4-3 Recent results and future plans of atmospheric study using CRL all-sky imagers

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As part of an international cooperative research project between Communications Research Laboratory and Geophysical Institute of University of Alaska, we developed two all-sky imagers (CRL-ASI). We had conducted pilot observations in Japan, and developed some new observation techniques for atmospheric waves. We installed the CRL-ASI at Poker Flat (magnetic lat. 65.6N), Alaska, and started aurora/airglow observations from October 2000. CRL-ASI can be operated automatically, and controlled from CRL, Japan. Real-time summary data are opened to the public with WWW. Using these instruments, we successfully observed some new phenomena: simultaneous appearance of gravity waves and aurora, co-rotating aurora in the evening sector. These results show the advantage of sensitivity and spatial resolution of the CRL-ASI. Observation data by CRL-ASI will contribute to a study on the magnetosphere-ionosphere-thermosphere coupling.

Keywords
Airglow, Aurora, Image, Middle atmosphere, Gravity wave

1 Introduction

Very weak atmospheric emission (referred to as airglow) exists in the mesopause and lower thermosphere (MLT) region. Capturing images of airglow from the ground makes it possible to observe the atmosphere in this region continuously. In situ observation of the atmosphere in this region is very difficult.

Since around 1960, auroras in the Polar Regions have been observed and studied, using film or video cameras equipped with image intensifiers(II)[1][1]. In the 1980s, researchers attempted to take monochromatic images using an interference filter in addition to the II[2]. An aurora is a phenomenon caused by impact excitation of atmospheric molecules, atoms, and ions owing to electrons and protons precipitating from the magnetosphere. The emission intensity may reach tens of kilo-rayleighs (several tens as large as that of the Milky Way). Observation of auroras makes it possible to understand the state of the magnetosphere (a source of auroras) and to estimate the energy of aurora particles that precipitate from the magnetosphere[3].

In the MLT region, atmospheric molecules and atoms collide with one another, resulting in light-emitting excitation without the precipitation of electrons. After the 1980s, in the low- and mid-latitude regions (where no auroras form), cameras equipped with II were used to capture monochromatic images of very weak airglow. This allowed observation of traveling ionospheric disturbances (TID) and atmospheric gravity waves that propagate through the region[4][5]. Recently, charge-coupled devices (CCD) without an II have begun to be used[6]. These devices are far superior to those featuring an image intensifier in terms of durability, operability, and spatial resolution, but are slightly inferior in terms of time resolution. A CCD can be cooled to raise its sensitivity, and has therefore gained wide use as a detector of airglow-images.

As a part of the cooperative study between

Communications Research Laboratory (CRL) and the University of Alaska Fairbanks, which is referred to as the Alaska Project [7], we developed two high-sensitivity all-sky imagers (CRL-ASI) by applying the above-referenced CCD-imaging technology. After conducting many modes of trial observation and developing data-processing technology, we installed the equipment in Alaska in order to begin continuous observation in October 2000. In the next section, we present an outline of the CRL-ASI. Section 3 describes the results of the domestic trial observation and the technique of data-analysis developed during the trial observation. Section 4 presents an outline of the observations in Alaska and the initial results. Section 5 discusses future prospects.

[1]There are many types of two-dimensional amplifiers for illuminance: image orthicon tubes, SEM tubes, SIT tubes, devices using MCP, and so on. These are all included among the image intensifiers (II) described in this report.

2 Outline of apparatus

During the development stage of the CRL all-sky imagers (CRL-ASI), we attempted to obtain more accurate data by adding a focus-adjustment function to conventional imagers. This function improved data accuracy to a great extent, made it much easier to remove starlight as a source of error in measurements of airglow, and enabled us to estimate the quantity of nighttime clouds from extracted star images. This latter benefit was an unexpected outcome. We developed our own technical software for automated observation and Internet-based remote control of the imagers. This allowed for the stable automatic operation of the CRL-ASI in Alaska. Fig.1 is a schematic diagram of the overall system of the CRL-ASI.

