Spectroscopy of Highly Charged Ions in Solar and Astrophysical Plasmas

Tetsuya Watanabe 1, 2)
1) National Astronomical Observatory, Japan
2-21-1 Osawa, Mitaka, Tokyo 181-8588 Japan
2) Graduate School for Advanced Studies
Hayama, Miura-gun, Kanagawa Pref., 240-0193 Japan
E-mail: watanabe@uvlab.mtk.nao.ac.jp

Abstract. Spectroscopic observation of EUV emission lines in the transition-region and corona provide unique information on physical conditions in these outer atmospheres of the Sun. The EUV Imaging Spectrometer (the EIS) on board the Hinode mission is capable of observing, for the first time in Solar EUV observations, spectra and monochromatic images of possibly non-ionization-equilibrium plasmas in the solar transition-region and corona at two-wavelength bands of 170 - 210Å and 250 - 290Å, with typical time-resolutions of 1 - 10 seconds. Dynamic plasma acceleration and heating are found to take place in the solar atmospheres, and they are confined in tiny structures. A time-dependent collisional-radiative model for the iron plasmas is developed to diagnose temperatures and densities in the outer atmospheres of the Sun; no systematic models yet exist for iron ions at the ionization stages of L- and M-shells, which are very important for coronal plasma diagnostics. Adopting the best available theoretical calculations of atomic parameters of these iron ions, as well as generating the experimental data by a compact electron beam ion trap (EBIT), is essential to one of the aims of our research that the mechanism of coronal heating is explored via accurate diagnostics information obtained by the EIS instrument.

1. Introduction
Matter in the Universe is not distributed uniformly; some is very hot, highly ionized, may not be in thermal equilibrium, or even not thermalized. Spectroscopy of lines originating from highly charged ions is therefore of crucial importance to understand the characteristics of these hot plasmas. One of the fastest ways to understand the characteristics of astrophysical plasmas is to understand those of solar plasma, because it is believed that most of the phenomena happening elsewhere in the Universe also take place on the Sun. In addition, the Sun serves as “a laboratory in space,” which shows interesting phenomena of plasma physics on a gigantic scale. Spectroscopic observation of EUV emission lines in the transition-region and corona provide unique information on the physical conditions in these outer atmospheres of the Sun.

In this paper, a progress report of our research project is presented by briefly introducing new understanding of observations in the laboratory, the universe, especially in the Sun, and, of theoretical
predictions. The newly-constructed Sun-observing satellite, Hinode presented very dynamic nature of magnetic fields and plasmas in the solar outer atmospheres.

An analysis tool is developed to handle these plasmas in non-equilibrium states with improved atomic datasets, which are obtained by evaluating the theoretical calculations and by laboratory measurements. The ultimate goal is that the time-dependent collisional-radiative model will be applied to solar coronal plasmas to understand the mechanism of coronal heating.

2. Progress of EUV spectroscopy for Solar and Astrophysical Plasmas

2.1. Non-solar observations
Since the launch of EUVE [1] in 1990, a new era of EUV and X-ray spectroscopy started in astrophysics with the availability of high resolution spectrographs. At the beginning of the 21st century, X-ray satellites such as Chandra [2] and XMM-Newton [3] enabled grating spectroscopy in X-ray regions, though it was a major loss of scientific capability on board Suzaku, that the micro-calorimeter failed before the start of its observation. Emission lines from hot plasmas in stars, especially in galaxies, and/or clusters of galaxies, are for the first time revealed by these highly resolved spectra in EUV and X-ray wavelengths.

![Fig 1 Spectrum of the first order of the primary region of NGC1068, together with the model: The model does not yet include Fe L-shell transitions [4].](image1)

Fig. 1 shows a spectrum of NGC1068 taken by Chandra in its primary region [4]. Similar spectra are also taken by RGS on board XMM-Newton. Highly charged ions of various elements are clearly seen. Diagnostics such as that of using the density-sensitive line ratios in the He-like triplets of N, O, and Ne are possible. In this example, however, these forbidden lines appear significantly stronger than predicted. This is likely due to inner shell ionization in the corresponding Li-like ions, which enhance only the forbidden line of the triplet.

