^{25} \text{erg} \]
\[ = \frac{1}{8\pi} \Delta B^2 V = \frac{1}{8\pi} (\sim 100 \text{ G})^2 (\sim 300 \text{ km})^3 \]
Projects in the solar physics group

- **Hinode (2006-, 13 years old)**
- **Nobeyama Radio Heliograph (1992-) and Polarimeter**
- **Solar Flare Telescope (1990-) IR magnetoagraph (2010-)**
- **ALMA solar (2016-)**
- **CLASP/CLASP2 (2015, 2019)**
- **FOXSI-3 (2018)**
- **SUNRISE-3 (2022)**
- **Solar-C EUVST**

**NOTE:** I picked up scientific results according to my interest.

Anomally large Zeeman splitting → Field strength > 6000 Gauss.

This kind of observation is possible only with a high-resolution spectro-polarimeter.
Super-strong fields found in a bright region sandwiched by two opposite-polarity umbrae, not in a darkest region.

Horizontal flows push the umbra boundary to strengthen the field (?)
Siu-Tapia et al. (2019, A&A)

- Reported >7kG field near the boundary of “counter-Evershed” flow.
  - Used more sophisticated technique for deconvolution and to get height dependence.

Suggested possibility to create strong magnetic fields by dynamical compression using a numerical simulation.
  - But it was not successful yet.


Result by a numerical simulation
Bright gyro-resonance radio source, suggesting 4 kG at the base of corona above a flare productive active region.

Extrapolation of coronal B from the surface B, and confirmed the super-strong field.

Important to quantify free energy to drive a solar flare
Pathfinder mission in solar physics
  - Aim to establish means to diagnose the magnetic field in upper solar atmosphere with UV spectropolarimetry
    - CLASP: Ly $\alpha$ @ 121 nm
    - CLASP2: Mg II h/k 280 nm

International project by Japan, USA, Spain, France and Norway
  - NAOJ led the development of the instrument

See the poster by R. Ishikawa for initial results
Flight in 2022

- **Φ1m optical telescope** (x2 of Hinode-SOT)
- Flight at >35 km from Sweden to Canada over the Atlantic for a week.
  - Wide λ coverage: 300 nm to 860 nm
  - High polarimetric sensitivity without affected by atmospheric seeing.

**SCIP**
(Sunrise Chromospheric Infrared spectroPolarimeter)

**Linear pol. measured by SCIP**

- Ca II 849 nm
- Fe I 846 nm
- K I 766 nm

**Quintero Noda et al. (2019, MNRAS)**

**Iijima and Yokoyama (2017)**
Key features

- High spatial resolution
  - 0.21" (Diff. limit at 850 nm)
- High polarization sensitivity
  - 0.03% (1σ) sensitivity in 10 sec at Ca II line to measure ~ 5 G magnetic fields
- Multi-line spectro-polarimetry for 3D diagnostics

Poster by Y. Katsukawa
"Remote-sensing obs”

HINODE-SOT  HINODE-XRT/EIS

"In-situ measurement”

Parker Solar Probe

Distance from the solar surface

RMS transverse velocity

CLASP

Corona

Chromosphere

Photosphere

Non-thermal velocity (Hara et al. 2019)

Small-scale turbulence
(Ishikawa et al. 2019, submitted)

High frequency wave

Cranmer et al. (2017, SSRv)
Significant line broadening in the photosphere not known so far

Intensity (T fluctuation) Velocity gradient  
Line width

Ishikawa et al. (2019, submitted)

Sporadic enhancement of the spectrum line broadening.

Excessive line broadening in fading granules, that cannot be explained only by the LOS velocity gradient.
Significant line broadening in the photosphere not known so far

Enhancement of turbulence

In a fading granule

Δν=0, large FWHM

Δν<0, small FWHM

In a downflow lane

Excess Broadening

Fading out!!!