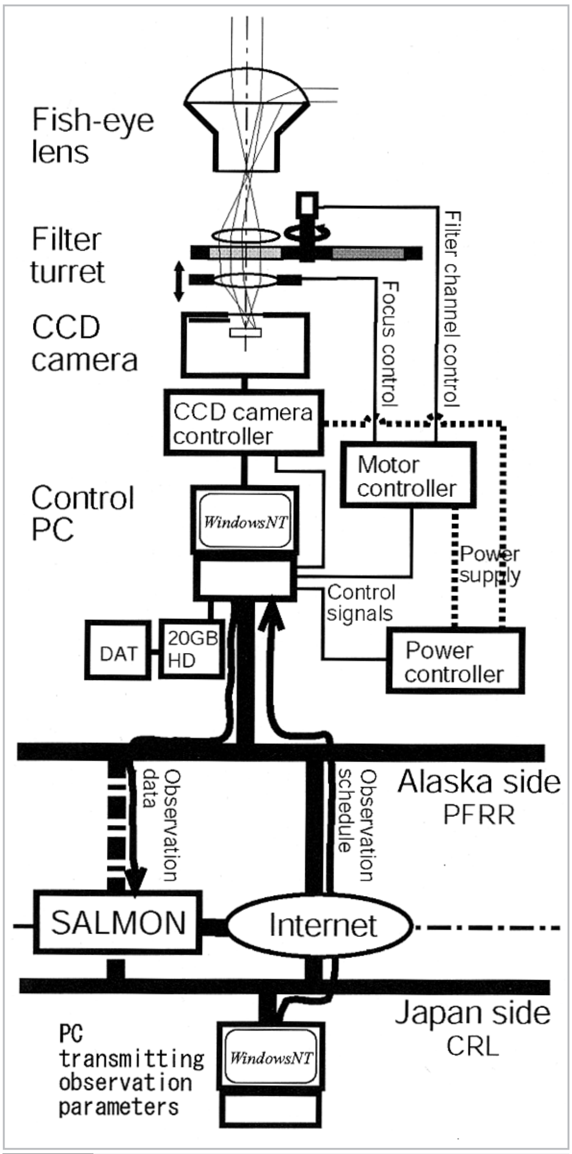

Fig.1 Schematic diagram of the overall CRL-ASI system

As an objective lens, the CRL-ASI has a fish-eye lens with a 6-mm focal length and an F1.4 made by Nikon Technologies Inc. It is capable of a 180 °all-sky field of view, which enables it to observe a wide area within a radius of several hundreds km range around the observation point. Rays of light pass through the objective lens and then through a collimator lens to become a collimated beam, through an interference filter for spectral separation, and is then focused on a CCD device unit. This optic system is based on the all-sky auroral imager developed by the National Institute of Polar Research (NIPR) in 1996[8][9] as well as on the airglow-observation imager developed later at Kyoto University. Interference filters are mounted on the five-channel filter turrets, enabling observation at any of five channel-selected wavelengths. The telecentric lens has a focus-adjusting mechanism to enable the capture of high-resolution images. The detector unit is a cooled camera with a 512 × 512-pixel back-illuminated CCD, achieving high-sensitivity and convenient in handling.

A control PC is programmed to operate the imagers so that the shutter may be opened and closed, filters may be switched, the focus may be adjusted, image data may be displayed and stored, and so on. Filter channels are switched to allow for continuous capture of images according to a preset schedule. The order of observation is described in a parameter file, which can be prepared not only with the on-site PC but may also be prepared and sent via the Internet from a remote PC.

We cooperated with NIPR to examine the sensitivity and other characteristics of the CRL-ASI. From this examination, we confirmed that the CRL-ASIs are achieving expected sensitivity. For example, we successfully obtained an acceptable S/N ratio for a 557.7-nm emission of oxygen atoms which is a representative auroral emission line, within a three-second or shorter exposure. Reference [10] shows a method of estimating the absolute intensity of airglow from observation data as well as details of the CRL-ASI calibrations.

3 Test in Japan

Development of the CRL all-sky imagers (CRL-ASI) started in 1997. These imagers were tested until 2000 in the context of various observation projects. During this period, we developed a suitable procedure for analysis of data, producing good scientific results.

Between January and March of 1998, we participated in the Planetary Scale Mesopause Observing System (PSMOS) Campaign. We then cooperated with Nagoya University and Kyoto University to conduct simultaneous observation of airglow from two locations. It was the first successful experiment in which we obtained a two-dimensional distribution of wave-structure heights in the emission layer. Fig.2 shows the two-dimensional distribution and airglow images. A method of determining wave-structure heights [11] was established in this experiment and has since been applied to the study on the mesopause and lower thermosphere (MLT) region[12].

In May 1998, we participated in the F-region Radio and Optical Measurement of Nighttime TID (FRONT) Campaign. We cooperated with Tohoku University, Niigata University, Nagoya University, Kyoto University and the Geographical Survey Institute to simultaneously observe airglow at five locations (Moshiri, Zaoh, Kiso, Shigaraki, and Miboshi)[13][14][15]. It was found that the airglow imagers served as effective tools in obtaining visually comprehensible images of ionospheric disturbances in the mid-latitude regions. Fig.3 shows an intensity distribution of 630-nm airglow due to oxygen atoms obtained for a wide area from Hokkaido to Kyushu in the course of the above simultaneous observation. This figure also shows the distribution of total electron content (TEC) obtained during observations using the domestic GPS network. It was found that distinct atmospheric waves (wavelength of 100 km) were present in airglow and were accompanied by ionospheric disturbances.

In January 2000, we participated in the Waves in Airglow Structures Experiment over Kagoshima in 2000 (WAVE 2000) project. We cooperated with the Institute of Space and Astronautical Science, Tohoku University, the University of Tokyo, Rikkyo University, and others to conduct simultaneous observation experiments on the ground and via rocket. These experiments were aimed at observation of atmospheric gravity waves of horizontal wavelengths between several kilometers and 100 kilometers, and succeeded in obtaining our first data set of (1) the horizontal distribution of airglow intensities and (2) vertical profiles of oxygen atoms, electron densities, and airglow intensities[16]. These data indicate periodic variations accompanying atmospheric waves and were analyzed to determine the structure of three-dimensional atmospheric