2.2. Solar observation; Hinode Mission and EUV Imaging Spectrometer on board Hinode
Hinode was successfully launched from Uchinoura Space Centre (USC)/JAXA at 18:36:00 on 22-Sep-2006 (UT); "Hinode" is the sunrise in Japanese. Its science objectives are to understand the basic
questions of solar physics; a) the coronal heating mechanism, b) the origin of strong magnetic fields, and c) the trigger mechanism of solar flares along with other questions.

**Fig 2** The 22nd Japanese Scientific Satellite, “Hinode,” and the optical layout of EIS

**Table 1. EIS Parameters**

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Wavelength Bands           | 170 - 190Å & 250 - 290Å                    |
| Peak Effective Areas       | 0.30cm² & 0.11 cm²                         |
| Primary Mirror             | 15cm diameter, two Mo/Si multilayer coating|
| Grating                    | Toroidal & laminar, 4200 grooves mm⁻¹, two Mo/Si multilayer coating |
| CCD Cameras                | Two back-thinned E2V CCDs, 2048x1024x13.5μm pix. |
| Plate Scales               | 13.53μm/arcsec at CCD; 9.40μm/arcsec at slit |
| Spatial Resolution (pix)   | 2 arcsec (1 arcsec)                        |
| Field of View              | 6 arcmin x 8.5 arcmin                     |
| Raster                     | 1 arcsec in 0.7sec, min. step 0.123 arcsec |
| Slit/Slot Widths           | 1, 2, 40, & 266 arcsec                    |
| Spectral Resolution        | 47mÅ (FWHM) at 185Å; 1pix = 22mÅ, approx. 25km s⁻¹/pix |
| Temperature Coverage       | log T = 4.7 – 7.3 K                       |
| CCD Frame Read Time        | 0.8 sec                                   |
| Line Observation           | Simultaneous observation of up to 25 lines |

It was successfully put into a sun-synchronous polar orbit at an altitude of 680 km above sea level, *Hinode* started initial scientific observations in December 2006. A guest-investigation-type program was announced in the Call for Proposals. This program encourages the world-wide scientific involvement in the *Hinode* observations. All the data taken by the telescopes, as well as those for house-keeping purposes, have been immediately open to the public and available since 27-May-2007 with instruction for data users.
Three telescopes are accommodated on board the *Hinode* mission; Solar optical telescope (SOT), X-ray telescope (XRT), and EUV imaging spectrometer (EIS). The SOT instrument consists of the Optical Telescope Assembly (OTA), and the Focal Plane Package (FPP). It is a Gregorian telescope with an effective aperture of 50 cm that is aiming at diffraction-limited performance of the OTA with the tip-tilt movable mirror (TCM) system, namely, 0.2 – 0.3 arc seconds at the wavelengths 380 - 670 nm. The X-ray telescope (XRT) is a grazing incidence mirror telescope accommodating a 2k × 2k CCD as a detector. The spatial resolution is improved to 1 arcsec, about three times better than that of *Yohkoh/SXT*, and its measurable plasma temperature range is increased to 1 – 20 million K.

The major improvement of the EIS telescope throughput was achieved by applying multi-layer coatings to the primary mirror and the toroidal grating (groove density = 4200 gr/mm) used in the EUV wavelength range. The two wavelength bands observed with the EIS instrument are 170 – 210 Å and 250 – 290 Å and include the emission lines of He II and Fe VIII – Fe XXIV, lines formed in the temperature range 4.7 < log T < 7.2 [5].

