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博士学位論文

Development of the Nayoro Optical Camera and
Spectrograph (NaCS) and Spectral Monitoring of the
Double-peaked Emission Line of Active Galactic Nuclei

(可視撮像分光装置 NaCS の開発と
活動銀河核のダブルピーク輝線の分光モニター観測)

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Abstract

Active galactic nuclei (hereafter AGNs) are the central regions of galaxies that are emitting an energy originated from non-stellar objects. The emitted energy is comparable to the energy emitted by all of the stars in the galaxy (10^{10} – $10^{13} L_{\odot}$). The radiation from the AGNs is a result of the mass accretion into a super-massive black hole (10^6 – $10^8 M_{\odot}$) at the center of the galaxy.

AGNs may play a critical role in the process of galaxy formation and evolution. The strong radiation, winds, and radio jets from the AGN can interact with the interstellar medium in the galaxy and lead to ejection or heating of the gas, and then terminates the star formation in the galaxy and stifles accretion on the black hole of AGN. However, there are several unknown issues that prevent from understanding this AGN feedback mechanism. For example, about 10 % of AGNs have a strong radio emission and radio jets. It is unclear why the AGNs clearly separates into two groups, that is, the AGNs with a strong radio emission (radio-loud AGNs) and the AGNs without a radio emission (radio-quiet AGNs). The mechanism of formation of radio jets is also unclear.

One of the possible mechanisms of creating the difference in the radio-loudness of AGNs is the presence of a radiatively inefficient accretion flow (hereafter RIAF) at the inner part of the accretion disk of the radio-loud AGNs because of their low-mass accretion rate. Some of the radio-loud AGNs show double-peaked emission lines in their spectra, which originate in the emission from the accretion disk illuminated probably by a geometrically extended ionizing central source such as a RIAF.

AGNs are very compact and very distant. Even the current highest resolved observations are unable to resolve spatially the insides of the AGNs directly. The monitoring of time variations in the emission from AGNs is an effective alternative way to investigate the phenomena inside the spatially unresolved AGNs. The detection of reverberation effects from an accretion disk in AGNs, which is predicted by Stella for the double-peaked line AGNs, can illuminate the structure and kinematics of the accretion disk and the broad-line regions (BLRs) of the AGNs and permit a measurement of the size of the extended ionizing central source such as a RIAF. In order to test the presence of the reverberation effects from an accretion disk in the double-peaked AGN, we performed a high-frequency imaging and spectroscopic monitoring of the double-peaked $H\alpha$ line of Arp 102B with a short interval of a day.

To enable us to achieve such a high-frequency monitoring observations, we newly developed a visible imager and spectrograph, Nayoro Optical Camera and Spectrograph (NaCS) for the 1.6-m Pirka telescope of the Hokkaido University. This instrument has a $2k \times 1k$ fully-depleted thick back-illuminated Hamamatsu CCD, which has quite a high quantum efficiency (≥ 80 %) over optical wavelength. In addition, it is designed to enable to switch the observation modes quickly between the imaging and spectroscopic modes, improving the observing efficiency. The combination of this high efficient instrument and the Pirka telescope, which is intensively focusing its telescope time on monitoring observations, enables us to do high-frequency monitoring observations efficiently.

The monitoring observations of Arp 102B were carried out during 2013 May–June, 2013 August, and 2014 February over a month each period, and we succeed in obtaining 25 spectra of Arp 102B. We found that the double-peaked $H\alpha$ line of Arp 102B was unusually faint, which is an half of the flux at the past bright state, during our observation periods. Nevertheless, we detected a small rapid variability of the double-peak $H\alpha$ line of Arp 102B

with 5–10 % in flux, about 10 Å in blue-peak wavelength, and about 10 % in blue-to-red flux ratio, with a time scale of a few to ten days.

To test the presence of the reverberation effects from an accretion disk in the observed variations, we modeled the double-peak line profile with an elliptical accretion disk and computed the response of the H α line profile from the accretion disk to a step-like flux variation of the ionizing central source. As a result, we found that the model predicts the constancy of the blue-to-red flux ratio against the change in the blue-peak wavelength and that this behavior is almost independent of the disk parameters of accretion disk model. This predicted behavior is inconsistent with our observed behavior of the flux ratio and blue-peak position. We also could not find any drifting bumps that move from the wings of the line profile towards the line center with a time scale of 5–7 days, which is predicted as a result of light travel-time effects of the echo front of the source flux variation. Therefore, we conclude that the reverberation effect from the accretion disk does not dominate our observed rapid variability of the double-peaked profile. It may imply that the central source ionizing the accretion disk of Arp 102B had not a large rapid flare with a time scale of shorter than about ten days and an amplitude of above 100 % during our observation periods. We suggest that the observed small rapid variability is possible to originate in the variability of an ordinary broad-line or outflow components in the BLR of Arp 102B. Long-term high-frequency spectroscopic monitoring observations with a short interval of a day scale over a month are much important to construct the model of AGN including the RIAF and accretion disk in detail.

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Chapter 1

Introduction

1.1 What is AGN?

Active galactic nuclei (hereafter AGNs) are the central regions of galaxies that are emitting an energy originated from non-stellar objects. The emitted energy from AGN is quite huge and is comparable to the energy emitted by all of the stars in the galaxy (10^{10} – $10^{13} L_{\odot}$ ¹). AGN is one of the most energetic objects in the universe. The radiation from AGN is a result of the mass accretion into a super-massive black hole (10^6 – $10^8 M_{\odot}$ ²) at the center of the galaxy.

There are various types of AGNs characterized by optical luminosity (Seyfert galaxy or quasar), radio luminosity (radio-loud or radio-quiet), the shape of continuum, emission lines (broad-line or narrow-line), and etc. Also, some correlations between the type of AGN and its host galaxy are known. For example, the most of host galaxy of radio-quiet quasar and Seyfert galaxy are a spiral galaxy, and radio-loud quasar and broad-line radio galaxy are a elliptical galaxy (Gehren et al., 1984; Malkan, 1984; Hutchings, Janson, & Neff, 1989).

AGNs may play a critical role in the process of galaxy formation and evolution (Fabian, 2012). The strong radiation, winds, and radio jets from AGN can interact with the interstellar medium and lead to ejection or heating of the gas, and then terminates the star formation in the galaxy and stifles accretion on the black hole of AGN. However, there are several unknown issues that prevent from understanding this AGN feedback mechanism. For example, about 10 % of AGNs have a strong radio luminosity and radio jets. It is unclear why AGNs clearly separates into two groups, that is, AGNs with a strong radio emission and AGNs without a radio emission. The mechanism of formation of radio jets is also unclear.

AGNs are very compact and very distant from us, the apparent size is very small. Even the current highest-resolved observations (1 milli arcsecond) are unable to resolve spatially the inside of AGNs directly. Spectroscopic monitoring of variations in the emissions from the AGNs is an effective alternative way to investigate the phenomena inside the spatially unresolved AGNs. In this chapter, I introduce the basic properties of AGNs and the recent spectroscopic monitoring observations of AGNs and their results.

¹ $L_{\odot}$ is the solar luminosity ($= 3.84 \times 10^{26}$ W).

² $M_{\odot}$ is the solar mass ($= 1.99 \times 10^{30}$ kg).

1.1.1 Structure of AGN

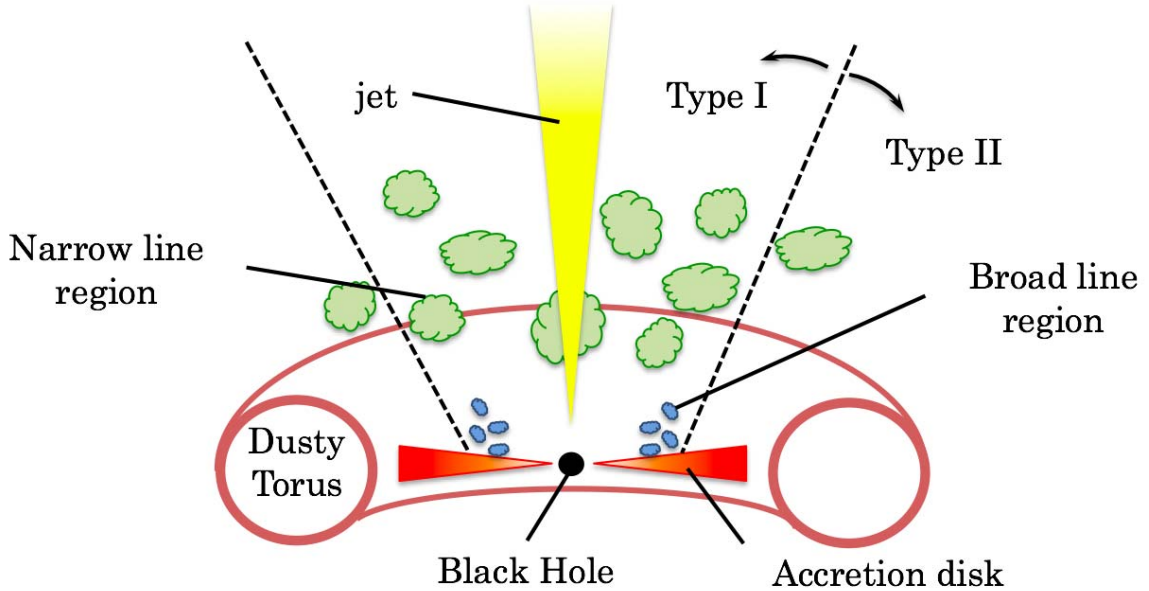


Figure 1.1: Structure of AGN

The schematic view of the basic structure of AGN is shown in Figure 1.1. There is a super-massive black hole in the center of AGN. It is thought that the black hole mass is 10^7 – $10^8 M_{\odot}$, and the radius of black hole (Schwarzchild radius³) is 10^{12} – 10^{13} cm. An accretion disk surrounds the central black hole. It has a temperature distribution depending on the distance from the center. The continuum emission over a wide spectral range (optical to X-ray) is emitted from the innermost hot region (radius $< 10^{15}$ cm) of the accretion disk. This radiation ionizes gas in nearby regions of the accretion disk, and the ionized region emits line emission. The gases in the nearby region of the accretion disk are thought to consist of many randomly moving gas clouds. Consequently, a broad emission line is observed as a result of combination of various radial velocity components. Such regions are called as broad-line regions (BLRs). The typical radius of BLR is about 10^{16} – 10^{17} cm. The accretion disk and BLRs are surrounded by optically and geometrically thick dust region. The geometry of dust regions is generally thought to be like a torus drawn in Fig.1.1 and is called as dust torus, although the geometry of dust region is still unclear and other geometries, for example, a gathered clouds (Krolik & Begelman, 1988) and the shell shape (Ohsuga & Umemura, 1999) are proposed. The inner and outer radii of dust torus are about 0.1 – 1 pc⁴ and about 100 pc, respectively. Low density gas clouds beyond torus emit narrow lines, and thus it is called as narrow line region (NLR). The size of NLR is about 70 pc to 10 kpc. In the radio loud AGNs, the radio jet from the center of AGN is often seen.

³Schwarzchild radius is radius at where the escape velocity from the surface of the sphere would equal the speed of light.

⁴1 parsec (1 pc) is the distance at which one astronomical unit ($1 \text{ AU} = 1.50 \times 10^{13}$ cm) subtends an angle of one arcsecond. $1 \text{ pc} = 3.08 \times 10^{18}$ cm.

1.1.2 Types of AGNs

AGNs are divided into the various types by differences of luminosity, continuum and emission line spectrum. The types of AGNs are described below.

Seyfert Galaxies

Seyfert galaxies has a low luminosity relatively among the all AGNs. It is distinguished from quasars (see below) by the criterion of luminosity with $M_B > -22.3 + \log h_0$ (Schmidt & Green, 1983), where M_B is the absolute magnitude with B -band and h_0 is the Hubble constant normalized by $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This galaxy is most numerous in the neighborhood of the local universe. Because of the Seyfert galaxy is relatively low luminosity and is in the neighborhood of us, it is possible to distinguish between the AGN and the host galaxy. The host galaxy of the Seyfert galaxy is almost an early type spiral galaxy. Many Seyfert galaxies are observed as radio sources, however the radio emission from Seyfert galaxy is weak relative to other types of AGNs.

Seyfert galaxy is classified by whether there are broad line emissions in the optical spectrum into type 1 and type 2 (Khachikian & Weedman, 1974). In the type 1 Seyfert, both the narrow-line emissions ($\text{FWHM}^5 \sim 500 \text{ km s}^{-1}$) and the broad-line emissions ($\text{FWHM} \sim 500\text{--}10000 \text{ km s}^{-1}$) are observed in their spectrum. In the type 2 Seyfert galaxy, only the narrow line emissions are observed. Figure 1.2 shows the optical spectrum of NGC 5548, which is the typical type 1 Seyfert galaxy.

The broad lines are observed in only the permitted lines ($\text{H}\alpha \lambda 6563$, $\text{H}\beta \lambda 4861$, $\text{He I } \lambda 5876$, and etc), and are not observed in the forbidden lines ($[\text{O III}] \lambda 4956$, 5007 , $[\text{N II}] \lambda 6548$, and etc). The difference between two types of emissions originates from the density difference of the ionized gases that emit emission lines. The density of gases emitting broad lines are higher ($n_e \gtrsim 10^9 \text{ cm}^{-3}$) than that of gases emitting narrow lines ($n_e \sim 10^3\text{--}10^6 \text{ cm}^{-3}$), where n_e is the number density of electrons.

Quasar

Quasar has the largest luminosity among AGNs. There are a lot of quasars in a distant galaxies, but are not in our neighborhood. The quasar is classified by its radio intensity into the radio-loud quasar (RLQ) and radio-quiet quasar (RQQ). Most of quasars are RQQ, and only about 5–10 % of quasars are RLQ. The SED (spectral energy distribution) of RQQ is similar to that of the type 1 Seyfert galaxy. It is thought that these are the same type, however, the luminosity is different. The optical spectrum of quasar is also similar to that of the type 1 Seyfert galaxy. There are both broad lines and narrow lines in their optical spectrum. RLQ is classified by the slope of the radio continuum spectral shape from a few GHz to a few hundred MHz into the two types: the steep spectrum radio quasar (SSRQ) and the flat spectrum radio quasar (FSRQ). Most of the radio emission from AGNs including quasars are synchrotron radiation.

⁵Full Wide Half Maximum (FWHM) is used to describe the width of emission lines.

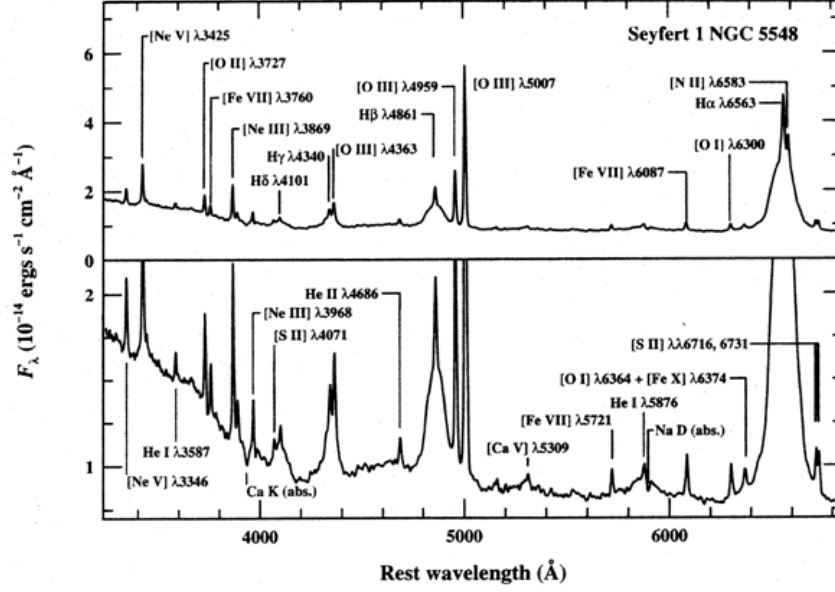


Figure 1.2: The optical spectrum of the Seyfert 1 galaxy NGC 5548. The spectrum shows the broad Balmer lines $H\alpha$ $\lambda 6563$, $H\beta$ $\lambda 4861$, $H\gamma$ $\lambda 4340$, and $H\delta$ $\lambda 4101$ and the narrow lines like $[O III]$ $\lambda 5007$, 4959 , and $[O II]$ $\lambda 3727$. The vertical scale is expanded in the lower panel to show the weaker features. This figure is taken from Peterson (1997).

OVV

Quasars with a variability over 0.1 magnitude within a day are called as optically violent variable (OVV) quasar. Most of OVV have high polarization (up to a few percent). Both the polarization magnitude and polarization angle are also variable.

Radio Galaxy

The radio galaxy is observed as a strong radio source. The optical spectrum of the radio galaxy is similar to that of the Seyfert galaxy, and the radio galaxy is also classified by optical spectrum into two types like the Seyfert galaxy. The radio galaxy that both narrow line emissions and broad line emissions are observed in their spectrum is called as a broad-line radio galaxy (BLRG), while one that only narrow line emissions are observed is called as a narrow-line radio galaxy (NLRG). The radio galaxy is basically similar to the Seyfert galaxy and it is thought that the radio galaxy is a radio-loud Seyfert galaxy, however most of the host galaxy of the radio galaxy is an elliptical galaxy rather than a spiral galaxy.

The two types with difference in radio intensity and spatial intensity distribution exist in NLRG (Fanaroff & Riley, 1974). The low luminosity galaxies that show a rather compact emission arising from close to the core are called as Fanaroff-Riley class I (FR-I), and the high-luminosity galaxies in which the structure is dominated by the radio lobes and most of the emission appears to come from the far end of the extended emission are called as Fanaroff-Riley

class I (FR-II). Figure 1.3 shows the image of Cygnus A at 5 GHz. The radio lobes of Cygnus A extend out to 50 kpc from the core, thus it extends far outside of the host elliptical galaxy.



Figure 1.3: Grey-scale representation of image of Cygnus A at 5 GHz with $0.4''$ resolution made with the VLA. The AGN core is located at the bright spot at the center of figure. The radio lobes extend out to about 50 kpc.

BL Lac objects

In the spectrum of the BL Lac objects, there are no strong emission lines and absorption lines, thus the BL Lac objects are different from other AGNs. The BL Lac objects were originally identified as a highly variable star, thus they are called as BL Lac objects. The BL Lac objects shows a strong variability and high polarization like OVV, thus OVV and BL Lac are sometimes referred to as blazars. All known blazars are strong radio sources.

LINER

Low luminosity AGN that shows low-ionized emissions in their optical spectrum are called as LINER (Low-Ionization Nuclear Emission line Region). The optical spectrum of LINER is similar to the type 2 Seyfert, however the low-ionized emissions ($[\text{O II}] \lambda 3727$, $[\text{O I}] \lambda 6300$, $[\text{N II}] \lambda 6548$, 6583 , and etc) are seen strongly. LINER is a very general AGN, because LINER exists in an half of all the spiral galaxy (Ho, Filippenko, & Sargent, 1994). Baldwin, Philips, & Terlevic (1981) demonstrate how LINERs can be distinguished from H II regions and type 2 AGNs (type 2 Seyferts and NLRG) on the basis of their $[\text{O III}] \lambda 5007 / \text{H}\beta$, $[\text{N II}] \lambda 6583 / \text{H}\alpha$ flux ratios (BPT diagrams). Figure 1.4 shows one of the BPT diagrams. LINERs have a lower $[\text{O III}] \lambda 5007 / \text{H}\beta$ than the type 2 AGNs and have a higher $[\text{N II}] \lambda 6583 / \text{H}\alpha$ than the H II regions.