In a fading granule

Δν>0, large FWHM

Δν>0, small FWHM

In a granule
Clear detection of propagating high frequency waves by Ly-alpha spectrotoscopic obs.

Energy flux carried by the high frequency waves was estimated and was probably a minor contribution to the coronal heating.

Trigger of high-f waves associated with a driver of a jet(?) We need more statistics.

Nonthermal motions in a corona as the source of solar winds

- Nonthermal component $V_{NT}$ in an emission line width is a measure of velocity fluctuations associated with coronal Alfvén waves.

Emission Line width (FWHM) of Fe XII from HINODE-EIS Observation

$$W = \sqrt{W_{instr}^2 + 4ln2(2k_B T_i / M_i + V_{NT}^2)}$$

- Weak signals on the background by scattering from other regions are measured and subtracted during the on-orbit eclipse.

Hara (2019, ApJ) trend showing no dissipation of Alfvén waves

This Study

FOV of HINODE-EIS
Nonthermal motions in a corona as the source of solar winds

- Estimate energy flux carried by the Alfvén wave.
- The damp of the $V_{NT}$ is a signature of Alfvén wave dissipation in the inner corona.

Need confirmation by theoretical/numerical studies as well as in-situ measurements by Parker Solar Probe.

- Launched in Aug 2018
- Already experienced three perihelions at ~25Rs.
  - HINODE ran coordinated observations to observe the roots of magnetic fields.
- Finally it approaches the Sun as close as ~10Rs.
Initial results just published

WISPR (coronagraph observation)

• Imaging of flux rope and plasmoid (magnetic islands) ejection.
  • Plasmoids generated by the tearing-mode instability in the current sheet?
• Dust-free (low scattered light) zone near the Sun.

FIELDS (direct measurement of E and B)

Radial magnetic field $B_r$ shows quasi-periodic reversals of sign (switch-back)

Howard et al. (2019)
Bale et al. (2019)
Solar Physics is a pioneer of “multi-messenger” astronomy!!

– We have observed energetic particles and disturbances of magnetic fields at 1 AU for major solar flares.
– But it has been difficult to use such obs for understanding of coronal heating and acceleration.

Synergy with HINODE in coming years

– Combination of remote-sensing obs near the Sun by HINODE and in-situ measurements of particles and B by PSP.
– Many science cases:
  - Relationship of transverse velocity amplitude between near and outer coronae.
  - Identification of a source of “switch-back” near the Sun.

PSP data are already released for the past two contacts

The multi-messenger approach is expected also for the Solar Orbiter

– To be launched in Feb. 2020. Good for high-latitude targets although SO’s perihelion is at 60 Rs.
- **Φ4m solar telescope in Hawaii**
  - The largest aperture was 1.6 m so far.

- Coordination with HINODE is highly demanded.
  - Cross-calibration of polarimetric obs because HINODE-SP is a ”world-standard” with larger FOV.
  - HINODE-EIS coronal spectroscopy is the unique capability to diagnose corona (until Solar-C EUVST).

**Generation of small-scale turbulent velocity and magnetic fields**

**Direct evaluation of “Poynting flux” by a polarimetric observation**

**Impacts to the corona measured by EIS**
EUVST: high resolution EUV spectroscopy

High resolution (0.4")
Wide temperature coverage

Example of an “elemental” jet

Hinode SOT Ca II H (~10^4 K)
IRIS SJ Mg II (~10^4 K) Si IV (~10^5 K)

IRIS
T~10^4 K

IRIS Si IV (~10^6 K) H
T~10^6 K

Lack of high resolution observation in a corona (>10^6 K)
HINODE is already 13 years old, but is continuously providing unique data.
  - We can still do new science using existing data.

The strategic coordination with ALMA, PSP, SO, and DKIST is critical to enhance scientific outcomes.
  - The coordination is also important to strengthen the international collaboration for future projects such as EUVST.

The small-scale experimental projects (rockets, balloon etc.) are important to keep and develop uniqueness of our group.