The parameters of the instrument are summarized in table 1. The optical layout is shown in Fig.2. The plate scale is such that one CCD detector pixel corresponds to 1 arcsec in the spatial direction along the slit and the spectral resolution is 0.00223 Å/pixel. Four kinds of slit/slots, slits of 1 and 2 arcsec(s) and slots of 40 and 266...
arcsecs, are accommodated and can be interchanged in a housing near the focal plane of the primary mirror. A total of 25 emission line windows can be selected on two CCDs, dedicated to the shorter and longer wavelength bands, respectively. The small-scale velocity structure and non-equilibrium nature of solar coronal plasmas can be observed for the first time in these EUV wavelengths with this capable instrument.

2.3. New discoveries by the Hinode Mission

More than 40 papers describing the first results of Hinode were published in the special issue of Publication of Astronomical Society in November 2007 [6]. A Science special issue accommodates 9 papers [7]. New discoveries and findings during the first year observations of Hinode can be summarized as follows.

New discoveries that Hinode made so far during the first year of operation are: 1) Strong magnetic fields (B> 1 kG) were observed in the polar regions, where the magnetic fields have previously been thought to be weak and vertical; 2) Horizontal strong magnetic fields, though transient by nature, were observed in the quiet sun and in the polar region as well. They are numerous; 3) Convective collapse, one of the mechanisms to make up strong magnetic fields in the photosphere, could be observed in the diffraction limited magnetograph images; 4) Alfvén waves were seen to propagate throughout the photospheres and the chromospheres; 5) Jets and/or supersonic flows were also present everywhere in the quiet sun and also in the coronal holes.

First detections and detailed analyses are continuing for the following science topics: 1) Collapsing processes in sun spots; cancellation and escape of magnetic fluxes from sunspots will be studied in detail with continuous magnetograph observations; 2) Flows associated with flares will be studied. Inflows/outflows to/from the magnetic reconnection sites, chromospheric evaporations and down flows above flare arcades will be closely investigated with all three instruments; 3) Turbulence or turbulent flows at the foot points of coronal loops seem universal in most active regions. This will provide clues to allow identification of the mechanism of coronal heating; 4) Temperature structures along with height will be investigated through XRT and EIS by calibrating their diagnostic capabilities; 5) Polar jets found in the polar coronal holes will be studied in detail, to understand their contribution to coronal heating, polar plumes, and the fast and slow solar winds; 6) Oscillations are seen everywhere in the photosphere. Umbral oscillations in particular will reveal a method for energy transport in strong magnetic fields; 7) Numerous interesting phenomena, such as flows at the roots of the fast solar wind, coronal hole formation, white light flares and others will be further discussed in detail.

Fig 4 Sample of spectra taken from corona high-temperature emission lines (Fe XV, Fe XIV, Fe XIII): The vertical axes show the intensity, and the horizontal axes show the wavelength. The vertical dashed lines show the line center of the emission lines, which are emitted from stationary ions. The upper panels show reference emission lines, which seem to be emitted from a stationary plasma, to determine the line center, (a)–(c); the lower panels show the emission lines of the plage region, which exhibit strong blueshifts.

2.4. EIS discoveries

The EIS instrument on board the Hinode mission is unique, as it is capable of taking solar EUV emission line spectra at its high spectral resolution, for the first time, to analyze their
profiles. The dynamics and fine structure of plasma motions in the transition region and corona are thus revealed by this instrument.

Fig. 3 shows the structure of non-thermal line broadenings in an active region [8]. coronal lines always show additional line width to that expected from thermal Doppler motions. In the disk centre observation subsonic up flow motions of tens of kms$^{-1}$ and enhanced non-thermal velocities have been found near the footpoints of the active-region loops assuming a single Gaussian approximation for the emission-line profiles. When the same part of the active region is observed near the limb, both up flows and enhanced non-thermal velocities essentially decrease. There is a strong correlation between Doppler velocity and non-thermal velocity. Significant deviations from a single Gaussian profile are found in the blue wings. These suggest that there are unresolved high-speed up flows that might be closely related to coronal heating mechanisms.