1.1.3 Unified Model of AGNs

As mentioned previous section, many different types of AGNs have been observed. Antonucci (1993) and Urry & Padovani (1995) suggested that much of the variety in the AGN types is just the result of varying orientation relative to the line of sight, and that the difference

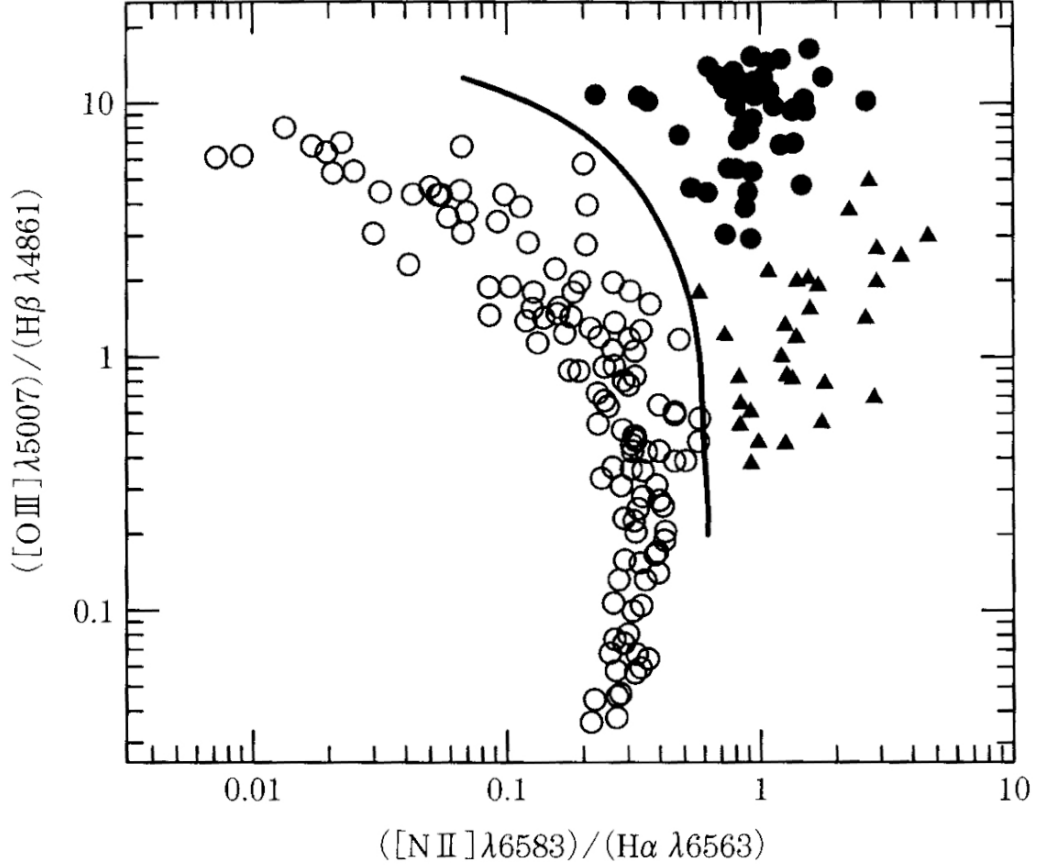


Figure 1.4: BPT diagram: the relation of $[\text{O III}] \lambda 5007 / \text{H}\beta$ and $[\text{N II}] \lambda 6583 / \text{H}\alpha$ flux ratios. The open circles are H II regions, the filled circles are type 2 Seyfert and NLRG, and the filled triangles are LINERs (Veilleux & Osterbrock, 1987).

between individual AGNs are only three parameters (viewing angle, optical luminosity, and radio intensity). This is called as the unified model.

According to the unified model, the difference between type 1 and type 2 AGNs is only difference of viewing angle of dust torus. In the case that the nuclear and BLR are hidden by dust torus, it is seen as the type 2 AGN. In the case of radio loud AGNs, AGNs in which the direction of jet toward us are seen as blazars. Thus, the blazars are also called as the type 0 AGNs.

The classification of AGNs by the unified model is shown in Table 1.1. In this table, the AGNs on the same row are the same AGN fundamentally. The type 2, radio quiet quasar is not found yet. The galaxy with a high infrared luminosity (ULIRG: Ultra Luminous Infra-Red Galaxy) is a candidate, however it is unclear whether ULIRG is type 2 radio-quiet quasar, because the spectra of almost ULIRG are similar to that of starburst.

Table 1.1: Classification of AGN by unified model

Radio Loudness	Optical Luminosity	Orientation		
		Type 0	Type 1	Type 2
Loud	High	FSRQ / OVV	SSRQ	NLRG (FR II)
	Low	BL Lac object	BLRG	NLRG (FR I)
	High		RQQ	(ULIRG?)
	Low		Seyfert 1	Seyfert 2

1.2 Radio Jet

In many radio-loud AGNs, narrow jets are seen to emerge from the nucleus. They are probably launched and kept narrow by strong magnetic fields that build up in the surrounding disk of inflowing matter. The spectrum of the jet across all the wavelengths is a steep power-law and reflects the power-law that describes the energy distribution of electrons. The typical SEDs for luminous radio-loud and radio-quiet AGNs are shown in Figure 1.5. Because some jets are extended over a few Mpc scale, which is larger than their host galaxy and have a high intensity in the radio wavelength, it should have an influence on evolution in the host galaxy. A positive feedback mechanism, which is induced by the AGN jet and leads to enhance the star formation, has also been considered as a source powering luminous starbursts (Silk, 2005). Numerical simulations of radio jet-induced star formation have also been recently performed (Gaibler et al., 2012).

The mechanism of launching the jet is not well understood, because the region launching jet is very compact and in distant and the apparent size is very small. Therefore, even the current maximum high resolved observation (1 milli arcsecond), it is not possible directly to resolve it spatially to examine its size and structure.

Radio luminosity is roughly linearly correlated with accretion rate for quasars. The factors that create the difference of the radio strength of AGN are thought to be that a radio-loud AGN have a radiatively inefficient accretion flow (RIAF) because of its low mass accretion rate (Trump & Charistopher, 2011).

1.3 AGN with Double-Peaked Emission Lines

The AGN with double-peaked emission lines are found in about 20 % of the radio-loud AGNs (Eracleous & Halpern, 1994, 2003) and in about 4 % of SDSS galaxies, which contain both radio-loud AGN and radio-quiet AGN (Strateva, 2003). The double-peaked AGNs are 1.6 times more likely to be radio sources and are predominantly (76 %) radio-quiet, with about 12 % of the objects classified as LINERs (Strateva, 2003). About 40–50 % of double-peaked $H\alpha$ profiles can be described by the relativistic, circular, Keplerian disk model of Chen, Halpern, & Filippenko (1989) and Chen & Halpern (1989). The schematic view of double-peaked $H\alpha$ from the accretion

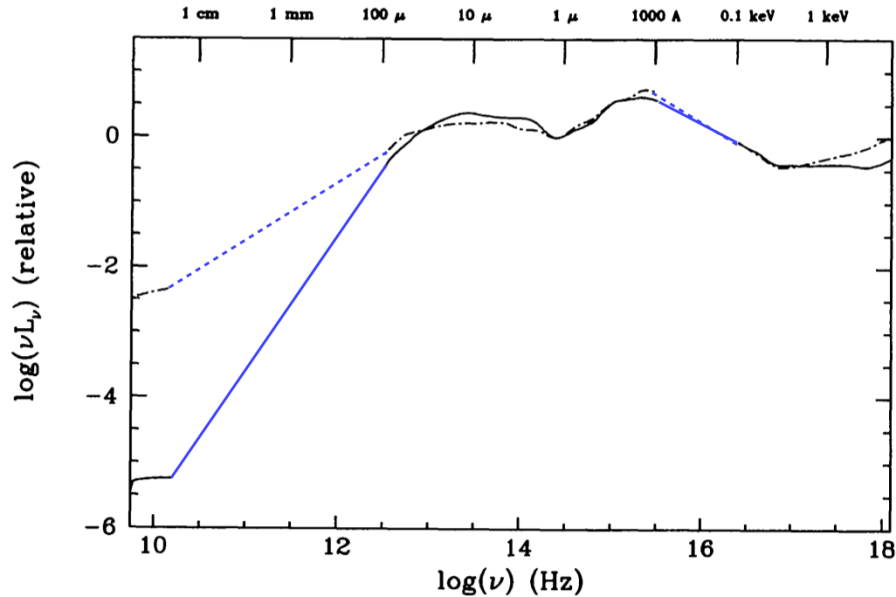


Figure 1.5: Mean SEDs for luminous radio loud (dashed line) and radio quiet (solid line) AGNs. The flux scale has been arbitrarily normalized at $1\mu\text{m}$. This figure is reproduced from Elvis et al. (1994). The blue lines are interpolations of lack of observation data.

disk is shown in Figure 1.6.

The fitting of Double-peaked profile by Keplerian disk model of Chen & Halpern (1989) can derive the disk radius that emits double-peaked emission, the inclination of accretion disk, and the velocity dispersion of emitting particles as parameters. However, there are some issues in the disk model of Chen & Halpern (1989). The disk model of Chen & Halpern (1989) very well reproduced the spectral line profile of Arp 102B at 1988, however the line profile of Arp 102B shows a time variability and it is insufficient to reproduce of the double-peaked profile at anytime. Their model is not able to reproduce the spectral shape when the red-side intensity is higher than blue-side intensity in particularly (Schimoia et al., 2012). To fit the line profiles at different periods, one should change the disk parameters such as the inclination or the emissivity power-law index (Popović et al., 2014). This is unrealistic. The main problem of Chen & Halpern (1989) model was not able to reproduce the non-axisymmetric components. To obtain an adequate fit, different disk models, for example, the elliptical accretion disk model (Eracleous et al., 1995), the spiral arm model (Gilvert et al., 1999), the saturated spiral model (Schimoia et al., 2012), and the hot spot model (Lewis, Eracleous, & Storchi-Bergmann, 2010), have been suggested.

Because the line luminosity is higher than powered by local viscous dissipation (Chen & Halpern, 1989), an external light source is necessary. Furthermore the light source should be extended vertically, because it must irradiate the outer portion of disk. The most probable candidate of such an extended light source is RIAF. Rees et al. (1982) proposed that the formation process of RIAF as follows: if the accretion rate into the central black hole is below the critical

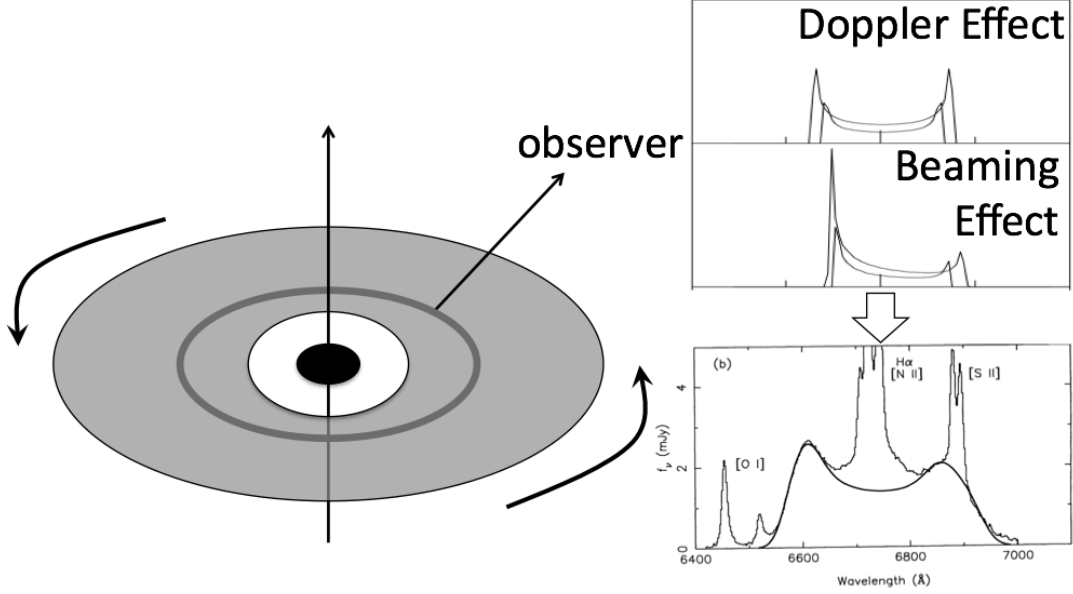


Figure 1.6: The profile of the double peaked line is caused by the interplay of mainly Doppler shift and relativistic beaming. The gravitational redshifting effect also causes a change of profile, however in the case of Balmer lines, this effect causes little change of profile. The two profiles in right top graph are emissions from inner and outer annuli respectively. The double-peaked profile in right bottom graph is combined spectrum between inner and outer annuli. This figure are reproduced from Fabian et al. (2006) and Chen & Halpern (1989).

rate (e.g. $0.01 M_{\odot} \text{ yr}^{-1}$ Trump & Charistopher, 2011), the accreting gas can no longer cool efficiently, so that the accretion flow will inflate vertically from a cool, dense thin disk into a much hotter, optically thin torus. Nagao et al. (2002) shows the difference of the inner structure between the single-peaked AGN and double-peaked AGN (see Figure 1.7).

The double-peaked emission lines afford us some information of inner region of accretion disk of AGN. The variability of the double-peaked line profiles can lead to understanding of the dynamical structure in these accretion disks and of the physical mechanisms that cause the profile variability. Frank, King, & Raine (2002) presented the relevant time scales of accretion disk as follows:

$$\begin{aligned}
 \text{light-crossing time} & : \tau_{lc} \sim r/c \approx 6M_8\xi_3 \text{ days} \\
 \text{dynamical time} & : \tau_{dyn} \sim (r^3/GM_{\bullet})^{1/2} \approx 6M_8\xi_3^{3/2} \text{ months} \\
 \text{thermal time} & : \tau_{th} \sim \tau_{dyn}/\alpha \approx 5(\alpha/0.1)^{-1}M_8\xi_3^{3/2} \text{ years} \\
 \text{sound-crossing time} & : \tau_s \sim r/c_s \approx 70M_8\xi_3T_5^{-1/2} \text{ years,}
 \end{aligned}$$

where M_8 is the black hole mass in units of $10^8 M_{\odot}$, ξ_3 is the radial distance in the disk in units of $10^3 GM_{\bullet}/c^2$, T_5 is the temperature in units of 10^5 K, and α is the viscosity parameter of Shakura & Sunyaev (1973).

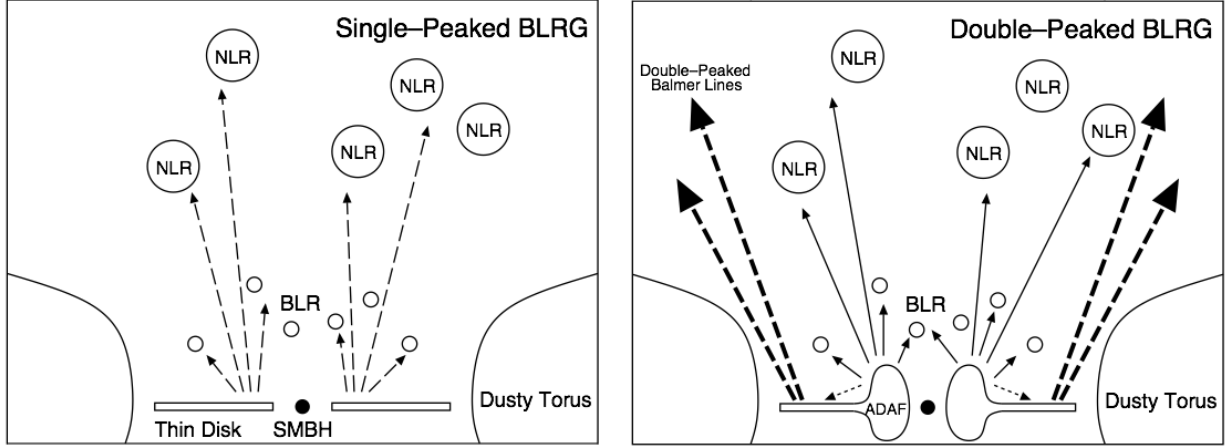


Figure 1.7: Difference of the nuclear region in BLRGs between single-peaked and double-peaked AGNs. In the single-peaked AGN (Left), because of no irradiance source for an outer part of standard disk, it does not radiate ionizing photons and permitted lines effectively. In the double-peaked AGN (Right), the inner region of the standard thin disk is replaced by a geometry thick structure (i.e. RIAF). The RIAF radiates a relatively hard continuum. A part of this hard continuum emission irradiates the outer thin disk (dotted arrows), from which the double-peaked Balmer lines arise (dashed thick arrows) (Nagao et al., 2002).

Significant changes in the line profiles occur on the order of the dynamical time, or longer as seen in long-term monitoring of some brighter double-peaked emitters, such as Arp 102B, 3C 390.3, and 3C 332 (e.g. Newman et al., 1997; Zheng, Veilleux, & Grandi, 1991; Sergeev, Pronik, & Sergeeva, 2000). For example, Sergeev, Pronik, & Sergeeva (2000) derived the typical rotation timescale (~ 1000 days) of accretion disk of Arp 102B from the line profile variability for 4 years. Figure 1.8 is the light curve of flux ratio at four segments of the double-peaked $H\alpha$ line profile. They found that the ratio of fluxes at different segments of the $H\alpha$ varied sinusoidally. This periodicity indicates the typical rotation timescale of accretion disk is ~ 1000 days, furthermore, this timescale suggests a very large mass of the central black hole of about $3.5 \times 10^8 M_{\odot}$.

As a short-timescale variability, Schimoia et al. (2012) discovered the variations with a timescale of ~ 7 days in NGC 1097, and Gezari, Halpern, & Eracleous (2007) also discovered the variability with a timescale of ~ 10 days in Arp 102B. The short timescale variability in NGC 1097 is interpreted as due to reverberation of the variability of the ionizing source luminosity. Stella (1990) calculated the change of double-peaked line profile by reverberation of the variability of the ionizing source luminosity. Figure 1.9 shows the response of the line profile from a relativistic accretion disk to flux variations in the central source calculated by Stella (1990). The profiles show a faster response in the line wings, after which the changes gradually move towards the center as the propagation to outer radius. If propagation of response in the double-peaked profile found, it is possible to derive the mass of central black holes and the size of the extended ionizing central source such as a RIAF.

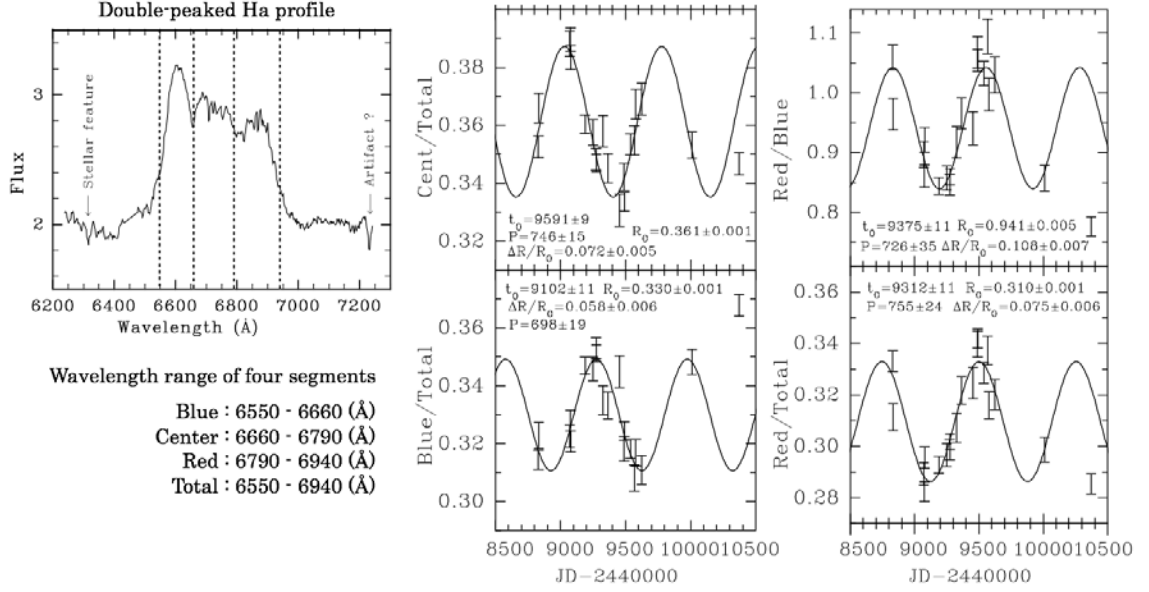


Figure 1.8: Light curve of ratios of fluxes at four segments of the double-peaked H α line profile of Arp 102B (Sergeev, Pronik, & Sergeeva, 2000). The left panel is the double-peaked H α profile observed and presents wavelength regions of four segments. The center and right panels are the light curves of Red/Blue, Red/Total, Center/Total, and Blue/Total. The solid line is a fit to a sinusoidal function: $R = \Delta R \sin[2\pi(t - t_0)/P] + R_0$. The fitted parameters are shown in each panel.

Eracleous & Halpern (1993) searched for rapid variability (1hr to 2days) suggested by Stella (1990), however they found no line profile variability on a time scale of a few days or less at the time. A possible reason of non-detection is insufficient observation period, because their observation periods are only 4 days.

Schimoia et al. (2015) have monitored the NGC 1097 nucleus in X-ray and UV continuum and H α flux and profile in optical spectrum for ~ 6 months, from 2012 August to 2013 February. They detected short-timescale variability of $\lesssim 5$ days. This is the shortest timescale variability ever seen in the double-peaked profile of this object. However, they could get only an upper limit on the shortest variation timescale, more frequent monitoring (within 5 days) is necessary. In order to detect such a variation, it is necessary to continuously monitor observations over several months with a short interval of within a few days.

As introduced in this chapter, the monitoring of time variations in AGNs is an effective way to investigate the structure and kinematics inside of the spatially unresolved AGNs. For example, the reverberation mapping (e.g. Peterson, 1993) can measure the distance between the central black hole of AGN and the BLR by observing time lags between variabilities in the continuum radiation from the inner accretion disk and the emission lines from the BLR.