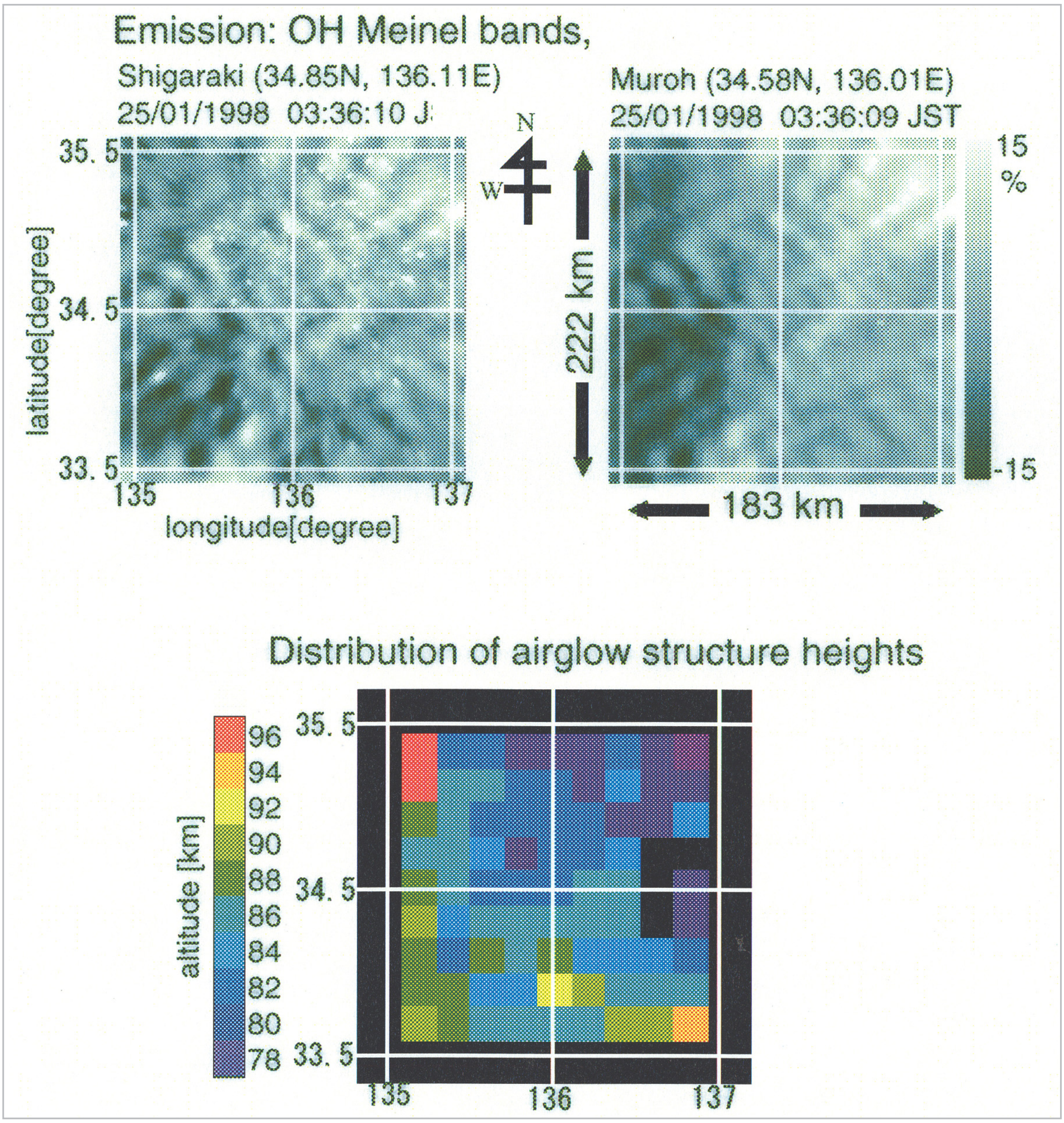

Fig.2 *Results of observation in the PSMOS campaign*

The upper panels show atmospheric gravity-wave structures in OH airglow simultaneously observed from Shigaraki and Muroh using the two ASIs. The lower panel shows a two-dimensional distribution of airglow wave-structure heights, indicating a shift in these heights by about 10 km from the northeast to the southwest.

waves in the MLT region[17].

4 Outline of observations in Alaska and initial results

4.1 Outline of observations

After the completion of domestic tests, the two CRL all-sky imagers (CRL-ASI) were placed at the Poker Flat Research Range (located on a mountain about 40 km northwest of downtown Fairbanks, Alaska, USA) in October 2000. The CRL-ASI remains in fully automatic continuous operation (or in remote-controlled operation from the CRL in Tokyo), except that the DAT data-backup tape, which has a large-capacity of 20 to 40 MB, is replaced every month. The PC transmitting the observation parameters is located at the