Temperature-dependent plasma motions (up flows) are observed in association with a transient coronal hole produced by a big flare (X3.2) that occurred on December 13 2006 [9]. Multi-wavelength spectral observations allow us to determine velocities from the Doppler shifts at different temperatures. Strong up flows as well as stationary plasma have been observed in the Fe XV line 284.2 Å (log T(K) = 6.3) in this region. The strong up flows reach almost 150kms$^{-1}$ estimated by a two-component Gaussian fitting in Fig. 4. On the other hand, at a lower corona/transition-region temperature (He II 256.3Å, log T(K) = 4.7), very weak up flows, almost stationary, have been observed. We find that these up flow velocities clearly depend on the temperature with the hottest line, Fe XV, showing the fastest up flow velocity, and the second-highest line, Fe XIV, showing the second-highest up flow velocity (130kms$^{-1}$). All velocities are below the speed of sound. The trend of the up flow dependence on temperature dramatically changes at 1 MK.

3. Development of time-dependent collisional-radiative model for iron

In order to understand the dynamic solar plasmas introduced in the previous sections, a time-dependent collisional-radiative model for iron has been developed to analyze the data taken by the EIS instrument, and to diagnose temperatures and densities of those plasmas in the outer atmospheres of the Sun. No systematic models yet exist for iron ions of L- and M-shells, which are very important for coronal plasma diagnostics.

Atomic data for these ions were calculated by the HULLAC code [10]. Electron collision rates on Fe XIII are adopted from Aggarwal and Keenan [11], which is the latest calculation by R-matrix method.

For developments of the analysis tool with high precision, selections of atomic data (wavelength (level energy), radiative transition probabilities, collisional excitation cross sections etc.) and constructions of the collisional-radiative model for spectral line analysis are important. Atomic data
for iron ions of Fe X to Fe XV were surveyed and evaluated, and most recommended data were determined. Parameters for analytical fitting functions were obtained and provided [12].

EUV spectra in the wavelengths of 170 – 190 Å were taken at the LHD, by injecting iron TESPEL (tracer-encapsulated solid pellets). Data taken by this experiment is analyzed. Calculations of collisional excitation cross sections of Fe XIII lines were compared with LHD spectra with cross sections of proton collisions taken into account, and Watanabe et al. [13] compared the density-sensitive Fe XIII line ratios seen in EIS, and checked the consistency of theoretical calculations of line intensity.

4. Compact electron beam ion trap for spectroscopy of moderate

During the course of our development for the model atom and ions, it was found that data accommodated in the iron model come almost entirely from theoretical calculations, and no systematic experimental data exist. Therefore, a compact electron beam ion trap (EBIT) has been fabricated [14]. EBITs have been designed to be operated with rather high electron beam energy (~10keV or more). With such a high-energy electron beam, light and moderate elements are easily ionized to few electron or bare ions. On the other hand, spectroscopic studies of moderately charged ions which still retain many electrons are more important in solar coronal plasma diagnostics.

A new compact EBIT was developed for spectroscopic studies of moderate charge state ions, especially iron ions with charge states of Fe VI to Fe XVII relevant to the diagnostics of the solar corona. The electron energy range of the present EBIT is 100–1000eV, so that the size of the device has been much reduced from that of ordinary EBITs. In addition, a superconducting wire with a high critical temperature is used for the central coil so that it can be operated at liquid nitrogen temperatures.

Spectra of iron ions in moderate charged states will be measured to give experimental line intensity ratios used for tool to diagnose solar coronal plasmas.

5. Summary

Progress of high-resolution spectroscopy in astrophysics was briefly reported, especially for solar plasma diagnostics. The EIS instrument on board the Hinode mission is a suitable instrument to understand the mechanism of coronal heating. A time-dependent model iron atom/ions was constructed to simulate these plasmas, using best available data sets, both from theoretical calculations and laboratory experiments.

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