Focusing on such a monitoring observation, especially a high-frequency monitoring with a short interval of a day over more than a month to close a more smaller region inside targets,

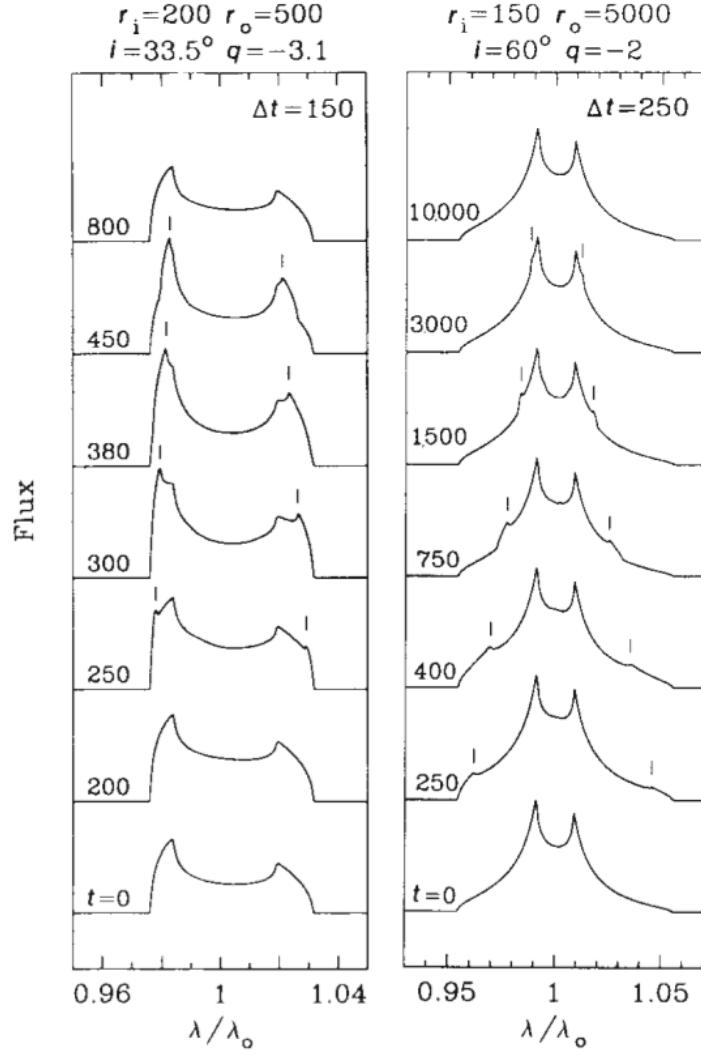


Figure 1.9: Response of the line profile from a relativistic accretion disk to flux variations in the central source produced by Stella (1990). The left and right panels are the model of H α profile of Arp 102B and the H β profile of 3C 390.3. The disk parameters are used of Chen, Halpern, & Filippenko (1989) and Chen & Halpern (1989), respectively. The profile variability first occur at the line wings, the variability propagation to at the center of line.

we newly developed a visible imager and spectrograph, namely Nayoro Optical Camera and Spectrograph (NaCS), for the 1.6-m Pirka telescope at the Nayoro Observatory, Faculty of Science, the Hokkaido University at Nayoro in Hokkaido. This instrument has a $2k \times 1k$ fully-depleted thick back-illuminated Hamamatsu CCD, which has quite a high quantum efficiency ($\geq 80\%$) over optical wavelength. In addition, it is designed to enable to switch the observation modes quickly between the imaging (to measure intensities) and spectroscopic modes (to obtain spectral line profiles), improving the observing efficiency. The combination of this high efficient instrument and the Pirka telescope, which is intensively focusing its telescope time on monitoring observations, enables us to do high-frequency monitoring observations efficiently.

Our main targets are nearby AGNs with a magnitude brighter than $r' = 15$ mag. S/N (signal-to-noise ratio) = 100 is required in order to observe a variability of 10 % of the AGN luminosity with an accuracy of 1 %. To resolve the broad-line profiles ($\sim 1500 \text{ km s}^{-1}$), a low spectral resolution ($R \sim 200$ @ 650 nm) is enough, therefore, we set the spectral resolution of the instrument at $R \sim 300$ (at 650 nm) to achieve $S/N = 100$ for an AGN with $r' = 15$ mag with a exposure time of about an half hour. In order to observe the $H\alpha$ and $H\beta$ emission lines and the continuum around these lines simultaneously, the spectral coverage of 450 to 730 nm is required.

In Chapter 2, we present the design, construction, integration, and performance of this newly developed instrument, NaCS. In Chapter 3, we present a brief introduction of our target, a double-peaked line AGN, Arp 102B, and we describe our imaging and spectroscopic monitoring observations of this target over a month with a short interval of a day, and then the data reduction to extract spectra of this target. In Chapter 4, we present our observed results and describe our analysis to parameterize the variability in the observed α line profile. In Chapter 5, we describe the accretion models to reproduce the double-peak line in the spectrum of this AGN and modeling of reverberation effects from accretion disk as a response of the line profile to flux variations in central source. In Chapter 6, we discuss whether we detect the reverberation effect from accretion disk in our observed rapid variability and other possible origins to produce this rapid variability. In Chapter 7, we present our conclusions.

Chapter 2

Development of Nayoro Optical Camera and Spectrograph (NaCS)

As introduced in the previous chapter, we newly developed a visible imager and spectrograph, namely Nayoro Optical Camera and Spectrograph (NaCS), for the 1.6-m Pirka telescope (see Figure 2.1) at the Nayoro Observatory, Faculty of Science, the Hokkaido University at Nayoro in Hokkaido, for monitoring observations, especially a high-frequency monitoring with a short interval of a day over more than a month to close a more smaller region inside a target such a AGN.

We note that this instrument have been also used for several astronomical observations such as light-curve measurements of asteroids and search of pre-main-sequence stars and brown dwarfs by slit-less spectroscopy as a major facility instrument of the Pirka telescope after the first light observation on November 2011. In this chapter, we present the design, construction, integration, and performance of this instrument, following the descriptions in Nakao et al. (2014).

2.1 Design Overview

Figure 2.2 shows the pictures of NaCS, and Table 2.1 summarizes the major specifications of the NaCS. We selected a similar optical design to WFGS2 (Uehara et al., 2004) of the University of Hawaii 2.2-m telescope (UH88), because this optics has a wide field of view (~ 11.5 arcmin), and a wide spectral coverage (380–970 nm), and the imaging mode and spectroscopy mode can be switched quickly.

Figure 2.3 shows the optical layout of NaCS. This optics consists of nine lenses and all of the lenses are treated with anti-reflection coating. The light from the Pirka telescope ($f/12$) is collimated by the collimator lenses and focused onto the CCD by the camera lenses after passing through a filter and/or a grism. The focal length of collimator is 285 mm and the focal length of camera is 185 mm, thus the f-number of NaCS is 6.6. The field of view of NaCS is 8.4×4.5 arcmin and the pixel scale is 0.247 arcsec pixel $^{-1}$. The spare lenses, filters and grism of WFGS2 are used.

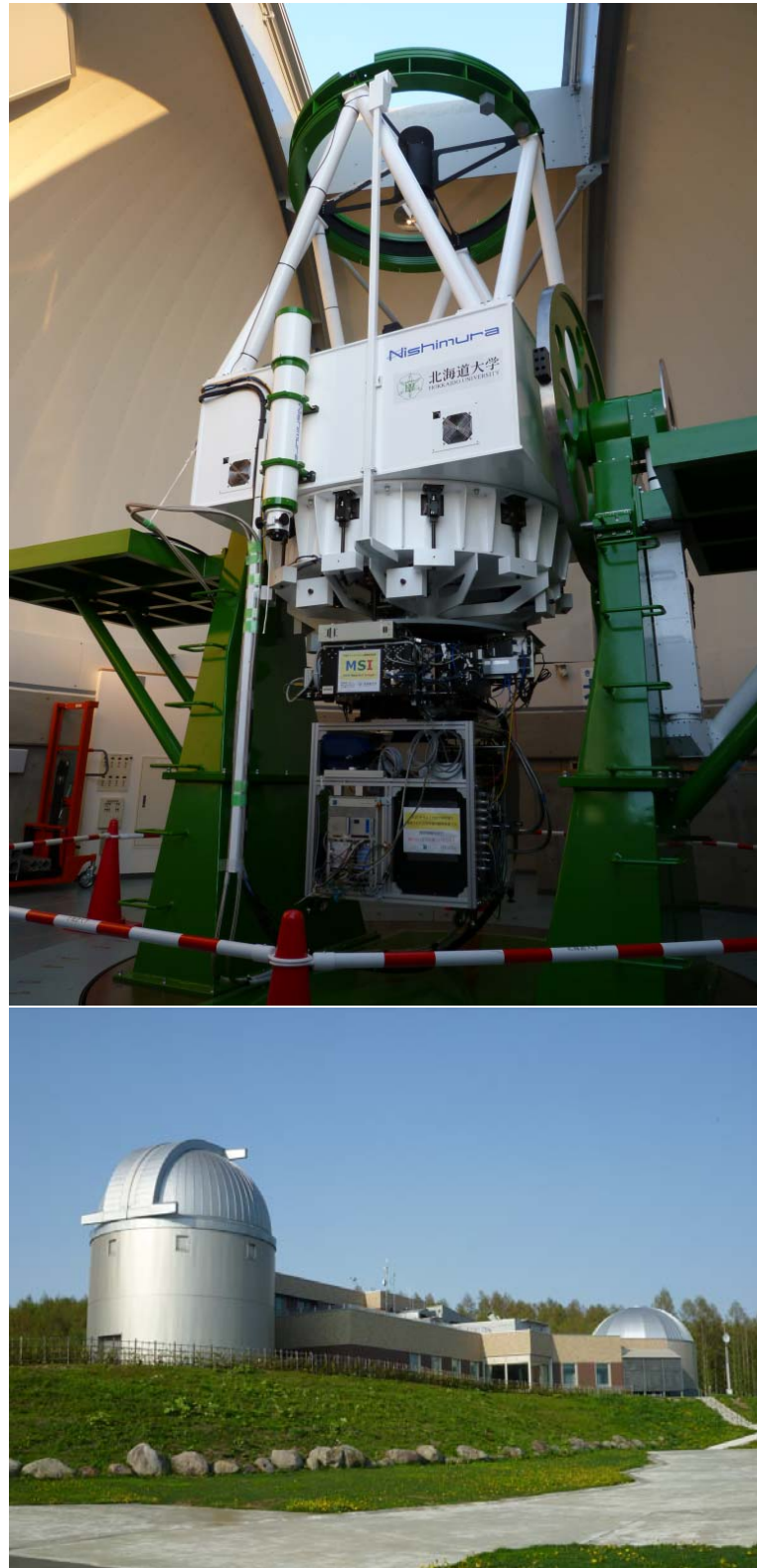


Figure 2.1: (Top) 1.6-m Pirka telescope, (Bottom) Nayoro Observatory, Faculty of Science, Hokkaido University at Nayoro in Hokkaido.

Table 2.1: Major specifications of NaCS

Spectral coverage	380–970 nm (Imaging), 435–820 nm (Spectroscopy)
Field of view	8.4×4.5 arcmin
Pixel scale	0.247 arcsec pixel ⁻¹
CCD	Hamamatsu 2k×1k
Array format	2048×1104 pixel (pixel size = 15×15 μm) + 2048×48 pixel (pixel size < 15×15 μm)
Broad-band filters	SDSS g', r', i', z' , Johnson B, V
Order-sort filter	GG435
Replica grism	
Groove spacing	300 gr mm ⁻¹
Prism angle	22.25°
Prism material	BK7
Blaze angle	17.5°
Blaze wavelength	520 nm
Undeviated wavelength	650 nm
Spectral Resolution	$R \sim 300$ @ 656 nm (slit width = 2 arcsec)
Size	560 mm $\times$ 560 mm $\times$ 1130 mm (without the interface box) 720 mm $\times$ 720 mm $\times$ 1200 mm (with the interface box)
Weight	75 kg (without the interface box) 100 kg (with the interface box)

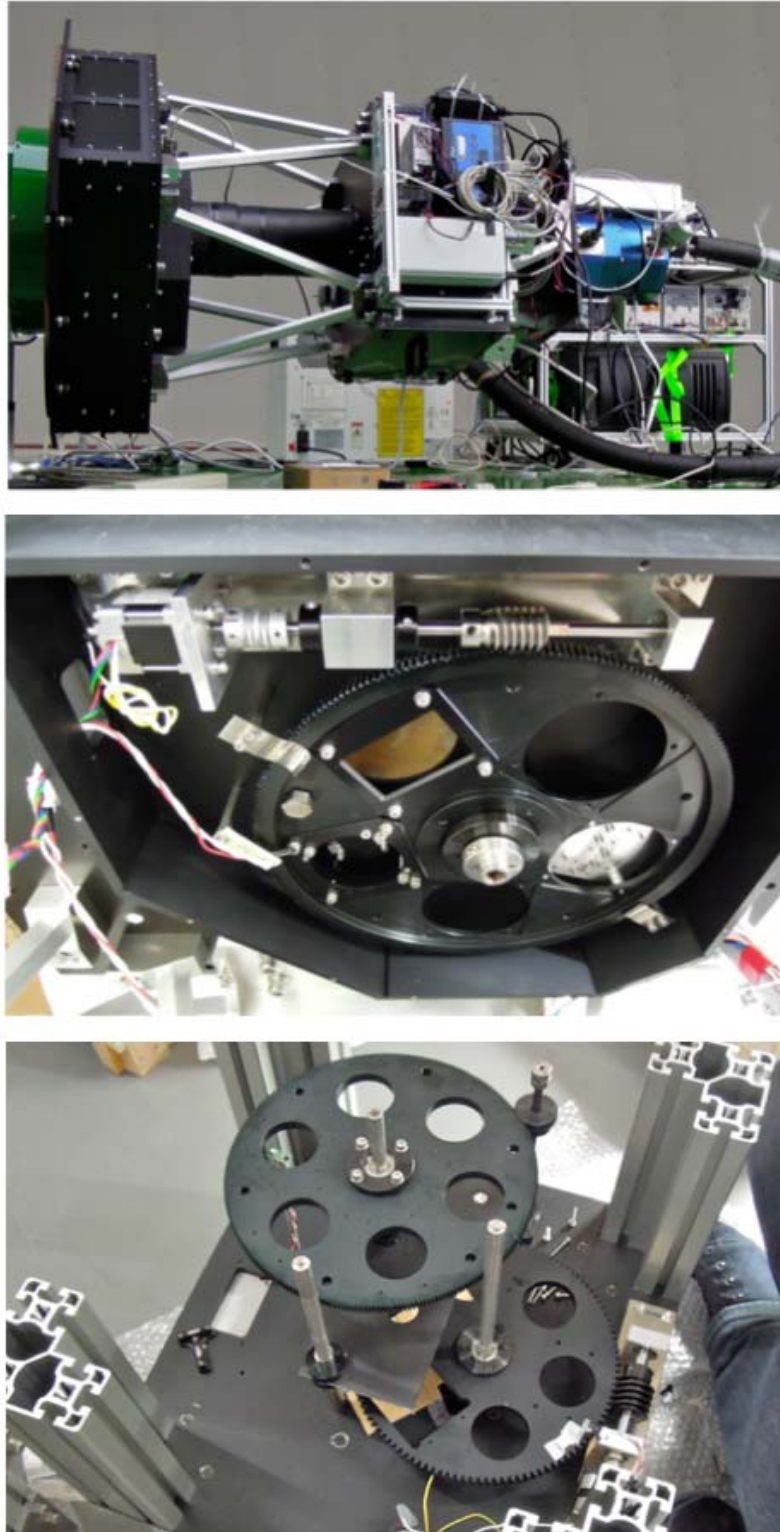


Figure 2.2: (top) NaCS mounted on the Nasmyth focus of the Pirka telescope. (middle) Slit wheel. (bottom) Filter and grism wheels.

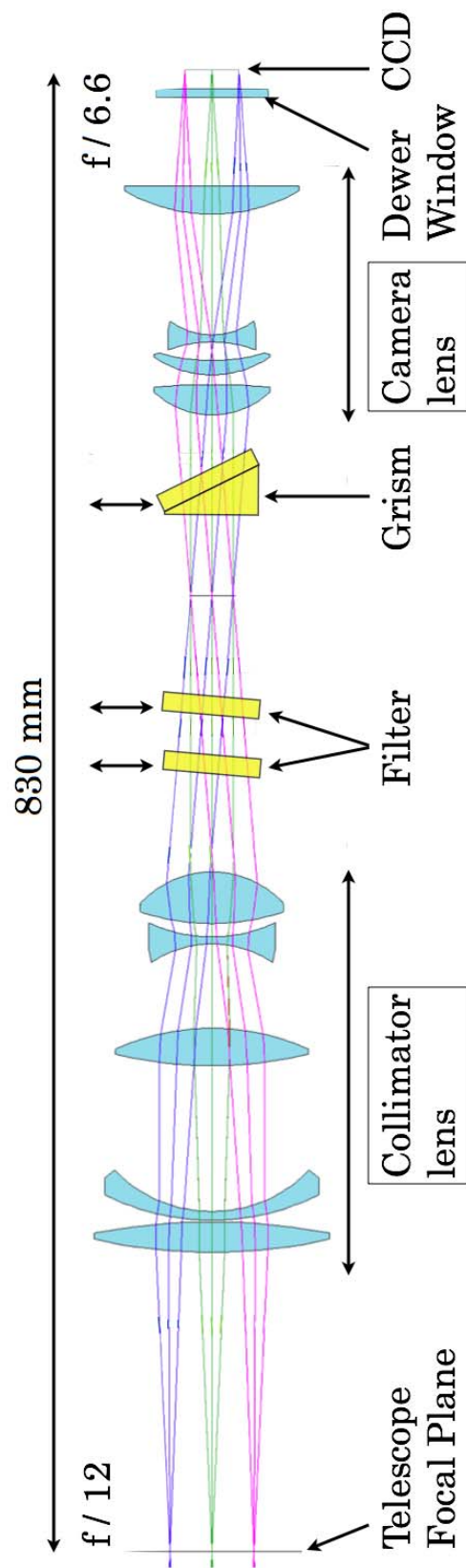


Figure 2.3: Optical layout of NaCS.

However, we changed the distance between the collimator lens and the camera lens from 187.8 mm of the original design to 257.8 mm in order to put a baffle at the pupil in the instrument and to improve the accessibility of the grism wheel. The Pirka telescope is also designed as an infrared telescope and the secondary mirror of the telescope works as the optical stop at the infrared observing mode. Therefore, there are no baffle around the secondary mirror when the telescope is set for the infrared observation and it is necessary to put a baffle at the pupil inside the instrument to avoid the stray lights from behind the secondary mirror. However, in the original design, the pupil was located inside the grism, therefore, we needed to expand that distance. As the result of this expansion, the rms radius of spot diagram got worse slightly (for example, from 0.04 to 0.10 arcsec at g' -band at the center of CCD), however, there are no influence to the imaging because it is still smaller than the typical seeing size (~ 1.8 arcsec FWHM) at the Naylor Observatory. Also, although the original specification of the parfocal band is 380–770 nm, we optimized the telescope focus individually per band to obtain a better imaging performance. Figure 2.4 shows the spot diagrams of imaging mode. The spots are within 1/3 of the typical seeing size. Figure 2.5 shows the spot diagrams of spectroscopic mode. At the longer wavelength (> 656.3 nm), these spots are within 1/3 of the typical seeing size. However, at the 435 nm, the spot size along the dispersion direction is comparable to the typical slit width of 2 arcsec, and then the spectral resolution got worse from 20 Å to 28 Å at this wavelength.

Figure 2.6 shows the mechanical layout of NaCS. NaCS is mounted on the Nasmyth instrument rotator. To reduce the weight, we selected a truss structure with a wheel box as similar to WFGS2. The whole size is $560 \times 560 \times 1130$ mm and the weight is about 75 kg. There are two filter wheels and one grism wheel, but one filter wheel is not installed yet. The filter wheel can be equipped with six filters and the grism wheel can be equipped with three grisms. These wheels are driven by stepper motors. The SDSS (g', r', i', z') filters and Johnson (B, V) filters can be used as the broad-band filters. Five of them and a order-sort filter can be installed simultaneously. To avoid ghost images produced by reflections on the CCD surface, the filter is tilted by five degrees.

A slit wheel is located at the focal plane of the Pirka telescope. NaCS has a slit with three slit widths of 2, 3, and 4 arcsec (0.19, 0.28, and 0.38 mm) with a length of 84, 94, and 88 arcsec. We can select one of them depending on the seeing conditions. Figure 2.7 shows a picture and the layout of this slit.

We used a low-dispersion replica grism with 300 gr mm^{-1} (prism angle = 22.25° , prism material = BK7, blaze angle = 17.5° , blaze wavelength = 520 nm, undeviated wavelength = 650 nm) and an order-sort filter (GG435) that cuts the wavelength less than 410 nm to prevent the contamination of the second-order light. The spectral coverage is 435–820 nm.