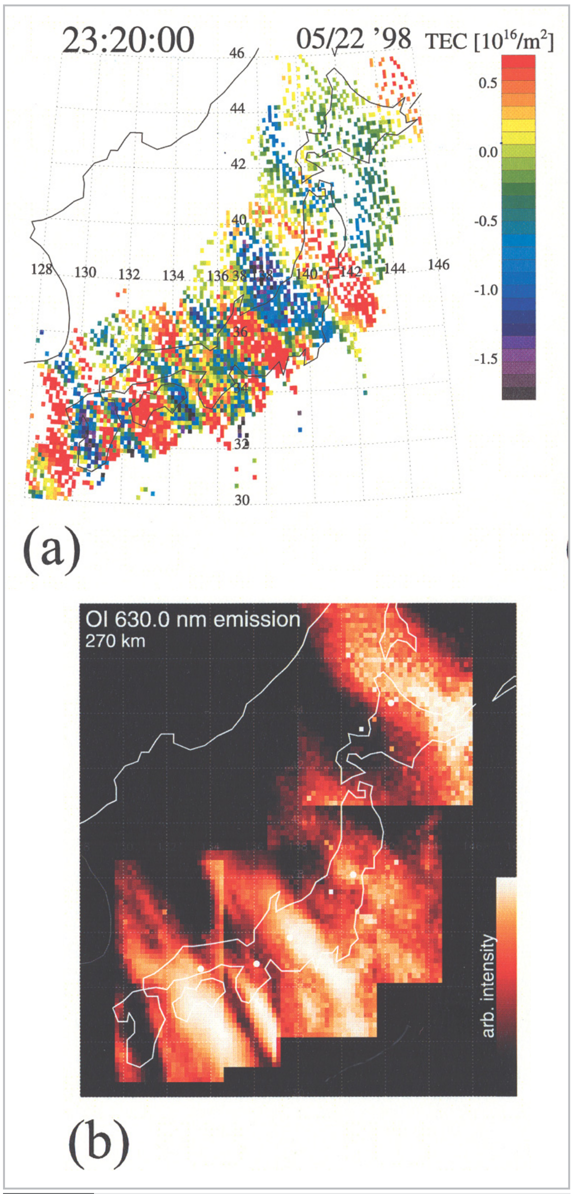

Fig.3 *Observational results of the FRONT campaign[14]*

(a) The distribution of total electron content (TEC) at 23:30 JST, May 22, 1998.
(b) The intensity distribution of 630-nm airglow due to oxygen atoms at nearly the same time.

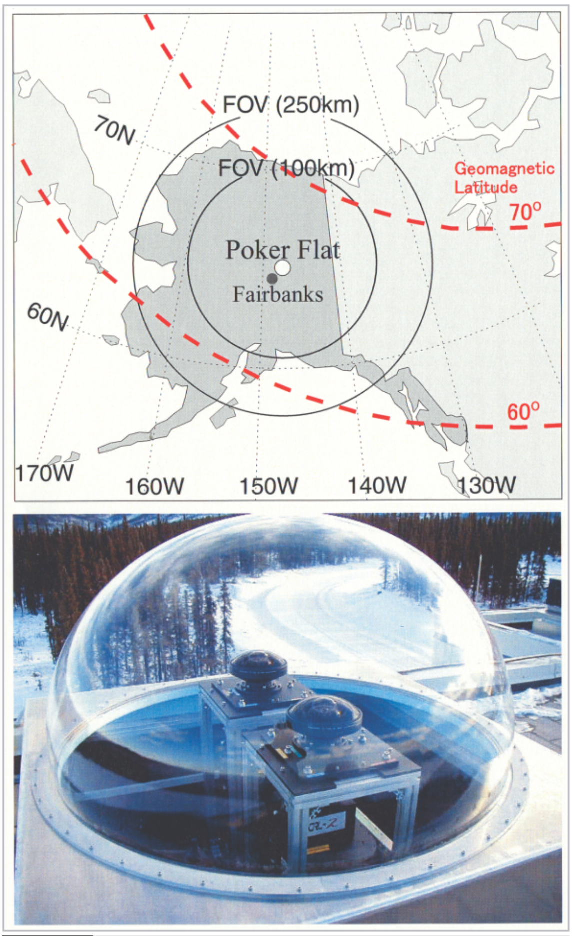

Fig.4 *Observation field of view and the state of installation of the CRL imagers*

In the top figure, Poker Flat is seen as located nearly in the center of Alaska. The red dashed lines represent the magnetic latitudes of 60 degrees and 70 degrees. The two circles show the observational field of view when the auroral emission altitude is assumed to be 100 km and 200 km, respectively. The bottom photo shows the two CRL-ASI placed within a dome at the Research Range.

CRL in Tokyo (refer to Fig.1). The observation point is located at a geographical latitude of 65.12 °N, a geographical longitude of 147.43 °W, and a magnetic latitude of 65.60 °N. Fig.4 shows the observation field of view and a photograph of the CRL imagers.

Observation by the CRL-ASI at Alaska have been conducted daily since October 20, 2000, with the exception of full-moon periods (the ten-day period surrounding a full moon) and the period of the midnight sun between the end of April and August. Observation data are automatically sent via the System for Alaska Middle Atmosphere Observation Data Network (SALMON)[18] to CRL, Tokyo. After processing, the observational results (including time, observed wavelengths, weather conditions, summarized data, and so on), are available to the public at the following URL: http://salmon-www.crl.go.jp/systemsum/

imagers/all_sky_imager_j.htm

4.2 Initial results

4.2.1 Interaction between atmospheric waves and auroras

Fig.5 shows atmospheric gravity waves and an aurora observed almost simultaneously around 08:30 UT on November 2, 2000.

As described earlier, an aurora is a phenomenon caused by impact excitation of the atmosphere owing to plasma particles precipitation from the magnetosphere. Thus, the shape and motion of an aurora depend on the magnetic and electric fields in the magnetosphere. The first negative band (427.8 nm) of N_2^+ is known as an aurora emission. The sodium D line represents airglow: specifically, an excitation caused by collision between atmospheric molecules and atoms. The shape and motion of airglow are strongly affected by atmospheric waves propagating in the MLT region. The 557.7-nm emission of an oxygen atom can be produced by auroral excitation as well as by collision between atmospheric molecules.