The CCD is installed in the dewar and it is cooled to -100°C by the CryoTiger refrigerator with PT-13 gas (Brooks Automation) and the temperature is regulated at -100°C with an error of 0.5°C p-v by the temperature controller E5GN-R101T-FLK (Omron). A shutter, CS65 (Vincent Associates) is located in the front of the dewar. The amount of time that the shutter is open is 29 ms.

There are an interface box between NaCS and the Nasmyth rotator flange. It will have a wavelength calibration unit and an auto-guider unit.

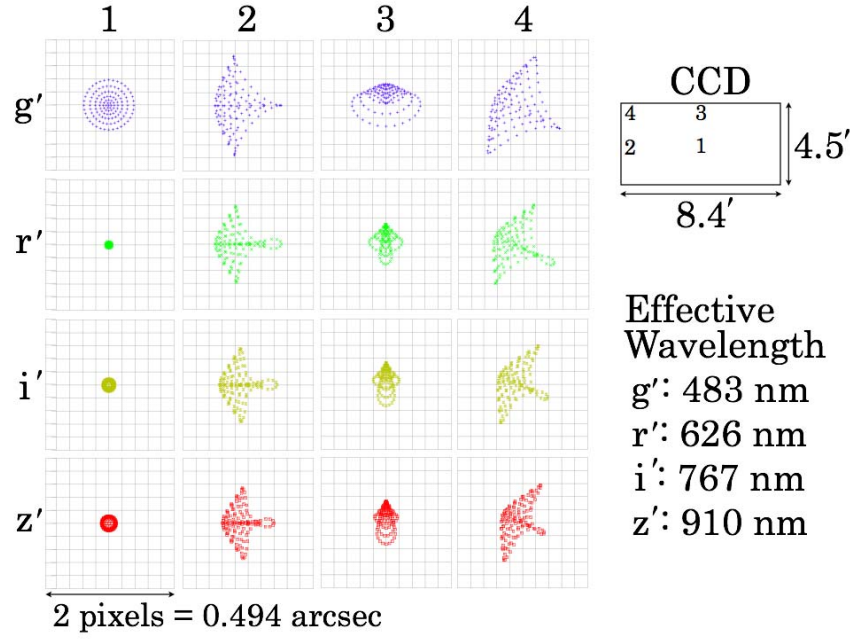


Figure 2.4: Spot diagram at the imaging mode. There are the four positions (1: center, 2: left, 3: top center, 4: upper left). A square shown on each spot diagram is 2×2 pixel ($30 \times 30 \mu\text{m}$).

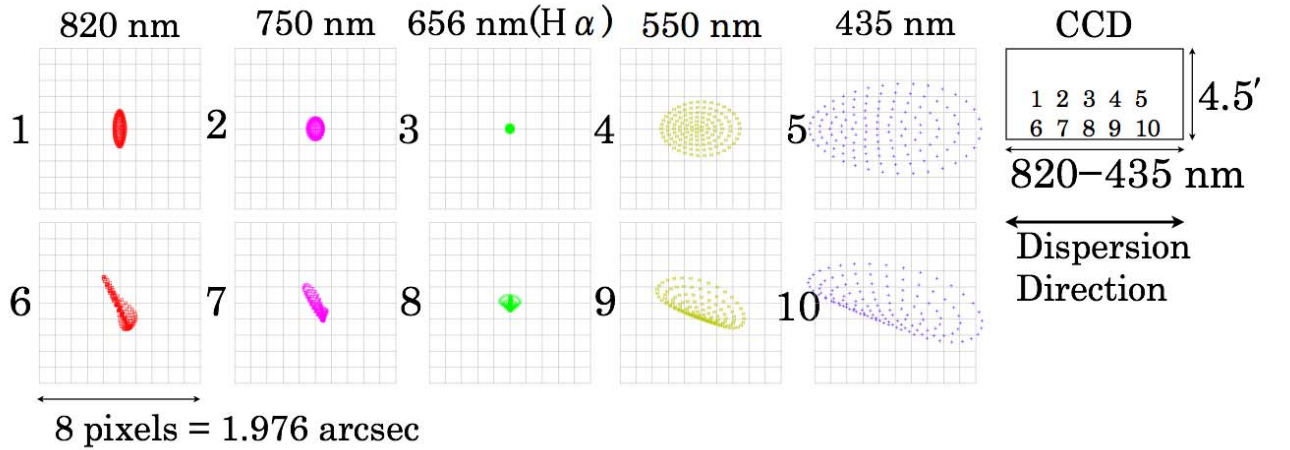


Figure 2.5: Spot diagram at the spectroscopic mode for objects at the center (1-5) and bottom center positions (6-10) of the CCD. A square shown on each spot diagram is 8×8 pixel ($120 \times 120 \mu\text{m}$).

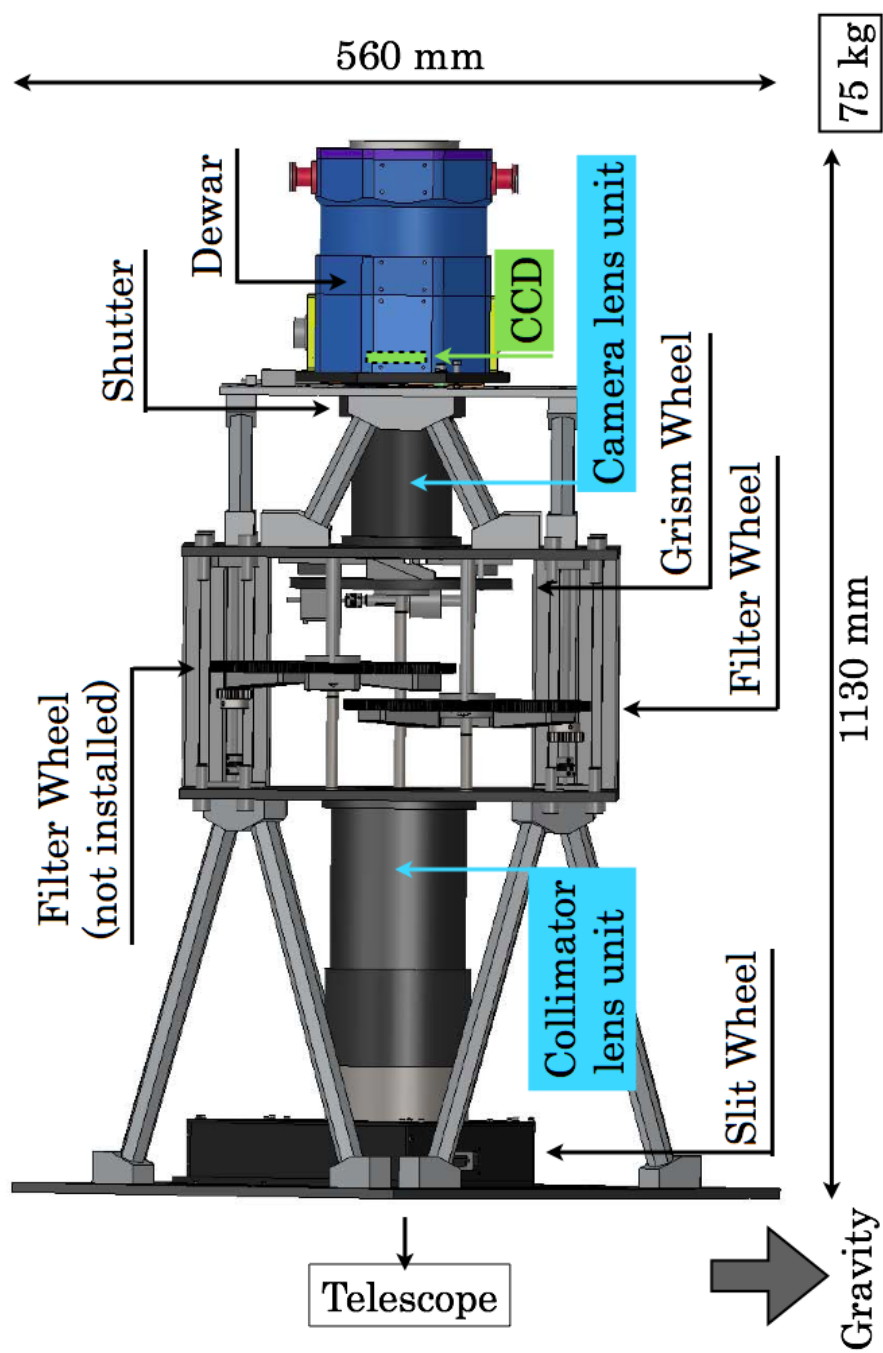


Figure 2.6: Mechanical layout of NaCS.

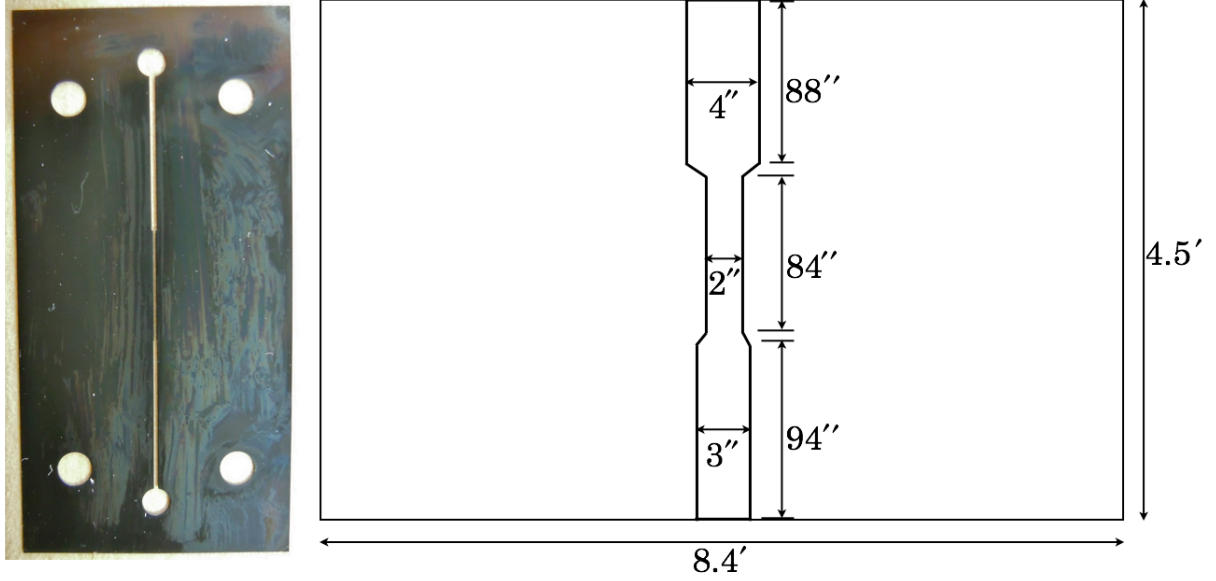


Figure 2.7: (left) Picture of slit. The slit is made on a stainless-steel plate with a thickness of 0.05 mm. (right) The layout of the slit.

2.2 Detector and Readout System

2.2.1 CCD

Figure 2.8 shows the quantum efficiencies of Hamamatsu (2k×1k CCD), SITe (ST002A), MIT (CCID-20), and e2v (CCD42-80) CCDs (Miyazaki et al., 2002). We selected a fully-depleted back-illuminated Hamamatsu 2k×1k CCD as a detector, because it has the highest quantum efficiency ($\geq 80\%$) over optical wavelength (440–920 nm) than any other CCDs here. Figure 2.9 shows a picture and the array format of the Hamamatsu 2k×1k CCD. This CCD is the same type as the 2k×4k CCD of Hyper Suprime-Cam (Kamata et al., 2010). The active area of the 2k×1k CCD is a quarter of the 2k×4k CCD, although the chip size is same. Because the Hamamatsu CCD has four readout channels, it can be readout faster than a CCD with a single readout channel. Each channel of the 2k×1k CCD has 1104×512 active pixels with $15 \mu\text{m}$ -square pixel and 48×512 active pixels with smaller size. These smaller pixels are not used. We usually use the 2×2 pixel binning readout with an effective pixel scale of $0.494 \text{ arcsec pixel}^{-1}$, because a stellar image is over-sampled under the typical seeing condition ($\sim 1.8 \text{ arcsec}$) at the Naylor Observatory.

2.2.2 Kiso Array Controller

The Kiso Array Controller (KAC; Sako et al., 2012) is the readout system developed in the Kiso observatory, the University of Tokyo for KWFC (Sako et al., 2012). This system was originally designed for the MIT CCD and SITe CCD, and has 16 readout channels. We adapted KAC

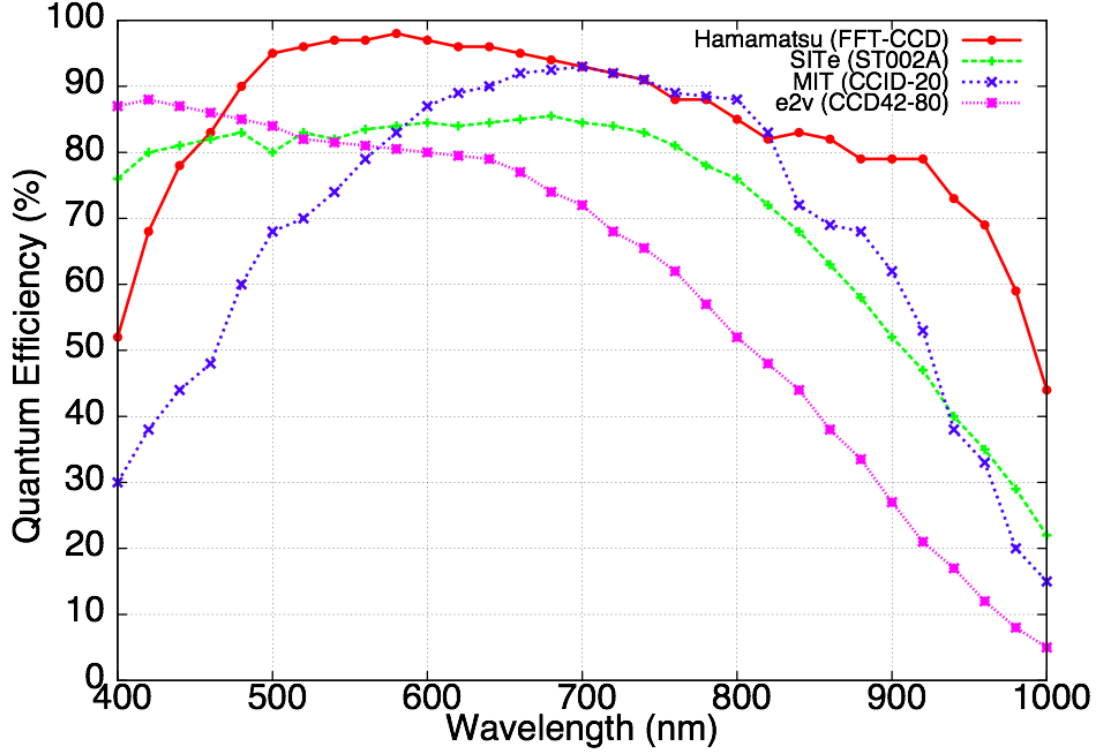


Figure 2.8: Quantum efficiencies of Hamamatsu, SiTe, MIT, and e2v CCD. Hamamatsu CCD has high quantum efficiency ($\geq \sim 80\%$) over optical wavelength (440–920 nm).

to the Hamamatsu CCD for NaCS. The main modification is the analog circuitry because the polarity of the Hamamatsu CCD is opposite to those of the original system in order to transmit not an electric charge but a hole. A picture of main board is shown in Figure 2.10(left). We reduced the readout channels from 16 to 4 for NaCS and then the size of the main board for NaCS is reduced to a quarter of that for KWFC. The readout modes for 2×2 and 4×4 pixel binning are available. The multi-sampling readout reduces the readout noise from $5.2 e^-$ to 3.8

Table 2.2: Measured readout noise and readout time

Number of sampling	Readout noise (e^{-1})	Readout time (s)		
		1×1	2×2	4×4
		binning	binning	binning
1	5.2	5.3	3.7	2.9
2	4.0	8.7	5.4	3.8
4	3.8	12	7.1	4.7

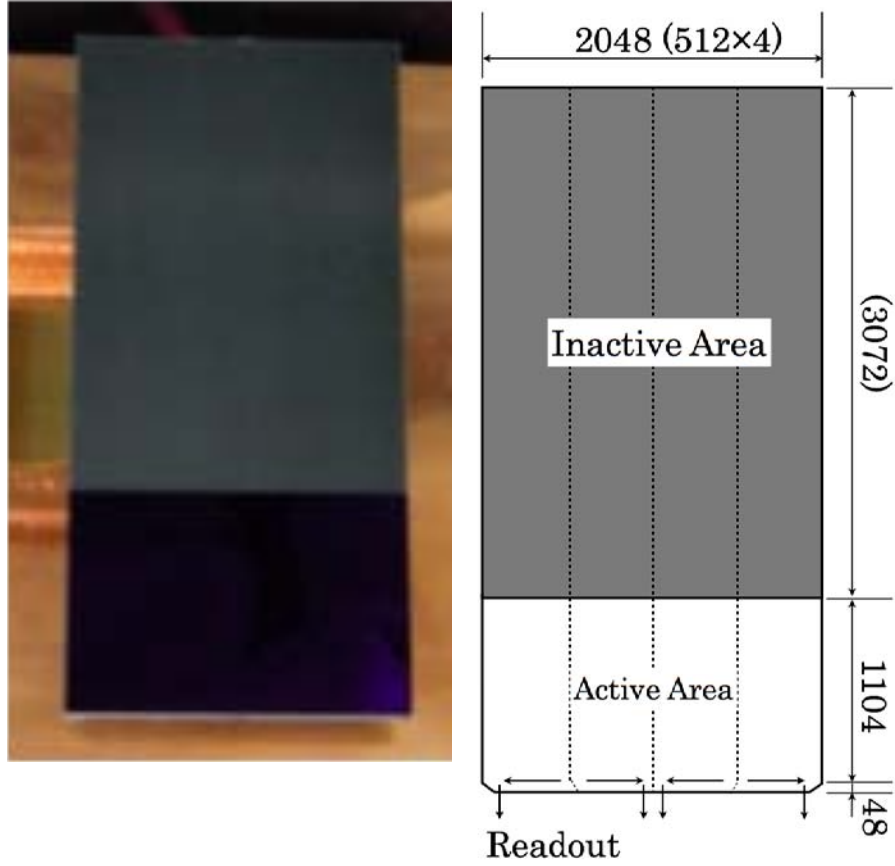


Figure 2.9: (left) Picture of Hamamatsu 2k $\times$ 1k CCD. (right) The array format of Hamamatsu 2k $\times$ 1k CCD. The first 48 $\times$ 2048 active pixels are smaller than 15 μ m-square pixels, so we don't use there pixels for observation.

e^- by sampling each pixel multiply. As the result, the limiting magnitude becomes deeper by about 0.14 mag at $H\beta$ in the spectroscopic observation (300 s exposure with a 3 arcsec width slit) of a point-like source under the dark night condition. The readout noise and readout time with several readout setting is shown in Table 2.2. As shown in Table 2.3, the gain and bias level

Table 2.3: Measured gain and bias level of each channel of detector

	Channel 1	Channel 2	Channel 3	Channel 4	Average
Gain (ADU e^{-1})	1.88	1.83	1.85	1.86	1.86
Bias level (ADU)	5717.8	5788.8	5699.7	5842.6	5762.2

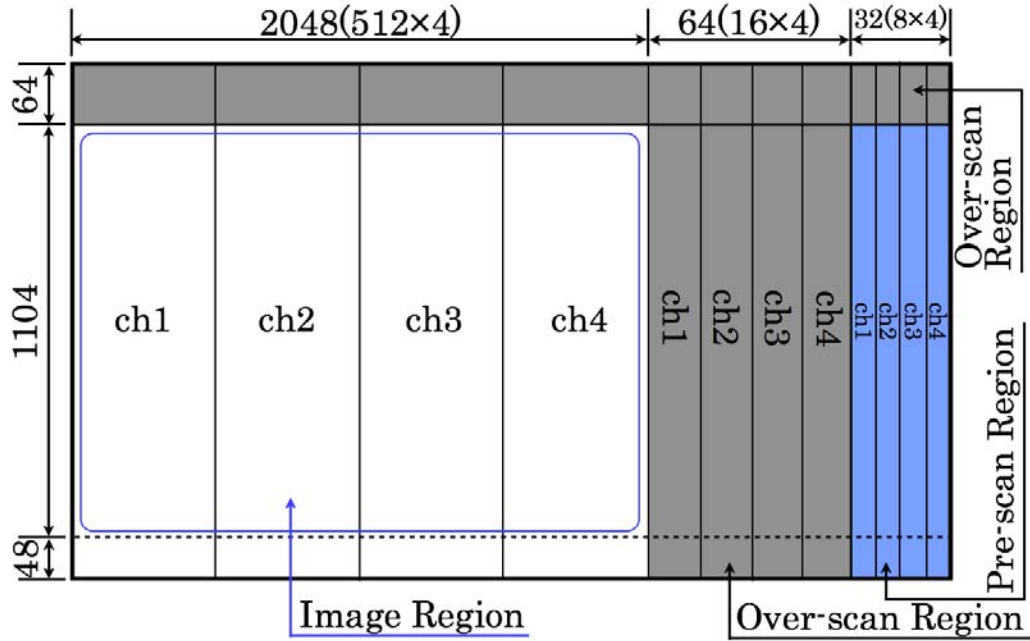
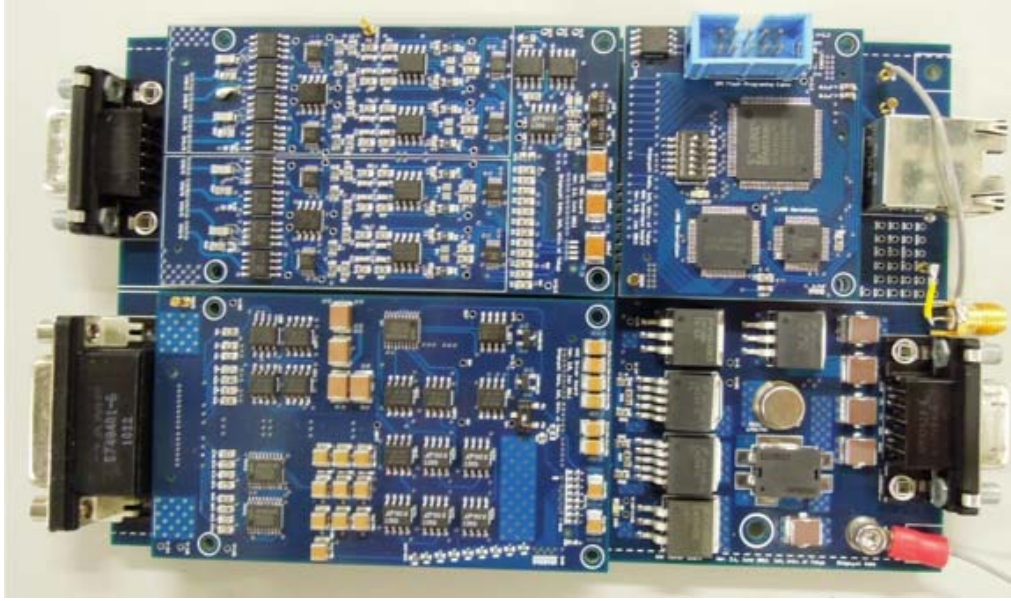


Figure 2.10: (top) Photograph of the KAC main-board. The outer dimensions of the main-board is 160×100 mm. (bottom) The layout of a raw data image of NaCS. the bottom 48 lines are not used, because the pixel size is smaller than $15 \mu\text{m}$.

are slightly different between the channels, because there are a slight difference of resistance of analog circuitry between the channels. The average of gains and bias levels over the four channels is $1.86 \text{ e}^- \text{ ADU}^{-1}$ and 5762.2 ADU . The bias level varies by 8 ADU p-v, depending

on the CCD and ambient temperatures, the exposure time, and the signal level of image area. Figure 2.10(right) shows the layout of a raw data image of NaCS. The pre- and over-scan regions are gathered together into one side of the image by readout software so that it becomes easy for us to do the quick look and data reduction easy.