In Fig.5, the sodium D line image has a wave structure composed of bright stripes. These stripes were caused by the appearance of atmospheric waves in sodium airglow. We examined the change over time of the atmospheric waves and found that they propagated northwestward at a phase velocity of about 60 m/s. The observed 557.7-nm airglow had a wave structure composed of dark stripes: an inversion of those found in the D line. Similar wave structures which had identical shapes and brightness-inverted stripes in two kinds of airglow emissions are often observed in the low- and mid-latitude regions. These are referred to as front structures[19]. In the 557.7-nm image, we can find another features extending east to west near the celestial zenith. An emission of the same shape as that described above appeared in the image of N_2^+ first negative band, and thus proved to be an aurora. The aurora seems to feature a periodic-change structure that may overlay the structure of the above airglow. If the two structures definitely prove to be identical, these observations may indicate a new characteristic of interactions between neutral atmosphere and aurora.

Observation by the CRL-ASI showed that the wave structures of airglow in the auroral zone can be frequently observed in the sodium D line emission. We expect that such data may provide new progress into the study on interactions between atmospheric waves and auroras.

4.2.2 Co-rotating aurora in the evening

Fig.6 shows images of the 557.7-nm aurora obtained every 20 minutes between 03:20 UT and 04:00 UT on October 27, 2000. It was found that the patch-shaped aurora did not sig-

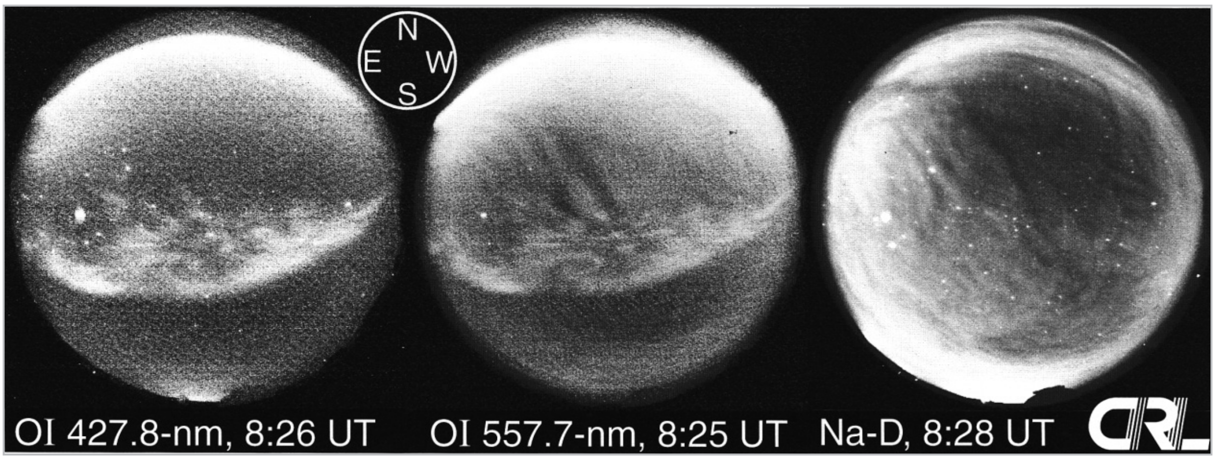

Fig.5 *Simultaneous observation of atmospheric gravity waves and auroras*

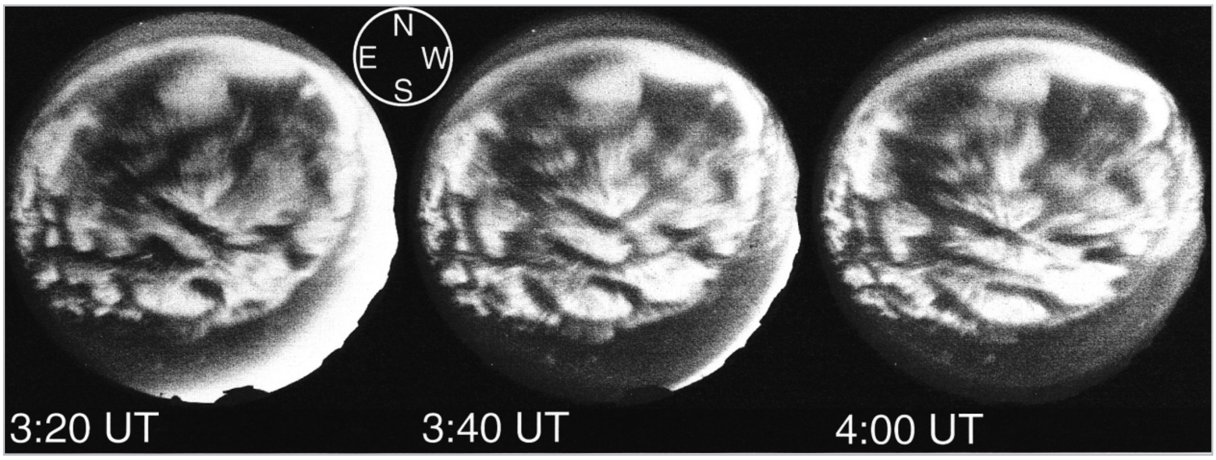

Fig.6 *Images of 557.7-nm aurora obtained every 20 minutes in the evening of October 27, 2000*

The time of integration was three seconds for each image. The images were histogram-equalized to emphasize the auroral structure.

nificantly change in position and shape over a period of 40 minutes. This indicates that the aurora co-rotated with the earth. Fig.7 shows the results of observation at five wavelengths.