Non-Linearity

The initial CCD readout electronics has a defect causing a non-linearity at below about 2000 e⁻. We determined the following equations to correct the non-linearity. The equations for the non-linearity correction of each channel are given by

$$I_{\text{cor}}(\text{ch1}) = I \times \left\{ \frac{235.52}{(I + 75.8329)^{1.20442}} \times \left(\frac{5.59025}{I + 2.8968} + 1 \right) + 1 \right\} \quad (2.1)$$

$$I_{\text{cor}}(\text{ch2}) = I \times \left\{ \frac{194.387}{(I + 73.7874)^{1.15859}} \times \left(\frac{8.90631}{I + 6.18976} + 1 \right) + 1 \right\} \quad (2.2)$$

$$I_{\text{cor}}(\text{ch3}) = I \times \left\{ \left(\frac{51.9}{(I + 73)^{1.07263}} - 42.5 \right) \times \left(\frac{15}{I + 22} + 1 \right) + 1 \right\} \quad (2.3)$$

$$I_{\text{cor}}(\text{ch4}) = I \times \left\{ \left(\frac{40.6}{(I + 57.6)^{1.01268}} - 31 \right) \times \left(\frac{0.87}{I + 1.2} + 1 \right) + 1 \right\}, \quad (2.4)$$

where I_{cor} is signal counts after correction, I is signal counts in ADU before correction. The non-linearity after correction for channel 1, 2, 3, and 4 is 1.62, 1.46, 10.1, and 1.07 % (rms), respectively. For the data obtained before 2014 this correction is required before flat-field correction. For the data obtained after the beginning of 2014, no non-linearity correction is required because the readout circuit was replaced with an improved version.

2.3 Performances and Examples of Observations

2.3.1 Broad-band Imaging

Table 2.4 summarizes the expected and measured overall efficiencies (including the transmittance of atmosphere at airmass = 1) and estimates of limiting magnitude at $S/N = 10$ with various exposure times t . The measured overall efficiency was lower than the expected one. It might be due to dirt of mirrors at this observation and the further investigation is needed.

The flatness of sky background after flat fielding is +1.6/−0.7, +0.6/−0.5, +2.3/−2.6, +1.5/−0.8, and +0.9/−0.5 % at the B , V , g' , r' , and i' -band respectively, although the flatness of about ±1 % or less is generally expected.

By limiting the field into 4×4 arcmin at the center of CCD, a better flatness of within ±1 % is achieved at the V , r' , and i' -bands, although the flatness is still +1.4/−0.6 % and ±1.6 % at the B and g' -bands. Moreover, the flat-field depends the rotator angle. For example, it changes by +6.6/−6.1 % at the corner of field of view at the r' -band. These reasons are under investigation.

Table 2.4: Limiting magnitude ($S/N = 10$) for broad-band imaging

	B	V	g'	r'	i'	z'
Effective wavelength ^a (nm)	438	545	483	626	767	910
Effective bandwidth ^b (nm)	94	87	138	138	154	137
Sky brightness (mag arcsec ⁻²)	21.3	20.5	21.4	21.1	19.9	19.1
Transmittance of atmosphere	0.697	0.754	0.715	0.815	0.862	0.881
Expected overall efficiency	0.190	0.316	0.335	0.397	0.284	0.252
Measured overall efficiency	0.124	0.277	0.260	0.373	0.250	0.195
Limiting magnitude ^c						
$t = 5$ s	18.1	18.2	18.8	18.9	18.0	17.5
$t = 60$ s	20.0	19.9	20.5	20.5	19.6	19.0
$t = 300$ s	20.9	20.7	21.4	21.4	20.5	19.9

^a From Bessell, Castelli, & Plez (1998) (B , V) and Fukugita et al. (1996) (g' , r' , i' , z').

^b From Fiorucci & Munari (2003) (B , V) and Fukugita et al. (1996) (g' , r' , i' , z').

^c 4 arcsec diameter aperture and 2 arcsec seeing are assumed. Magnitudes are presented in the Vega system for B and V bands and the AB system for g' , r' , i' and z' bands.



Figure 2.11: Pseudo-color image of three color of M88 (g' : blue, r' : green, i' : red). The angular size of M88 is 7×4 arcsec.

Figure 2.11 shows an example of broad-band imaging of M88. M88 is a nearby spiral galaxy with an angular size of about 7×4 arcmin. The total exposure time is $300 \text{ s} \times 3$ at each band. This figure demonstrates that NaCS has an enough large field of view for the relative photometry of galaxy with comparison stars around a galaxy.

2.3.2 Spectroscopy

Slit Spectroscopy

The estimates of limiting magnitude at $S/N = 10$ with a 3 arcsec width slit is shown Figure 2.12 (left). The measured throughput for the slit spectroscopy with a 3 arcsec width slit is shown Figure 2.12 (right). The loss of 25 % in throughput by the slit is not included. Transmittance of atmosphere at airmass = 1 is included. The measured throughput was lower than the expected one. It is probably due to the poor photometric condition because the transmittance of atmosphere at this observation was about 80 % of the typical value at the B and V -bands (58.1 % and 62.8 % respectively). Figure 2.13 shows the observed sky emission at the Nayoro Observatory at the dark night. This sky emission was used for the estimate of the limiting magnitude.

We have carried out the monitoring observation of AGN, Arp 102B. Arp 102B is a sub-luminous, radio-loud LINER at $z = 0.024$ that has double-peaked Balmer emission lines (Stauffer, Schild, & Keel, 1983) and is $r' = 15.0$ mag. The observed spectrum of Arp 102B with a 3 arcsec width slit in August 19, 2013 is shown in the Figure 2.14. The total exposure time is $300 \text{ s} \times 15$. The spectral resolution is about $R \sim 200 \text{ \AA}$ at $H\alpha$. The S/N ratio of continuum at 656 nm achieved is 160, although this is lower than the calculated one ($S/N = 260$) because of the moon influence.

Slit-less Spectroscopy

We also carried out search of pre-main-sequence stars. The pre-main-sequence stars have a strong $H\alpha$ lines in there spectrum. Figure 2.15 is r' -band image and slit-less spectroscopic image of the bright-rimmed cloud BRC 9 (Sugitani, Fukui, & Ogura, 1991) around IRAS 02326+6110 in the IC1805 region. The total exposure time is $900 \text{ s} \times 2$. For a star with $r' = 14.8$, $S/N = 20$ at 650 nm was achieved. This is lower than calculated one ($S/N = 80$) because of the poor photometric condition. Unfortunately, no emission line stars were found in this field.

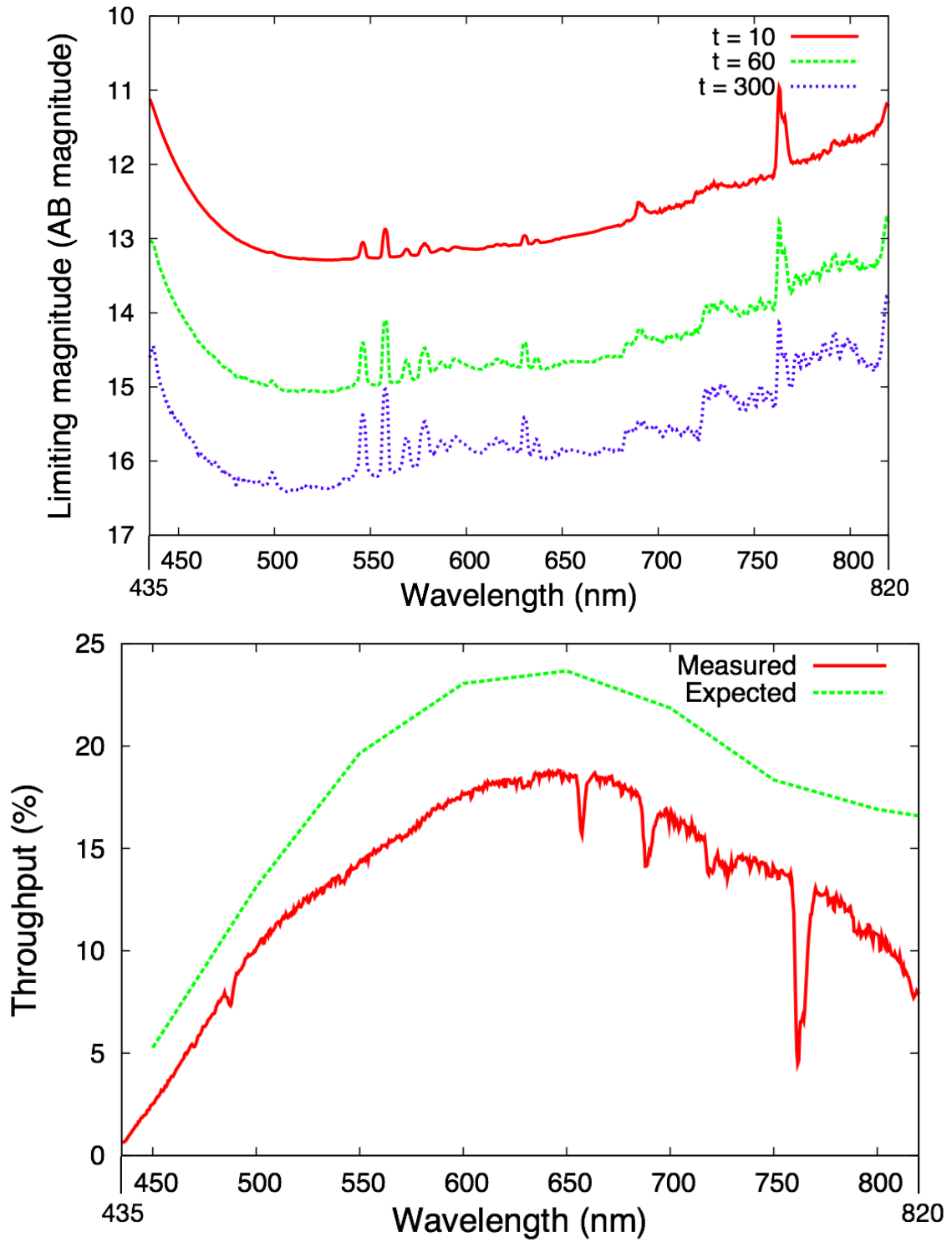


Figure 2.12: (top) Limiting magnitude ($S/N = 10$) for slit spectroscopy (slit width = 3 arcsec). (bottom) The observed throughput of slit spectroscopy.

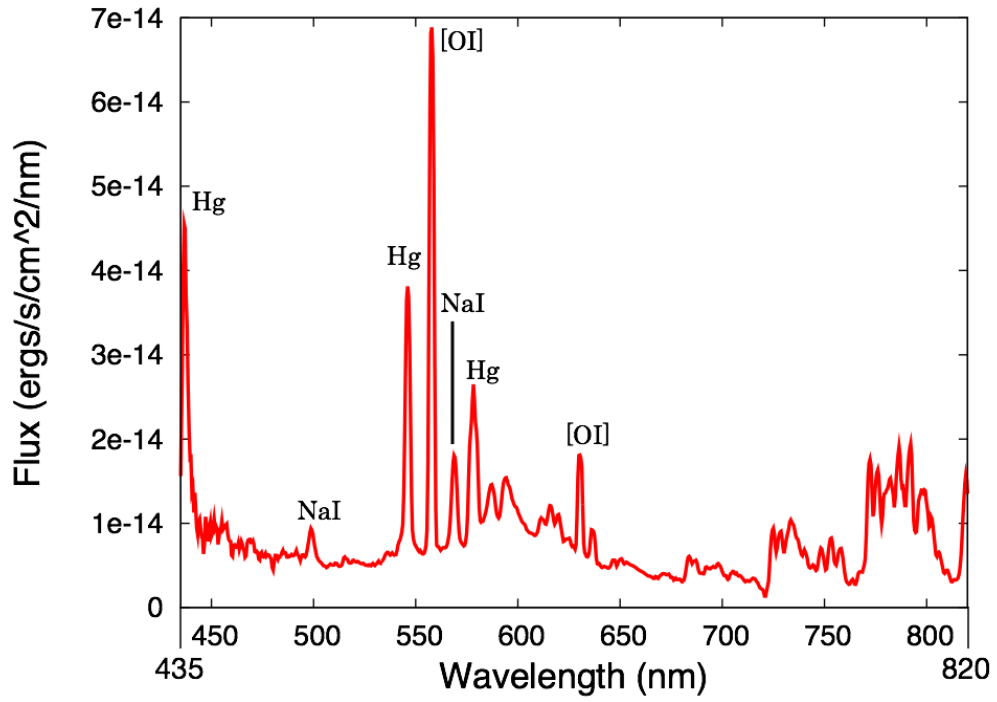


Figure 2.13: Observed spectrum of sky emission with 3 arcsec width slit

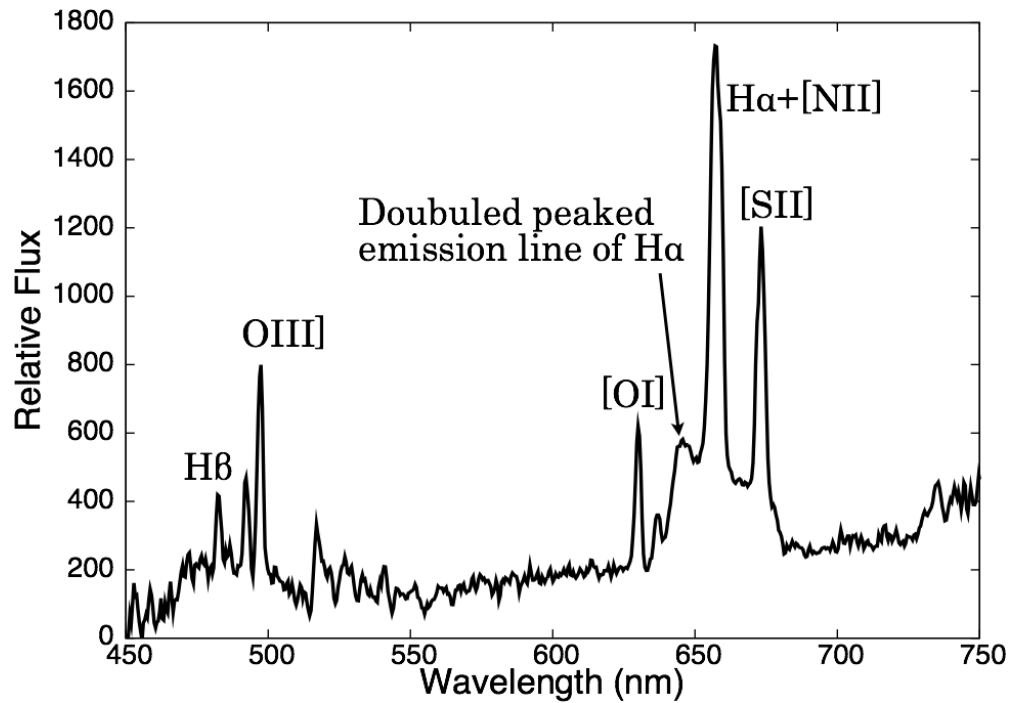


Figure 2.14: Observed spectrum of Arp 102B with 3 arcsec width slit. The flux of [O I] emission line was normalized to 1000.

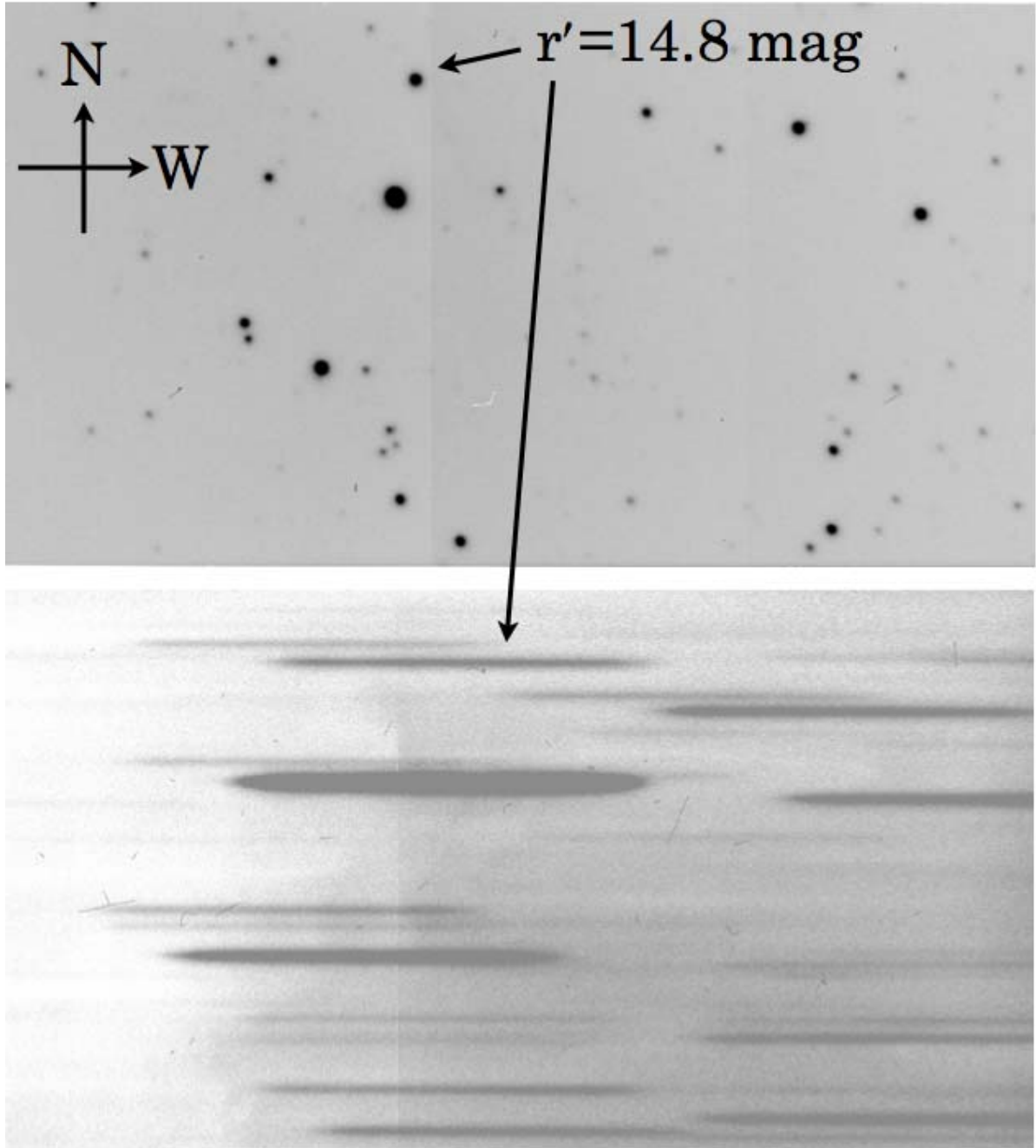


Figure 2.15: r' -band image (top) and slit-less spectroscopic image (bottom) of the bright-rimmed cloud (BRC 9).

Chapter 3

Observations and Data Reduction

3.1 Target

We chose Arp 102B (left in Figure 3.1) as our target to test the reverberation from an accretion disk around central black hole by spectroscopic monitoring of double-peaked $H\alpha$ line profile. This object is a sub-luminous, radio-loud LINER 1.8 galaxy at $z = 0.024$, which has double-peaked Balmer emission lines (Stauffer, Schild, & Keel, 1983). It is the first active galaxy where the double-peaked broad line profiles have been modeled with emission from an accretion disk around a central black hole (Chen, Halpern, & Filippenko, 1989; Chen & Halpern, 1989). After that time, this galaxy has been widely accepted as a prototype of the AGN with broad lines emitted from the disk (Chen & Halpern, 1989; Sulentic et al., 1990; Eracleous & Halpern, 1994; Eracleous et al., 1997) and several monitoring campaigns have been done intensively to investigate the structure and kinematics of the BLR and/or accretion disk and to measure of the central mass (Miller & Peterson, 1990; Eracleous & Halpern, 1993; Newman et al., 1997; Sergeev, Pronik, & Sergeev, 2000; Gezari, Halpern, & Eracleous, 2007; Shapovalova et al., 2013; Popović et al., 2014). Eracleous & Halpern (1993) mentioned that Arp 102B is one of the best candidates for finding the reverberation from accretion disk because it has broad emission lines known to be originated in accretion disk.

3.2 Observations

3.2.1 Slit-spectroscopy

To observe the short-timescale variability of the double-peaked line profile of Arp 102B, we carried out two monitoring observation runs over a month in 2013. The first run is from 2013 May 16 to June 10, and the second run is from 2013 July 18 to August 31. In addition, a short observation run was also carried out from 2014 February 25 to 28.

All observations were done with the Nayoro Camera and Spectrograph (NaCS; Nakao et al., 2014, or see Chapter 2) mounted on the Nasmyth focus of the 1.6-m Pirka telescope of the Hokkaido University at Nayoro in Hokkaido, Japan. A low-dispersion replica grism with 300 gr mm^{-1} and an order-sort filter (GG435) were used for slit-spectroscopy. The slit was aligned



Figure 3.1: Picture of Arp 102B (left of image) with the companion galaxy Arp 102A (top-middle of image) taken on the WIYN 3.5m telescope. The size of field is about $4.4' \times 9.2'$. North is the right, East is up. [Credit: C. F. Claver, N. A. Sharp (NOAO)/WIYN/NOAO/NSF. Copyright WIYN Consortium, Inc., all rights reserved.]

along the North-South direction and the slit width was set to $3''.0$. The typical wavelength range was from $4400 \text{ \AA}$ to $8000 \text{ \AA}$, and the typical spectral resolution was $\sim 1000 \text{ \AA}$. The slit width was wider than the typical FWHM of the seeing (about $2''$ or more), therefore, the actual spectral resolution varied daily between 18 and $26 \text{ \AA}$, depending on the seeing condition.

We took several exposures with a exposure time of 300 or 600 s, switching the position of target on the slit between two positions separated by $25''$ along the slit. The log of slit-spectroscopy is given in Table 3.1.

A nearby spectrophotometric standard star, PG 1708+602 (Massey et al., 1988; Massey & Gronwall, 1990), was observed at the same night for flux calibration. Also, spectra of domeflat lamp and comparison lamps (Neon and Hydrogen) were taken each night for flat-fielding and wavelength calibration.

3.2.2 Broad-band Imaging

We also carried out broad-band imaging observations of Arp 102B to measure the continuum flux variability during the spectroscopic observation runs. The imaging observations were also done with NaCS usually before or after the spectroscopic observation of Arp 102B. The Johnson B and V filters were used. The log of imaging observations is given in Table 3.3.

For calibration of the instrumental response and the atmospheric effect, we used three comparison stars in the same field as Arp 102B for relative photometry. Figure 3.2 is V -band image of Arp 102B and these three comparison stars. The coordinates and B - and V -band magnitudes of these comparison stars are given in Table 3.2. These magnitude are taken from the GSC2.3

Table 3.1: Log of slit-spectroscopy

UT date	MJD	Exposure Time (s)
2013 May 24	56436.583	300×5
2013 May 25	56437.574	300×9
2013 May 28	56440.589	300×8
2013 May 30	56442.628	300×13
2013 May 31	56443.656	300×8
2013 Jun 1	56444.564	300×6
2013 Jun 4	56447.541	300×8
2013 Jun 6	56449.520	300×7
2013 Jun 7	56450.514	300×7
2013 Jun 8	56451.530	300×1
2013 Jun 9	56452.646	300×16
2013 Jun 10	56453.628	300×21
2013 Jul 19	56492.576	600×5
2013 Aug 6	56510.571	300×10
2013 Aug 7	56511.617	600×5
2013 Aug 13	56517.574	600×4
2013 Aug 19	56523.590	600×8
2013 Aug 20	56524.485	600×4
2013 Aug 23	56527.633	600×1
2013 Aug 26	56530.465	600×4
2013 Aug 27	56531.448	600×1
2013 Aug 28	56532.523	600×4
2014 Feb 25	56713.75	300×9
2014 Feb 26	56714.758	300×11
2014 Feb 28	56716.709	300×8

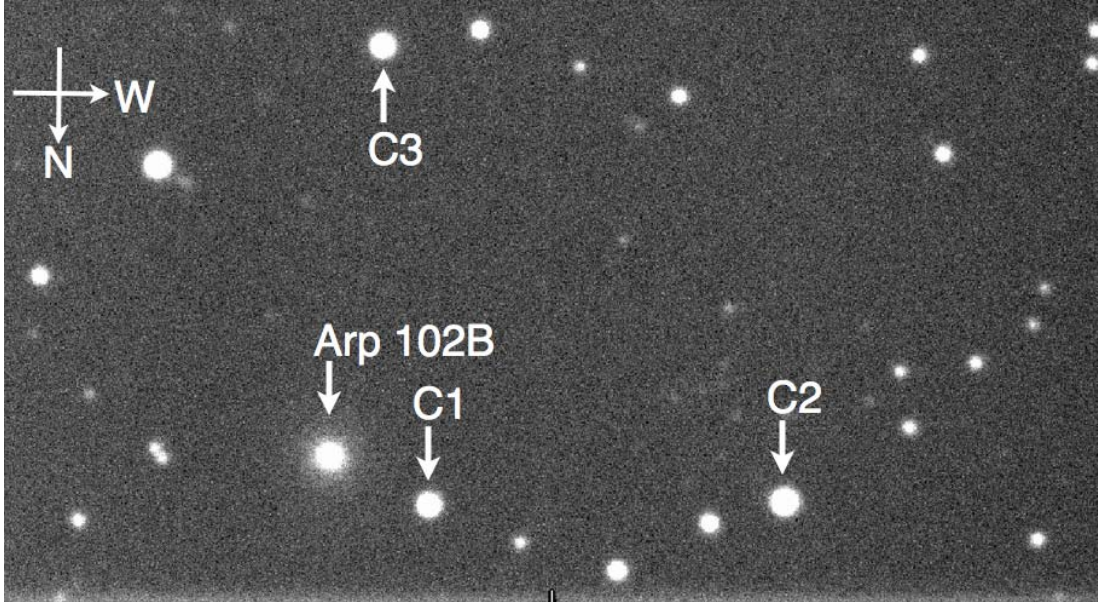


Figure 3.2: V-band image of Arp 102B and comparison stars, C1, C2 and C3, which are N5Y0000540, N5Y0000539 and N5Y0000544, respectively. The exposure time is 60 s. The S/N ratio of Arp 102B is ~ 150 .

Table 3.2: List of comparison stars

Object	RA(J2000)	DEC(J2000)	V (mag)	B (mag)
N5Y0000540	259.791085	+48.986681	14.34 ± 0.28	14.7
N5Y0000539	259.721947	+48.986485	13.71 ± 0.28	14.4
N5Y0000544	259.799937	+48.928180	14.10 ± 0.28	14.7

catalog and USNO-A2.0 catalog.

3.3 Data Reduction

The data reduction was carried out with the IRAF package¹. The image reduction process included bias and flat-field corrections and cosmic ray removal. For spectroscopic data, additional reduction process included wavelength calibration based on comparison lamps, sky spectrum subtraction, addition of the spectra for every night, and removal of telluric absorptions and flux calibration based on the observations of standard star.

¹IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 3.3: Log of imaging observations

UT date	B-band			V-band			UT date	B-band			V-band		
	Exposure Time (s)	Number of Frames		Exposure Time (s)	Number of Frames			Exposure Time (s)	Number of Frames		Exposure Time (s)	Number of Frames	
2013 May 17				360	6		2013 Aug 5				360	3	
2013 May 21	840	3		300	6		2013 Aug 6	1080	6		930	18	
2013 May 22	900						2013 Aug 7	750	5		220	6	
2013 May 24	900	5		360	6		2013 Aug 13	720	6		420	5	
2013 May 25	600	5		300	5		2013 Aug 19	1990	9		100	4	
2013 May 26	540	2		360	6		2013 Aug 20	1260	6		240	4	
2013 May 28	1800	2		1080	6		2013 Aug 21				540	5	
2013 May 30	1080	5		150	5		2013 Aug 22	780	4		180	6	
2013 May 31	720	6		150	5		2013 Aug 23	790	4		390	6	
2013 Jun 1	720	6		180	6		2013 Aug 24				300	5	
2013 Jun 6	720	6		150	5		2013 Aug 26	1230	10		450	10	
2013 Jun 7	900	6		180	6		2013 Aug 27	540	6		160	5	
2013 Jun 8	900	6		150	5		2013 Aug 28	1440	20		450	18	
2013 Jun 9	900	6		180	6		2014 Feb 4	870	3		360	6	
2013 Jun 10	900	6		180	6		2014 Feb 25	2700	12		1290	13	
2013 Jul 20		6		7320	109		2014 Feb 26	3630	13		1080	12	
2013 Jul 21	11100	27					2014 Feb 27	750	2		1260	6	
							2014 Feb 28	1560	7		360	6	

For the data obtained in 2013 the non-linearity correction was required before the flat-field correction, because of the non-linearity effect at the low intensity level under about 2000 e^- owing to a defect in the CCD readout electronics. The equations used for the non-linearity correction are given in Section 2.2.2. For the data obtained in 2014, no correction for non-linearity was required because of the replacement of the readout circuit with an improved version.

For imaging data, we performed the aperture photometry. The diameter of aperture was adjusted each frame so that it was twice of the FWHM size of image of Arp 102B. The typical size of aperture was $3''$ in diameter, which is about 1.5 times larger than the FWHM size of seeing measured from the comparison star image. To take account of every light from both AGN and host galaxy, we also performed the aperture correction by using the grow curve. For the comparison stars, we used a large aperture with a diameter of 6 times as the FWHM of seeing, and then no aperture correction was done.

The spectra were extracted using a window of $4''.94 \times 3''.0$. This extraction window was centered at the peak of the continuum emission, which coincides with the location of the unresolved source of the broad $H\alpha$ line.

To remove the host galaxy component from spectra, we used a spectrum of NGC 4339, which is chose as a stellar template for Arp 102B in Gezari, Halpern, & Eracleous (2007) and Shapovalova et al. (2013). The spectrum of NGC 4339 was taken with NaCS during our 2014 February observation run.

According to the calibration method as described in Sergeev, Pronik, & Sergeea (2000), we calibrated the scale of spectra using a narrow emission line on the assumption that the narrow emission lines are constant in flux. According to Sergeev, Pronik, & Sergeea (2000), the most appropriate narrow emission-line around the $H\alpha$ line is [O I] $\lambda 6300$, because this line is single and is little superposed on the broad $H\alpha$ emission line profile. Therefore, we assumed that the flux of the [O I] $\lambda 6300$ line remains constant during the interval covered by our observations, and then all spectra of Arp 102B were scaled to a constant flux value of $F([\text{O I}] \lambda 6300) = (1.76 \pm 0.18) \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ determined by Sergeev, Pronik, & Sergeea (2000). The [O I] $\lambda 6300$ line was fitted using a single Gaussian.

We smoothed the spectra with a Gaussian function so that the spectral resolution was scaled to $\sim 26 \text{ \AA}$ for all spectra. The S/N ratio of the final spectrum was > 70 in the continuum near $H\alpha$.

To remove the narrow lines and obtain only the broad profiles, we fitted all narrow lines with Gaussian functions. The narrow components are [O I] $\lambda 6300, 6364$, narrow $H\alpha$, [N II] $\lambda 6548, 6584$ and [S II] $\lambda 6717, 6731$ and we also assumed that there are a single broad $H\alpha$ line in the $H\alpha$ wavelength band. We assumed that the ratio of [O I] $\lambda 6300$ and [O I] $\lambda 6364$ is 3 (Sergeev, Pronik, & Sergeea, 2000), and made the same assumption for [N II] doublet: $F([\text{N II}] \lambda 6584) / F([\text{N II}] \lambda 6548) \sim 3$. To remove the single-broad and narrow $H\alpha$ lines and [N II] $\lambda 6548, 6584$ lines, we used three narrow and one broad Gaussian functions simultaneously. The fitting wavelength region of these lines are from 6485 to 6650 $\text{\AA}$. For removal of the [S II] doublet, we used two narrow Gaussian functions simultaneously and the fitting wavelength region are from 6655 to 6790 $\text{\AA}$. Figure 3.3 is an example of the best Gaussian fit of narrow lines subtraction. We note that the red peak of the double peaked $H\alpha$ line could be strongly affected by the narrow line removal procedure, because the narrow lines are right on top of the red peak.

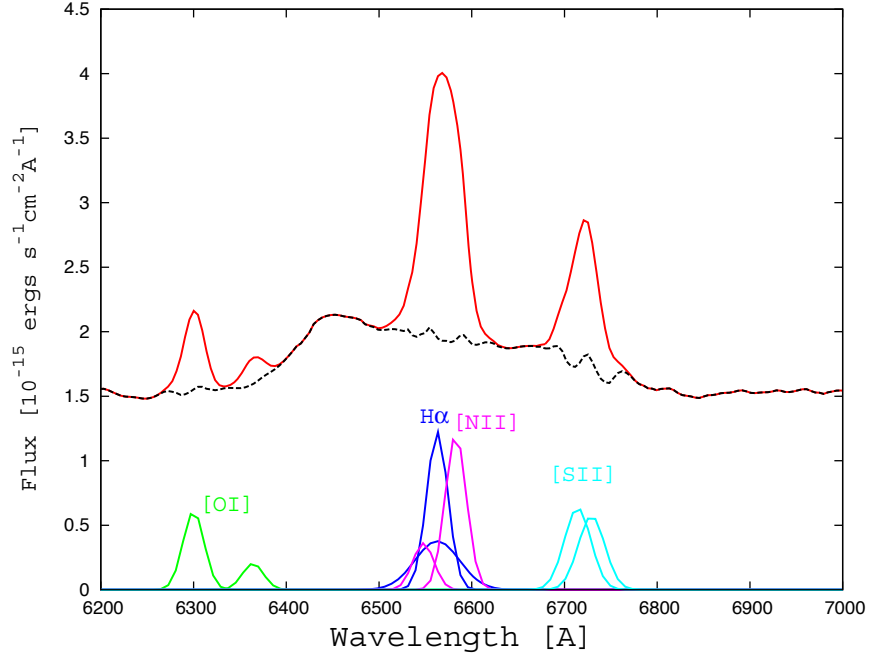


Figure 3.3: Example of the best Gaussian fitting of narrow-line subtraction. The spectrum is an averaged spectrum over our monitoring observation period. The green, blue, purple, and light blue lines are [O I], H α , [N II], and [S II] lines, respectively.

For the continuum subtraction, a linear continuum was constructed using windows of 50 and 60 Å width, located at 6205 and 6910 Å, respectively.

Chapter 4

Observational Results

4.1 Photometric data

The results of the aperture photometry are given in Table 4.1. Figure 4.1 shows the light curves in V and B bands. There are a variation of 10–20 % level in both bands, and the trend is roughly same in both bands. In 2014 February, the brightness becomes 1.5 times larger than that in 2013 August. It may imply the AGN continuum varies at this level. The amount of the variation agrees with the observed continuum variability measured by Shapovalova et al. (2013).

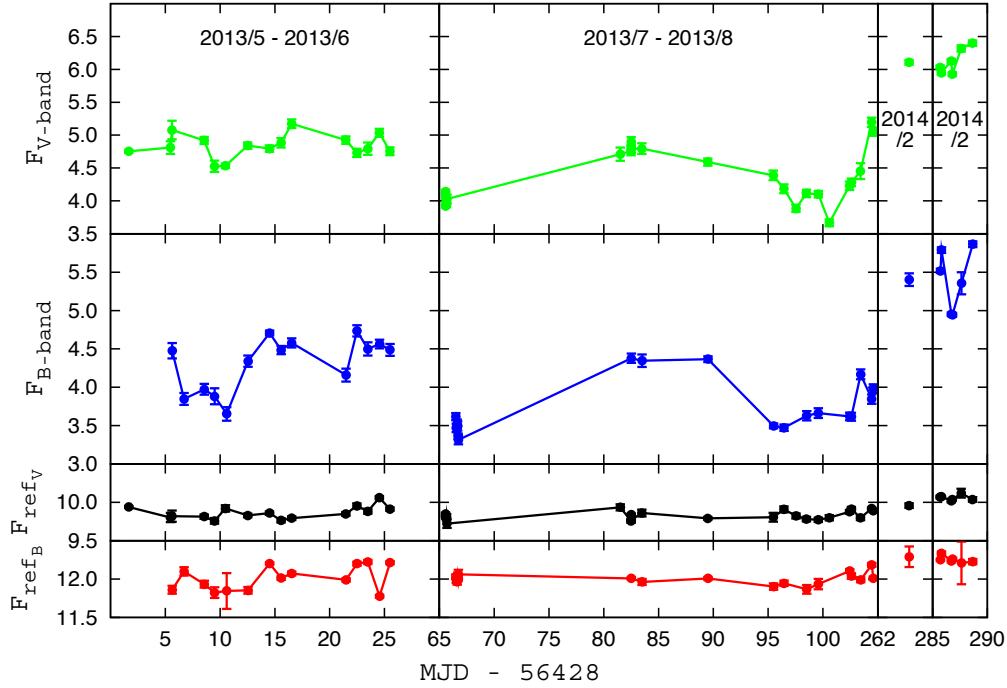


Figure 4.1: B and V -band light curves of Arp 102B and the comparison stars.

Table 4.1: Results of broad-band photometry of Arp 102B

UT date	<i>B</i> -band		<i>V</i> -band	
	MJD	Magnitude	MJD	Magnitude
2013 May 17			56429.662	14.49 ± 0.18
2013 May 21	56433.631	15.23 ± 0.02	56433.481	14.48 ± 0.19
2013 May 21			56433.613	14.42 ± 0.19
2013 May 22	56434.715	15.40 ± 0.02		
2013 May 24	56436.553	15.36 ± 0.02	56436.541	14.45 ± 0.18
2013 May 25	56437.497	15.39 ± 0.03	56437.489	14.54 ± 0.19
2013 May 26	56438.609	15.45 ± 0.03	56438.490	14.54 ± 0.18
2013 May 28	56440.541	15.27 ± 0.02	56440.519	14.47 ± 0.18
2013 May 30	56442.523	15.18 ± 0.01	56442.512	14.48 ± 0.18
2013 May 31	56443.571	15.23 ± 0.01	56443.562	14.46 ± 0.18
2013 Jun 1	56444.538	15.21 ± 0.01	56444.531	14.40 ± 0.18
2013 Jun 6	56449.494	15.31 ± 0.02	56449.484	14.45 ± 0.18
2013 Jun 7	56450.491	15.17 ± 0.02	56450.480	14.50 ± 0.18
2013 Jun 8	56451.490	15.23 ± 0.02	56451.482	14.48 ± 0.19
2013 Jun 9	56452.551	15.21 ± 0.01	56452.543	14.43 ± 0.18
2013 Jun 10	56453.510	15.23 ± 0.02	56453.502	14.49 ± 0.18
2013 Jul 20			56493.553	14.64 ± 0.18
			56493.570	14.66 ± 0.18
			56493.589	14.70 ± 0.18
			56493.609	14.70 ± 0.18
			56493.641	14.68 ± 0.18
			56493.652	14.69 ± 0.18
2013 Jul 21			56493.691	14.67 ± 0.18
	56494.504	15.46 ± 0.01		
	56494.537	15.51 ± 0.02		
	56494.627	15.49 ± 0.02		
	56494.665	15.50 ± 0.02		
	56494.710	15.54 ± 0.01		
	56494.735	15.56 ± 0.02		

Table 4.1: Continued.