We compared the characteristics of this event with various past observation data, and found that ours were similar to a phenomenon referred to as "Auger's detached arcs". These auroral phenomena were initially observed by the ISIS-2 satellite in the 1970s and are said to

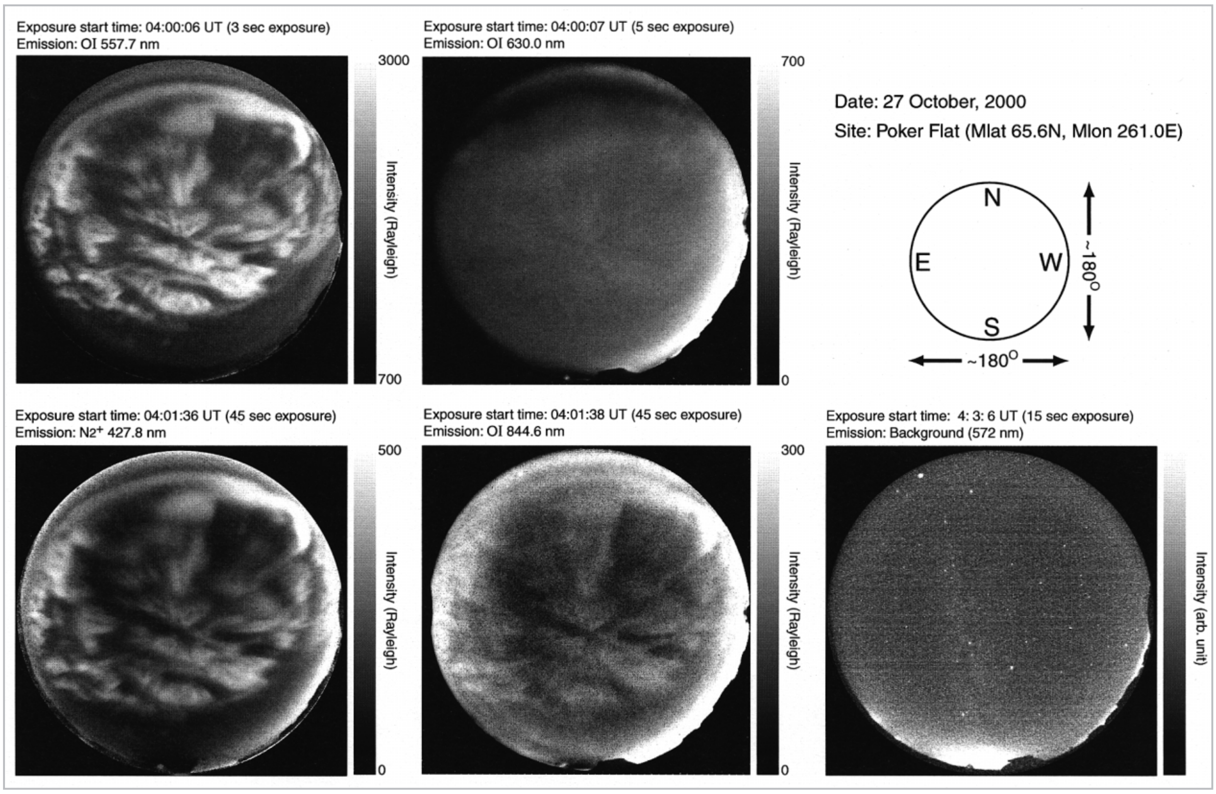

Fig.7 *Images observed at five wavelengths around 04 UT on October 17, 2000*

Patch-shaped auroras were seen at wavelengths of 557.7 nm and 427.8 nm. Patches were indistinct at 844.6 nm, while no patches were seen at 630.0 nm. Such wavelength dependency indicates that the energies of precipitating particles were high. Stars and the Milky Way were observed as background radiation, indicating that clouds did not affect the patches.

appear only in the evening above Alaska [20][21][22]. The co-rotation and long duration of the aurora observed by the CRL-ASI seem to be inconsistent with the fact that auroras are constrained by magnetic field lines. To explain this, a hypothesis has been framed suggesting that cold plasma around the magnetopause region might contribute to the formation of such auroras.

4.2.3 Estimation of the energy of precipitating electrons in an aurora

The patch-shaped aurora shown in Fig.7 appeared differently depending on the wavelength. From these differences we can estimate the energies of precipitating electrons. Fig.8 shows a horizontal distribution of the average energies of precipitating electrons estimated from ratios of emission intensity at 427.8 nm to that at 844.6 nm. Electrons with an average energy of 20 keV precipitated in the patch-shaped aurora. The conversion of the illuminance to the average energy was based on the results provided in Reference [23]. As we move away from the magnetic zenith, we view the ray structure in the transverse direction. Thus, we tend to underestimate the energy. If we can correct such apparent errors (which are dependent on the zenith angle), a horizontal distribution of energies of precipitating electrons in an aurora can be obtained from the observation with CRL-ASI.