UT date	<i>B</i> -band		<i>V</i> -band	
	MJD	Magnitude	MJD	Magnitude
2013 Aug 5			56509.507	14.50 ± 0.19
2013 Aug 6	56510.521	15.26 ± 0.02	56510.498	14.49 ± 0.18
			56510.503	14.46 ± 0.18
			56510.512	14.48 ± 0.18
2013 Aug 7	56511.493	15.26 ± 0.02	56511.484	14.48 ± 0.18
2013 Aug 13	56517.507	15.26 ± 0.01	56517.499	14.53 ± 0.18
2013 Aug 19	56523.501	15.50 ± 0.01	56523.464	14.58 ± 0.18
2013 Aug 20	56524.460	15.51 ± 0.01	56524.447	14.63 ± 0.18
2013 Aug 21			56525.535	14.71 ± 0.18
2013 Aug 22	56526.527	15.46 ± 0.02	56526.494	14.65 ± 0.18
2013 Aug 23	56527.586	15.45 ± 0.02	56527.577	14.65 ± 0.18
2013 Aug 24			56528.579	14.77 ± 0.18
2013 Aug 26	56530.444	15.46 ± 0.01	56530.436	14.62 ± 0.18
	56530.603	15.46 ± 0.02	56530.596	14.60 ± 0.18
2013 Aug 27	56531.440	15.31 ± 0.02	56531.434	14.56 ± 0.19
2013 Aug 28	56532.460	15.40 ± 0.02	56532.450	14.39 ± 0.18
	56532.599	15.36 ± 0.02	56532.594	14.43 ± 0.18
2014 Feb 4	56692.864	15.03 ± 0.02	56692.858	14.22 ± 0.18
2014 Feb 25	56713.706	15.01 ± 0.01	56713.683	14.23 ± 0.18
	56713.805	14.95 ± 0.01	56713.793	14.25 ± 0.18
2014 Feb 26	56714.714	15.12 ± 0.01	56714.699	14.22 ± 0.18
	56714.807	15.12 ± 0.01	56714.794	14.25 ± 0.18
2014 Feb 27	56715.627	15.04 ± 0.03	56715.598	14.18 ± 0.18
2014 Feb 28	56716.664	14.94 ± 0.01	56716.650	14.17 ± 0.18

4.2 Double-Peaked H α Line Profile

4.2.1 Mean line profile

Figure 4.2 and Figure 4.3 show our observed daily spectra during all observation runs before and after the removal of the narrow line components. First, we create mean spectra of each observation run, and then compare the previous data. Figure 4.4 shows our mean H α line profiles and the data obtained by Popović et al. (2014) as comparison. The shape and flux level of our double-peaked profile obtained at 2013 May–June agree well with those obtained by Popović et al. (2014) at 2013 April to June. The profiles at 2013 August and 2014 February have also almost the same shape and flux level as those at 2013 May–June.

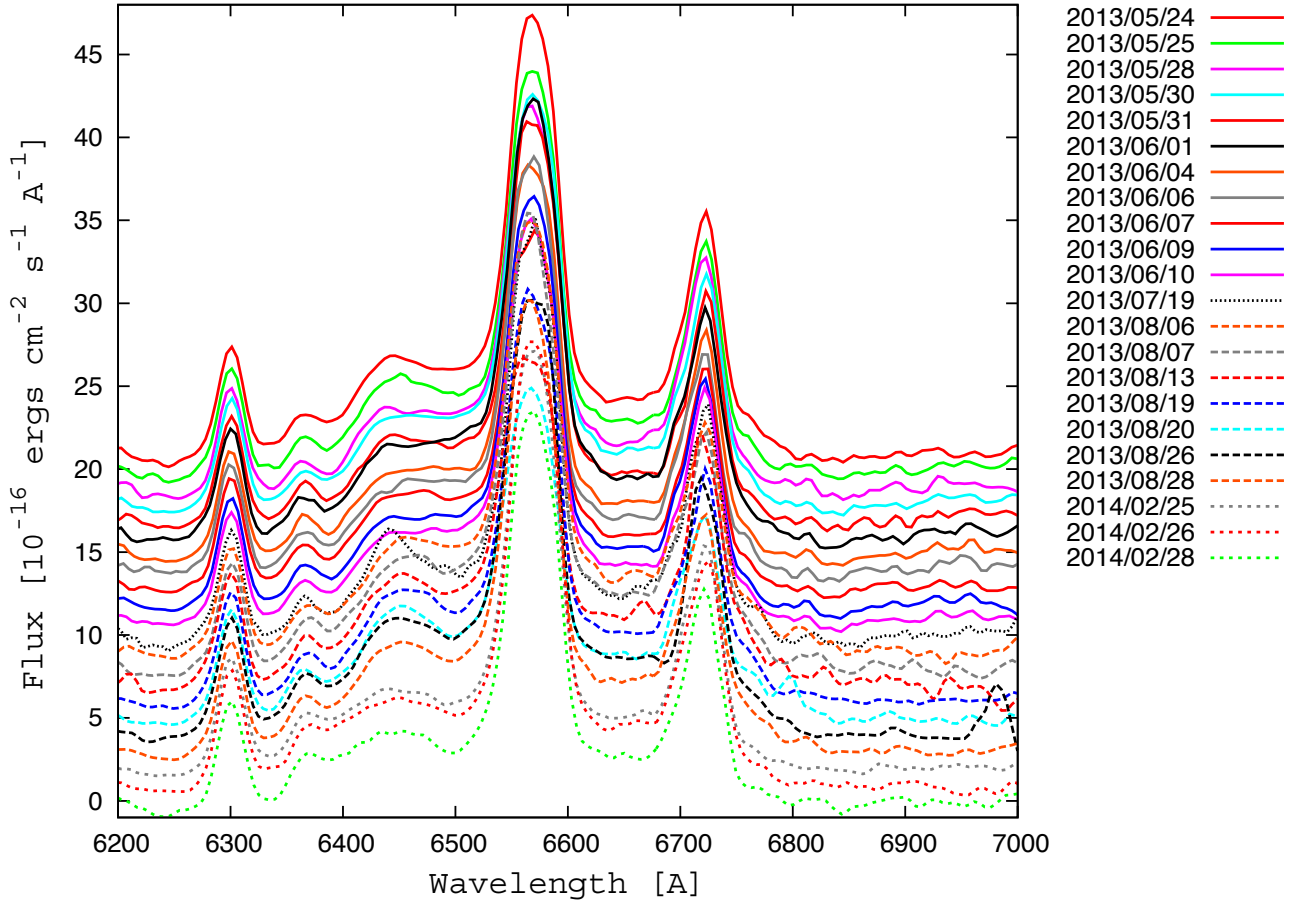


Figure 4.2: Observed spectra of double-peaked H α line of Arp 102B between 2013 May 24 and 2014 February 28

According to the results of the long-term monitoring by Popović et al. (2014), the flux level of double-peaked H α line is minimum in 2013 over the 1987–2013 period. Among our three

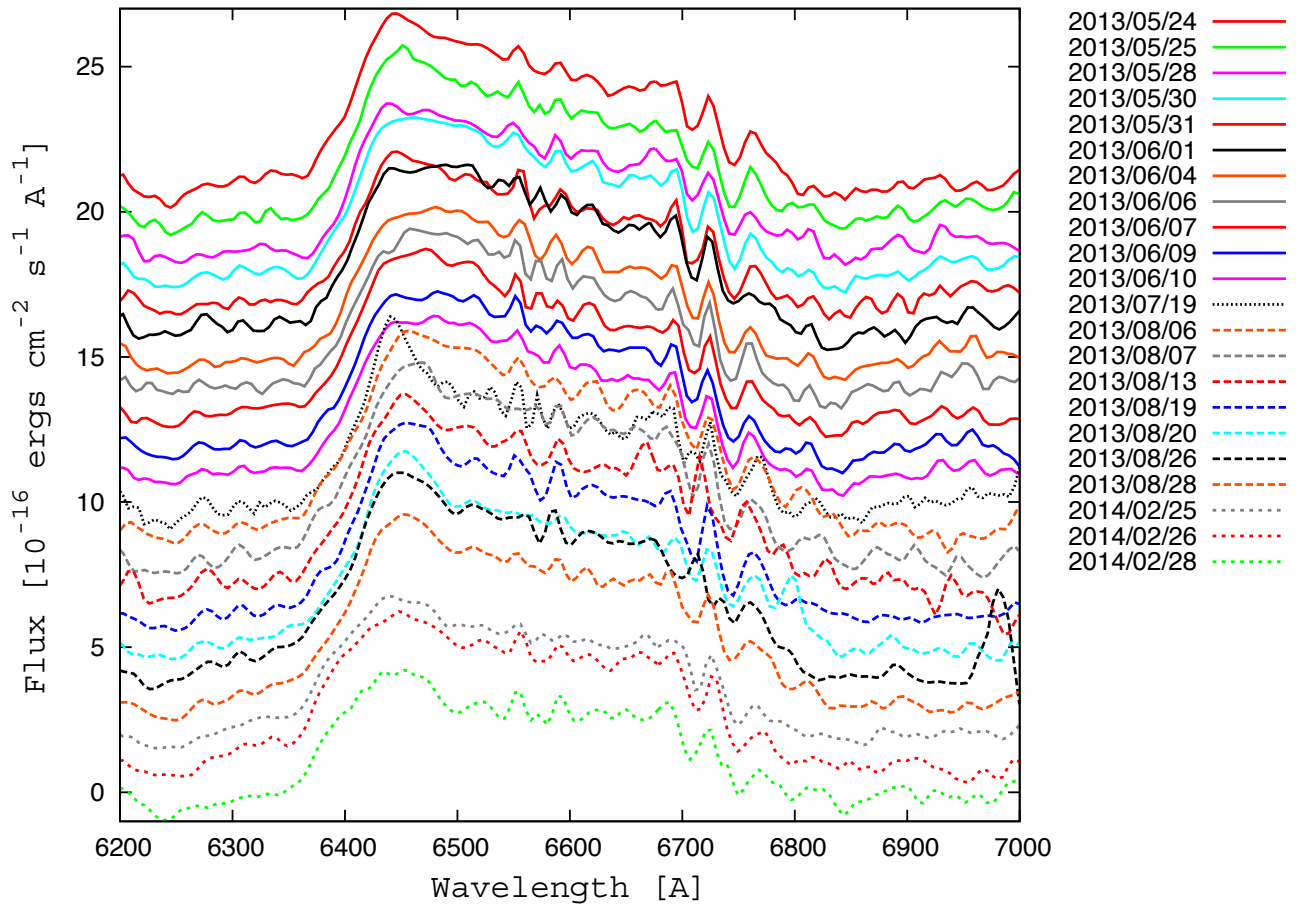


Figure 4.3: Observed spectra of double-peaked H α line of Arp 102B after removal of narrow-lines.

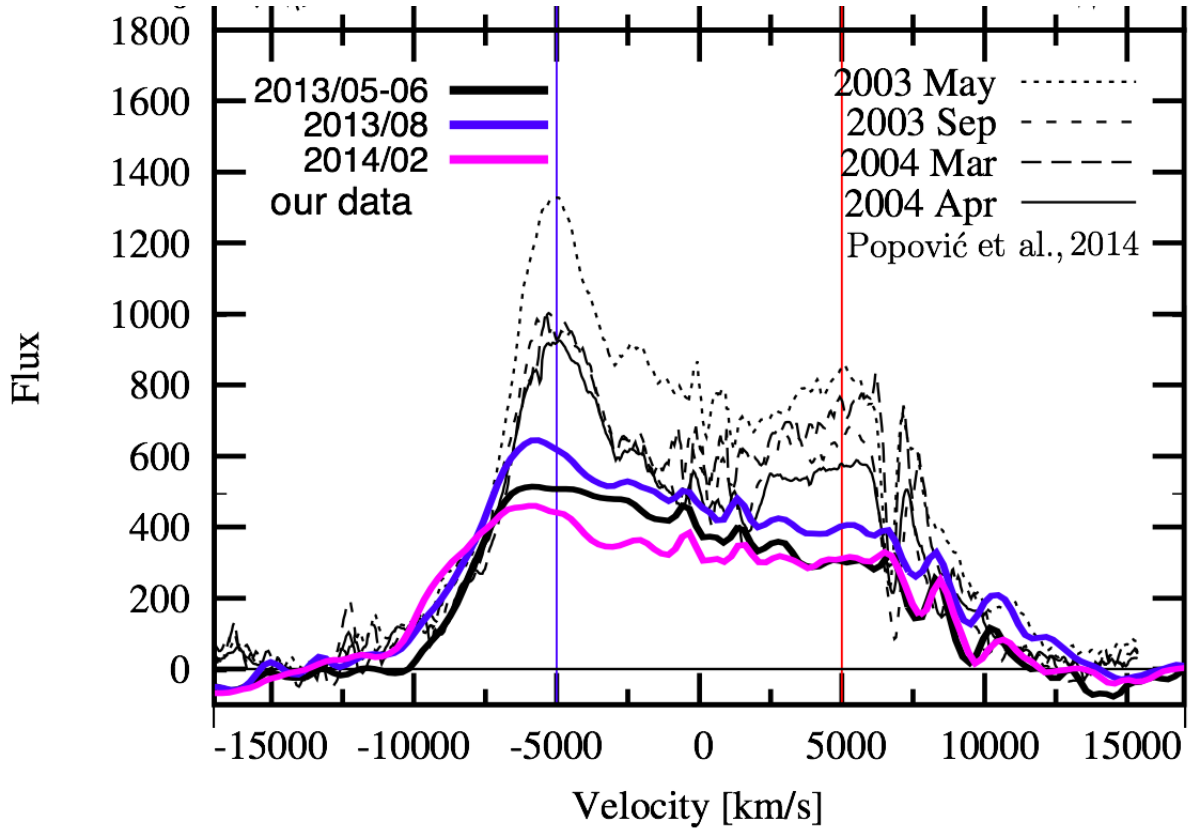


Figure 4.4: Mean double-peaked H α profiles observed at 2013 May–June (black thick solid line), 2013 August (purple thick solid line), and 2014 February (pink thick solid line). The data obtained by Popović et al. (2014) between 2013 May and 2014 April are also plotted for comparison.

mean spectra, the data of 2014 February has a minimum flux level and the data of 2013 August has somewhat a higher flux level than others.

The shape of double-peaked H α line profiles obtained by us has a smaller and wider blue peak than those of the typical shape in the previous observations (Eracleous & Halpern, 1993; Newman et al., 1997; Gezari, Halpern, & Eracleous, 2007; Shapovalova et al., 2013; Popović et al., 2014) and the red peak does not appear clearly. In addition, the blue peak is shifted into the bluer side by about -1000 or -2000 km s $^{-1}$ from the typical position (-5200 km s $^{-1}$), which is measured from the mean spectrum by Gezari, Halpern, & Eracleous (2007).

4.2.2 Variability of line profile

Figure 4.2 and Figure 4.3 show a small variation in flux and shape of double-peaked profile during our observation period. To parametrize this variation, first, we measure the overall H α line flux (H α_{all}), which includes every narrow line components around the H α line, integrating a flux spectrum over an interval of 6347–6801 Å. Second, on the narrow-line subtracted spectrum, we divide the double-peaked profile into three segments with an interval of 6395–6502, 6502–6629, and 6629–6775 Å, which is labeled by H α_{blue} , H α_{center} , and H α_{red} , respectively (see Figure 4.5). By considering an additional segment (H α_{broad}) with the same interval as H α_{all} to measure a total flux of double-peak line profile without narrow-lines, we measure the integrated flux over each segment. Table 4.2 shows these integrated fluxes and the continuum flux at 5100 Å [$F_{\text{cnt}}(5100 \text{ Å})$] determined by the removal process described in Section 3.3.

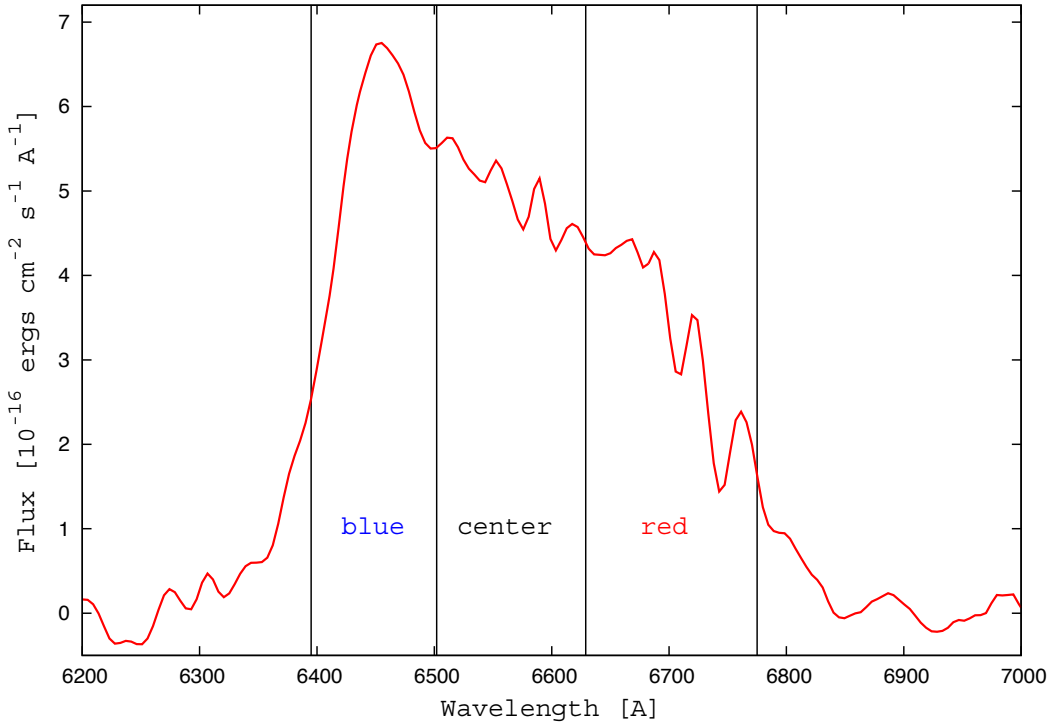


Figure 4.5: Line segments to measure a flux of double-peaked H α line profile.

Table 4.2: Observed broad H α line properties of Arp 102B.