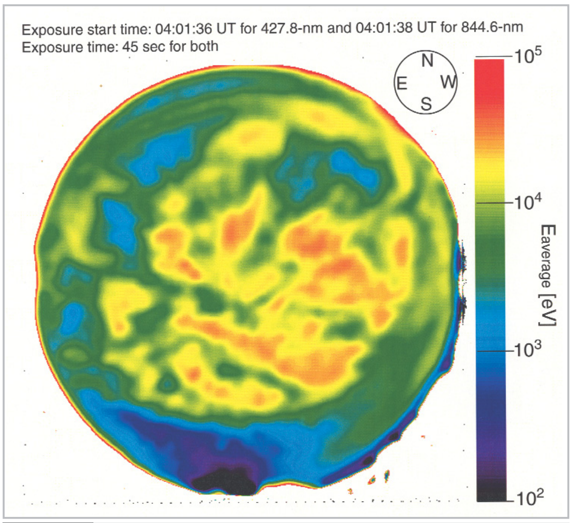

Fig.8 A horizontal distribution of average energies of precipitating electrons estimated from ratios of illuminance at 427.8 nm to that at 844.6 nm

5 Future prospects

There are two modes of auroral heating of the atmosphere: Joule heating and particle heating. If observation data by the CRL all-sky imagers (CRL-ASI) can be used to obtain a horizontal distribution of energies of precipitating electrons in an aurora, it will be possible to estimate both the Joule heating and particle heating of the atmosphere due to auroras in the MLT region. The above estimation may be analyzed in combination with measurements of wind speed and temperature in the mesopause and lower thermosphere (MLT) region using a Fabry-Perot interferometer [24] and observations in the mesosphere using CRL-MF radar [25] and Rayleigh lidar[26]. From such an analysis, we may be able to discuss the effect of auroras on the middle atmosphere, which represents one of the major themes of the Alaska Project.

Simultaneous observation of an aurora and other airglow (from Na and OH) may be used to formulate a description of the aurora and atmospheric gravity waves and to analyze the interaction between them. Such description and analysis may result in clarification of the effects of auroras on the atmosphere. Beside that, the data on multi-wavelength auroras obtained by the CRL-ASI may be expected to contribute to the study of the aurora itself.

6 Conclusions

We began development of the CRL all-sky imagers (CRL-ASI) in 1997. During the development stage, we conducted various types of test observations in Japan and successfully established methods of observing airglows. Since October 2000, we have continued observation of multi-wavelength auroras and airglow at the Poker Flat Research Range, Alaska. Satisfactory results have been obtained, including the first successful optical observation of Anger's detached arcs from the ground. These results indicate that the CRL-

ASI has advantages in terms of both sensitivity and accuracy.

The CRL-ASI has obtained data for two winter seasons (since October 2000). We intend to continue observations in Alaska for two more years. Our major aim is to conduct research on new aspects of interactions of the neutral atmosphere in the magnetosphere, ionosphere, and the MLT (mesopause and lower thermosphere). We hope that the above research will be successful in its effective use of long-term data sets.

The CRL-ASI can be expected to make a significant contribution to a very wide range of research projects. To this end, we intend to work in close cooperation with other research institutes to obtain the most effective results.

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References

1 Akasofu, S.-I., "The development of the auroral substorm", Planet Space Sci., 12, 273-282, 1964.

2 Ono, T., T. Hirasawa, and C.-I. Meng, "Weak auroral emissions and particle precipitations in the dusk auroral oval", J. Geophys. Res., 94, 11933-11947, 1989.

3 Rees, M. H., and D. Luckey, "Auroral electron energy derived from ratio of srectroscopic emissions 1. model computations", J. Geophys. Res., 79, 5181-5186, 1974.

4 Taylor, M. J., M. A. Hapgood, and P. Rothwell, "Observations of gravity wave propagation in the OI (557.7 nm), Na (589.2 nm) and the near infrared OH nightglow emissions", Planet Space Sci., 35, 413-427, 1987.

5 Kubota, M., S. Okano, and H. Fukunishi, "Relationship of Temporal and Spatial Variations of OI 630-nm Nightglow over Japan with Traveling Ionospheric Disturbances (TIDs)" , Earth, Planets and Space, 53, 741-751, 2001.

6 Taylor, M. J., M. B. Bishop, and V. Taylor, "All-sky measurements of short period waves imaged in the OI (557.7 nm), Na (589.2 nm) and near infrared OH and O2 (0,1) nightglow emissions during the ALOHA-93 campaign", Geophys. Res. Lett., 22, 2833-2836, 1995.

7 Mori, H., Y. Murayama, M. ishii, M. Kubota, H. Masuko, K. Mizutani, M. Yasui, T. Manabe, S. Ochiai, Y. Irimajiri, K. Igarashi, K. Nozaki, T. Kikuchi, T. Itabe, M. Kunitake, and S. Kainuma, "Radio and optical remote-sensing of the Alaskan sky - Japan-US cooperative study on the global environment - ", J. of the Comm. Res. Lab., 46, 235-244, 1999.

8 Okada, M., M. Ejiri, S. Okano, M. Taguchi, and S. Takeshita, "System design and initial results of all sky imager at south pole", Antarctic Record, 41, 613-630, 1997.

9 Ejiri, M., S. Okano, M. Okada, M. Taguchi and S. Takeshita, " All sky imager observation of aurora and airglow at South Pole: System design and the initial test results (extended abstract)", Proc. NIPR Symp. Upper Atmos. Phys., 11, 159-162, 1998.

10 Yamamoto, M.-Y., M. Kubota, S. Takeshita, M. Ishii, Y. Murayama, and M. Ejiri, "Calibration of CRL all-sky imagers using an integrating sphere", Advances in Polar Upper Atmosphere Research, submitted.

11 Kubota, M., M. ishii, K. Shiokawa, M. K. Ejiri, and T. Ogawa, "Height measurements of nightglow structures observed by all-sky imagers", Adv. Space Res. 24, 593-596, 1999.

12 Ejiri, M. K., K. Shiokawa, T. Ogawa, T. Nakamura, R. Maekawa, T. Tsuda, and M. Kubota, "Small-scale Gravity Waves Near the Mesopause Observed by Four All-sky Airglow Imagers", J. Geophys. Res. -D, 106, 22793-22799, 2001.

13 Kubota, M., K. Shiokawa, M. K. Ejiri, Y. Otsuka, T. Ogawa, T. Sakanoi, H. Fukunishi, M. Yamamoto, S. Fukao, A. Saito, and S. Miyazaki, "Tracking of Wave-like Structures in the OI 630-nm Nightglow over Japan Using an All-sky Imagers Network during FRONT Campaign", Geophys. Res. Lett., 27, 4037-4040, 2000.

14 Saito, A., M. Nishimura, M. Kubota, K. Shiokawa, M. Yamamoto, S. Fukao, T. Ogawa, Y. Otsuka, M. Ishii, T. Sakanoi, Y. Kiyama, K. Igarashi, and S. Miyazaki, "Traveling ionospheric disturbances detected in the FRONT Campaign", Geophys. Res. Lett., 28, 689-692, 2001.

15 Shiokawa, K., M. K. Ejiri, Y. Otsuka, T. Ogawa, M. Kubota, K. Igarashi, A. Saito, and T. Nakamura, "Multi-point obaervation of short-period mesospheric gravity waves over Japan during the FRONT Campaign", Geophys. Res. Lett., 27, 4057-4060, 2000.

16 Kubota, M., Y. Murayama, M. Ishii, Y. Yamada, H. Ohnishi, and H. Fukunishi, "Ground based imaging observation of airglow wave structures during WAVE 2000 campaign (translated title)", Institute of Space and Astronautical Science (ISAS) Report, 42, 13-21, May 2001.

17 Iwagami, N., T. Shibaki, T. Suzuki, Y. Yamada, H. Ohnishi, Y. Takahashi, H. Yamamoto, H. Sekiguchi, K. Mori, Y. Sano, M. Kubota, Y. Murayama, M. Ishii, K-I. Oyama, R. Yoshimura, M. Shimoyama, Y. Koizumi, K. Shiokawa, N. Takegawa and T. Nakamura, "The Wave2000 campaign: Overview and preliminary results", J. of Atmos. and Solar-Terr. Phys., submitted.

18 S. Oyama, Y. Murayama, M. Ishii, M. Kubota, "Development of SALMON system and the environment data transfer experiment", This Special Issue of CRL Journal.

19 Taylor, M. J., D. N. Turnbull, and R. P. Lowe, "Spectrometric and imaging measurements of a spectacular gravity wave event observed during the ALOHA-93 campaign", Geophys. Res. Lett., 22, 2849-2852, 1995.

20 Anger, C. D., M. C. Moshupi, D. D. Wallis, J. S. Murphree, L. H. Brace, and G. G. Shepherd, "Detached auroral arcs in the trough region", J. Geophys. Res., 83, 2683-2689, 1978.

21 Moshupi, M. C., C. D. Anger, J. S. Murphree, D. D. Wallis, J. H. Whitteker, and L. H. Brace, "Characteristics of trough region auroral patches and detached arcs observed by ISIS 2 ", J. Geophys. Res., 84, 1333-1346, 1979.

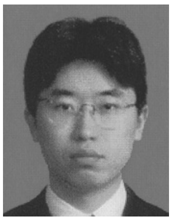
22 Wallis, D. D., J. R. Barrows, M. C. Moshupi, C. D. Anger, and J. S. Murphree, "Observations of particles precipitating into detached arcs and patches equatorward of the auroral oval ", J. Geophys. Res., 84, 1347-1360, 1979.

23 Ono, T, "Derivation of energy parameters of precipitating auroral electrons by using the intensity ratios of auroral emissions", J. Geomag. Geoelectr., 45, 455, 1993.

24 M. Ishii, et al., " Development of CRL Fabry-Perot interferometers and observation of the thermosphere", This Special Issue of CRL Journal.

25 Y. Murayama, et al., "CRL Alaska Project –International Collaborations for observing Arctic atmosphere environment in Alaska–", This Special Issue of CRL Journal.

26 K. Mizutani, et al., "Lidar instruments for observation of the arctic atmosphere in Alaska-project," This Special Issue of CRL Journal.



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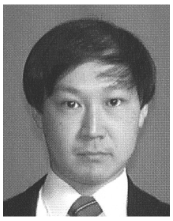

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