UT date	MJD	$F_{\text{H}\alpha}(\text{all})^a$	$F_{\text{cnt}}(5100\text{\AA})^b$	$F_{\text{H}\alpha}(\text{total})^a$	$F_{\text{H}\alpha}(\text{blue})^c$	$F_{\text{H}\alpha}(\text{center})^c$	$F_{\text{H}\alpha}(\text{red})^c$	$\frac{F_{\text{H}\alpha}(\text{blue})}{F_{\text{H}\alpha}(\text{red})}$	λ_{blue}^d
2013 May 24	56436.583	3.186 $\pm$ 0.002	1.604 $\pm$ 0.004	1.402 $\pm$ 0.016	5.07 $\pm$ 0.04	5.28 $\pm$ 0.14	3.67 $\pm$ 0.05	1.38 $\pm$ 0.02	6453.22 $\pm$ 0.79
2013 May 25	56437.574	3.019 $\pm$ 0.001	1.241 $\pm$ 0.009	1.269 $\pm$ 0.014	4.75 $\pm$ 0.04	4.86 $\pm$ 0.12	3.08 $\pm$ 0.05	1.54 $\pm$ 0.02	6456.48 $\pm$ 0.89
2013 May 28	56440.589	2.893 $\pm$ 0.002	1.321 $\pm$ 0.008	1.140 $\pm$ 0.015	4.14 $\pm$ 0.07	4.41 $\pm$ 0.12	2.86 $\pm$ 0.06	1.45 $\pm$ 0.03	6457.49 $\pm$ 1.76
2013 May 30	56442.628	3.082 $\pm$ 0.001	1.719 $\pm$ 0.004	1.321 $\pm$ 0.011	4.74 $\pm$ 0.03	5.23 $\pm$ 0.10	3.24 $\pm$ 0.04	1.46 $\pm$ 0.02	6459.91 $\pm$ 0.93
2013 May 31	56443.656	2.949 $\pm$ 0.001	1.323 $\pm$ 0.008	1.174 $\pm$ 0.013	4.30 $\pm$ 0.05	4.56 $\pm$ 0.11	2.89 $\pm$ 0.05	1.49 $\pm$ 0.03	6458.06 $\pm$ 1.02
2013 Jun 1	56444.564	3.266 $\pm$ 0.002	2.052 $\pm$ 0.006	1.471 $\pm$ 0.018	5.11 $\pm$ 0.05	5.86 $\pm$ 0.16	3.74 $\pm$ 0.08	1.37 $\pm$ 0.03	6463.25 $\pm$ 1.56
2013 Jun 4	56447.541	3.032 $\pm$ 0.001	1.535 $\pm$ 0.004	1.273 $\pm$ 0.014	4.59 $\pm$ 0.04	5.16 $\pm$ 0.12	2.98 $\pm$ 0.05	1.54 $\pm$ 0.03	6466.14 $\pm$ 1.79
2013 Jun 6	56449.520	3.102 $\pm$ 0.001	1.593 $\pm$ 0.006	1.322 $\pm$ 0.011	4.78 $\pm$ 0.05	5.36 $\pm$ 0.09	3.09 $\pm$ 0.05	1.54 $\pm$ 0.02	6465.92 $\pm$ 2.54
2013 Jun 7	56450.514	3.132 $\pm$ 0.002	1.083 $\pm$ 0.006	1.345 $\pm$ 0.020	5.12 $\pm$ 0.04	5.28 $\pm$ 0.19	3.06 $\pm$ 0.06	1.67 $\pm$ 0.03	6462.75 $\pm$ 1.28
2013 Jun 8	56451.530	3.207 $\pm$ 0.006	2.032 $\pm$ 0.007	1.434 $\pm$ 0.056	4.95 $\pm$ 0.22	6.37 $\pm$ 0.38	3.02 $\pm$ 0.35	1.64 $\pm$ 0.19	6479.22 $\pm$ 15.08
2013 Jun 9	56452.646	3.086 $\pm$ 0.001	0.885 $\pm$ 0.008	1.319 $\pm$ 0.011	4.76 $\pm$ 0.03	5.32 $\pm$ 0.09	3.11 $\pm$ 0.04	1.53 $\pm$ 0.02	6461.90 $\pm$ 1.09
2013 Jun 10	56453.628	3.147 $\pm$ 0.001	1.536 $\pm$ 0.011	1.356 $\pm$ 0.010	4.96 $\pm$ 0.03	5.39 $\pm$ 0.09	3.21 $\pm$ 0.04	1.54 $\pm$ 0.02	6461.69 $\pm$ 1.14
2013 Jul 19	56492.576	2.960 $\pm$ 0.002	1.270 $\pm$ 0.004	1.159 $\pm$ 0.018	4.68 $\pm$ 0.08	4.07 $\pm$ 0.13	2.85 $\pm$ 0.10	1.64 $\pm$ 0.06	6448.94 $\pm$ 0.93
2013 Aug 6	56510.571	3.594 $\pm$ 0.002	1.662 $\pm$ 0.005	1.812 $\pm$ 0.018	5.95 $\pm$ 0.07	7.05 $\pm$ 0.15	5.12 $\pm$ 0.08	1.16 $\pm$ 0.02	6464.73 $\pm$ 1.61
2013 Aug 7	56511.617	3.480 $\pm$ 0.002	1.997 $\pm$ 0.007	1.724 $\pm$ 0.016	5.82 $\pm$ 0.07	6.54 $\pm$ 0.12	4.89 $\pm$ 0.07	1.19 $\pm$ 0.02	6461.02 $\pm$ 1.63
2013 Aug 13	56517.574	3.497 $\pm$ 0.003	2.306 $\pm$ 0.004	1.689 $\pm$ 0.027	5.80 $\pm$ 0.05	6.07 $\pm$ 0.26	5.02 $\pm$ 0.06	1.15 $\pm$ 0.01	6457.35 $\pm$ 0.71
2013 Aug 19	56523.590	3.496 $\pm$ 0.001	1.509 $\pm$ 0.007	1.655 $\pm$ 0.014	5.83 $\pm$ 0.06	6.14 $\pm$ 0.12	4.58 $\pm$ 0.04	1.27 $\pm$ 0.01	6458.91 $\pm$ 1.12
2013 Aug 20	56524.485	3.432 $\pm$ 0.003	1.750 $\pm$ 0.004	1.566 $\pm$ 0.030	5.72 $\pm$ 0.05	5.62 $\pm$ 0.28	4.33 $\pm$ 0.09	1.32 $\pm$ 0.03	6453.24 $\pm$ 0.55
2013 Aug 23	56527.633	3.342 $\pm$ 0.005	1.372 $\pm$ 0.009	1.482 $\pm$ 0.044	5.61 $\pm$ 0.23	5.95 $\pm$ 0.27	3.25 $\pm$ 0.26	1.72 $\pm$ 0.14	6461.00 $\pm$ 4.20
2013 Aug 26	56530.465	3.675 $\pm$ 0.001	1.711 $\pm$ 0.006	1.826 $\pm$ 0.010	6.27 $\pm$ 0.04	6.71 $\pm$ 0.07	5.28 $\pm$ 0.05	1.19 $\pm$ 0.01	6455.98 $\pm$ 0.56
2013 Aug 27	56531.448	3.462 $\pm$ 0.004	1.875 $\pm$ 0.006	1.576 $\pm$ 0.036	5.11 $\pm$ 0.19	5.58 $\pm$ 0.22	5.07 $\pm$ 0.21	1.01 $\pm$ 0.04	6455.26 $\pm$ 8.31
2013 Aug 28	56532.523	3.526 $\pm$ 0.001	1.761 $\pm$ 0.005	1.706 $\pm$ 0.012	5.85 $\pm$ 0.05	6.20 $\pm$ 0.10	5.01 $\pm$ 0.05	1.17 $\pm$ 0.01	6456.24 $\pm$ 0.99
2014 Feb 25	56713.750	3.054 $\pm$ 0.001	1.634 $\pm$ 0.006	1.219 $\pm$ 0.011	4.49 $\pm$ 0.03	4.39 $\pm$ 0.10	3.32 $\pm$ 0.04	1.35 $\pm$ 0.01	6450.29 $\pm$ 1.10
2014 Feb 26	56714.758	3.204 $\pm$ 0.001	2.043 $\pm$ 0.007	1.363 $\pm$ 0.012	4.97 $\pm$ 0.04	4.93 $\pm$ 0.11	3.73 $\pm$ 0.05	1.34 $\pm$ 0.02	6452.08 $\pm$ 1.31
2014 Feb 28	56716.709	2.822 $\pm$ 0.002	1.706 $\pm$ 0.003	1.012 $\pm$ 0.015	3.85 $\pm$ 0.05	3.61 $\pm$ 0.13	2.65 $\pm$ 0.07	1.45 $\pm$ 0.04	6448.44 $\pm$ 1.45

^a Flux in units of $10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$.

^b Flux in units of $10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$.

^c Flux in units of $10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$.

^d Wavelength in units of $\text{\AA}$.

To estimate the net amount of the variability without measurement uncertainties, we used the method given by O’Brien et al. (1998) and determined several parameters characterizing the variability of the continuum, total line, and line-segment fluxes (and also the blue-segment to red-segment ratio and the blue-peak wavelength; see later) in Table 4.3 for three period (all monitoring term: 2013 May 24–2014 Feb 28, first term: 2013 May 24–Jun 10, second term: 2013 Aug 6–Aug 28). We computed the F_{var} parameter, which is an inferred (uncertainty-corrected) estimate of the variation amplitude with respect to the mean value, by the following equation (O’Brien et al., 1998):

$$F_{\text{var}} = \frac{\sqrt{\sigma_F^2 - \Delta^2}}{\bar{F}}, \quad (4.1)$$

where, $\bar{F}$ is the mean flux over the whole observing period, σ_F is the standard deviation, and Δ^2 is the mean square value of the individual measurement uncertainty (Δ_i) for N observations:

$$\Delta^2 = \frac{1}{N} \sum_i^N \Delta_i^2. \quad (4.2)$$

We also computed the $R(\text{max/min})$ parameter defined by the ratio of the maximal to minimal value in the monitoring period. Table 4.3 shows the computed F_{var} , σ_F , Δ , and $\bar{F}$ values.

Table 4.3 imply that there are a variation of a net amount (F_{var}) of 2–22 % in the H α line and line-segment fluxes. The net amount of variation through our all monitoring period is 11–22 %. It is consistent with the net amount of variability obtained by Shapovalova et al. (2013) from their long-term (1987–2010) monitoring. The net amount of variability during a month is 2–10 % and smaller than during the long-term. It imply that there are a non-negligible long-term variability with a time scale of more than a month in H α flux. It is consistent with the result of many previous long-term monitoring (Newman et al., 1997; Gezari, Halpern, & Eracleous, 2007; Shapovalova et al., 2013; Popović et al., 2014).

The continuum flux also have a variability of a net amount of 15–22%, and it is consistent with the result of Shapovalova et al. (2013). The net amount of variability during a month is still comparable to that during the long-term. It could imply that short-term variability with a time scale of less than month is more dominant than in the case of H α line flux.

We note that the F_{var} value for the red line-segment flux [$F_{\text{H}\alpha}(\text{red})$] is larger than other line-segment fluxes [$F_{\text{H}\alpha}(\text{blue})$ and $F_{\text{H}\alpha}(\text{center})$]. It could be an artificial effect due to an imperfect correction of absorption of telluric B-band (O_2).

Table 4.3: Parameters of the continuum and line variabilities

Feature	2013 May 24 – 2014 Feb 28 ($N=25$)					2013 May 24 – Jun 10 ($N=12$)					2013 Aug 6 – Aug 28 ($N=9$)				
	$\bar{F}$	σ_F	Δ	F_{var}^e	R	$\bar{F}$	σ_F	Δ	F_{var}^e	R	$\bar{F}$	σ_F	Δ	F_{var}^e	R
$F_{\text{H}\alpha}(\text{all})^a$	3.23	23.3	2.36	7.22	1.30	3.09	10.2	2.25	3.31	1.13	3.50	8.92	2.77	2.55	1.10
$F_{\text{cnt}}(5100 \text{ \AA})^b$	1.62	3.25	6.42	20.0	2.61	1.49	3.34	7.14	22.4	2.32	1.77	2.56	5.89	14.5	1.68
$F_{\text{H}\alpha}(\text{broad})^c$	14.2	20.8	5.66	14.1	1.80	13.2	9.15	4.80	5.91	1.29	16.6	8.54	7.52	2.44	1.23
$F_{\text{H}\alpha}(\text{blue})^c$	5.08	5.90	2.05	10.9	1.63	4.76	2.90	1.68	4.96	1.24	5.74	2.62	2.77	INDEF	1.23
$F_{\text{H}\alpha}(\text{center})^c$	5.42	7.97	2.69	13.8	1.86	5.25	5.00	2.50	8.25	1.44	6.17	3.89	3.33	3.25	1.26
$F_{\text{H}\alpha}(\text{red})^c$	3.71	8.43	6.42	22.2	1.93	3.16	2.61	1.46	6.86	1.29	4.69	5.41	2.26	10.5	1.57
$F_{\text{H}\alpha}(\text{blue})/F_{\text{H}\alpha}(\text{red})$	1.72	0.18	0.06	12.4	1.71	1.51	0.09	0.06	3.85	1.12	1.24	0.19	0.06	14.5	1.71
$\lambda_{\text{blue}} - 6563^d$	-105.09	5.18	1.30	4.77	1.18	-102.38	3.83	1.43	3.47	1.13	-104.79	3.49	1.11	3.16	1.12

^a $\bar{F}$, σ_F , and Δ are in units of 10^{-13} , 10^{-15} , and $10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$, respectively.

^b $\bar{F}$, σ_F , and Δ are in units of 10^{-15} , 10^{-16} , and $10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$, respectively.

^c $\bar{F}$, σ_F , and Δ are in units of 10^{-14} , 10^{-15} , and $10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$, respectively.

^d $\bar{F}$, σ_F , and Δ are in units of $\text{\AA}$.

^e F_{var} is in units of %.

Figure 4.6 shows the light curves of the overall flux around $H\alpha$ line with narrow lines [$F_{H\alpha}(\text{all})$] and the continuum flux [$F_{\text{cnt}}(5100 \text{ \AA})$]. During the 2013 May and June observation period, both fluxes agree with the observations by Popović et al. (2014) on average. The $H\alpha$ flux became about 17% higher during 2013 August, and then went back to the same level at the 2013 May–June period. The continuum flux shows a rapid variability of about 20 % level with a day time-scale, and a flare-like peak at August 6, 2013. This flare-like peak has an amplitude of 39% and a peak flux of $2.3 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$. The similar flare-like events have been observed in the previous observations (Shapovalova et al., 2013).

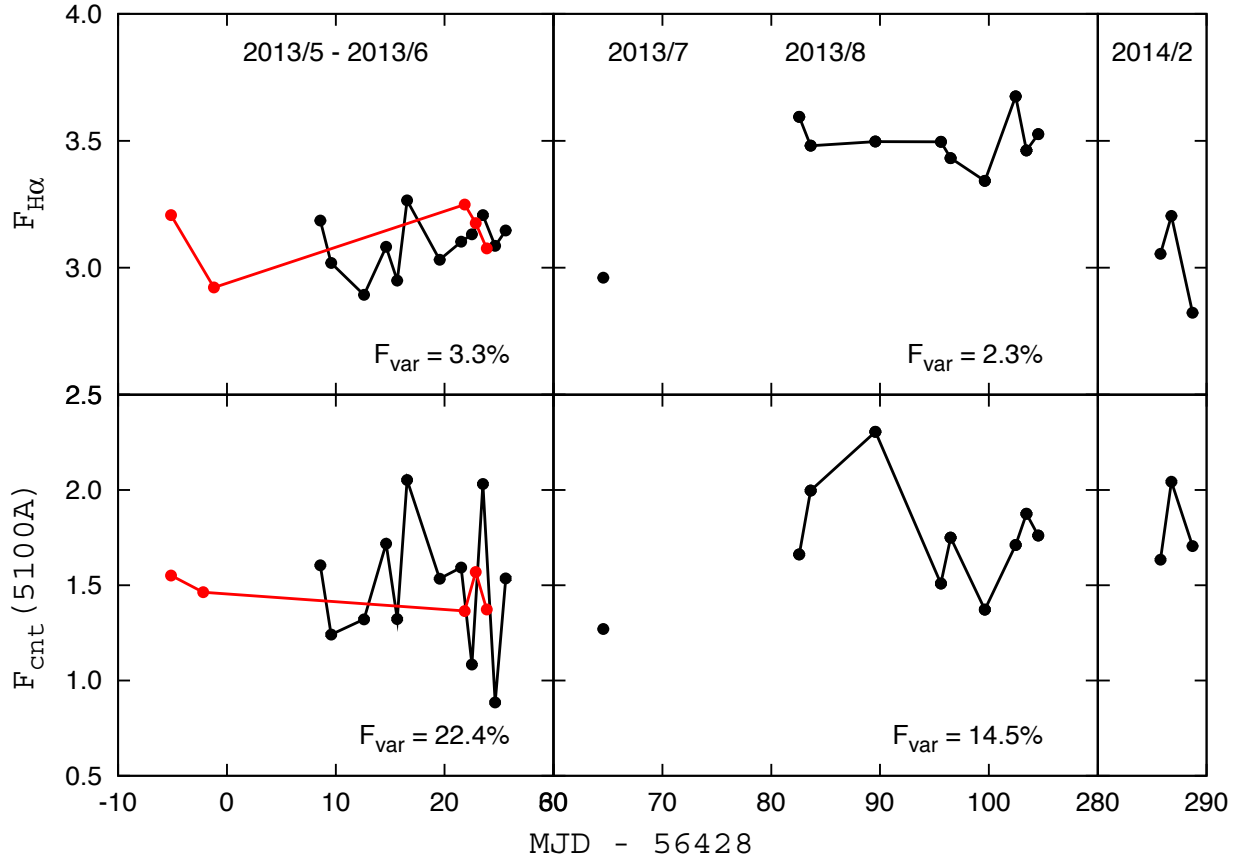


Figure 4.6: Light curves of overall flux around $H\alpha$ line with narrow-lines in units of $10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ (upper panel) and continuum flux in units of $10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ (lower panel) of Arp 102B between 2013 May and 2014 February. Red points show the data observed by Popović et al. (2014) for comparison.

Figure 4.7 shows the light curves of $H\alpha$ line-segment fluxes. The four light curves have basically the same trend. During the 2013 August observation period, the flux levels are somewhat

higher than in the other observation period. Four line-segment fluxes have a variation with a net amount of 2–10 % in each monitoring period.

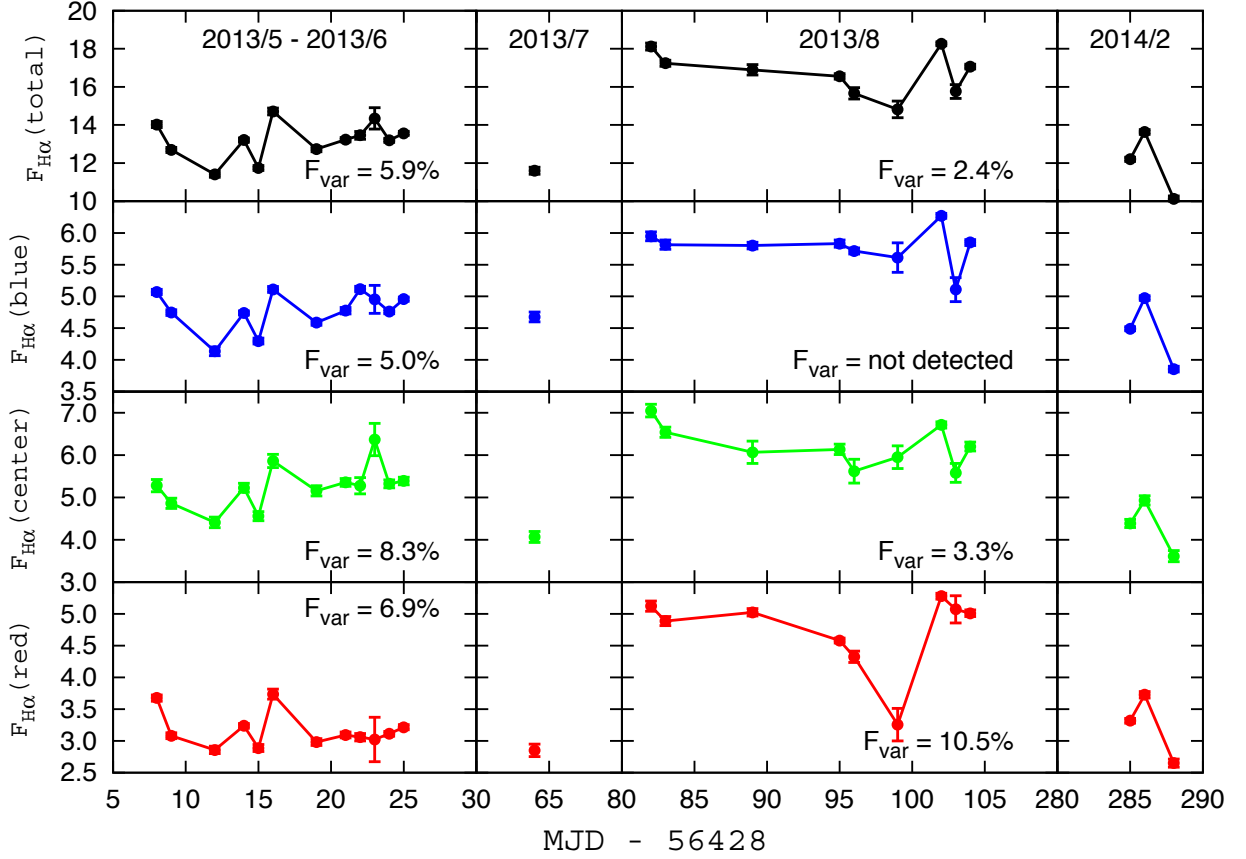


Figure 4.7: Light curves of H α line-segment fluxes. From top to bottom are the total, blue, central, and red line-segment fluxes in units of 10^{-13} erg s $^{-1}$ cm $^{-2}$ between 2013 May and 2014 February.

To estimate the variability of double-peaked H α profile, we computed the flux ratio of the blue line-segment to red line-segment [$F_{\text{H}\alpha}(\text{blue})/F_{\text{H}\alpha}(\text{red})$] and determined the peak wavelength of the double-peaked H α profile. At first, we tried the same analysis as Popović et al. (2014). They fitted a double-peaked line profile with three Gaussian functions corresponding to the blue, central, and red components. However, in our data, the central component very often changes in intensity, which affects the determination of the blue and red peak positions, especially the red peak position, because the red peak does not appear clearly in our data. The standard deviation of the fitted positions of the red peaks was about 3 times larger than that of the blue-peak position (~ 5.5 Å). Therefore, we determined only the blue-peak position using a single Gaussian function. The wavelength region used for fitting is only around the blue peak

(6400–6490 Å).

Figure 4.8 shows the variation of the flux ratio and blue-peak wavelength (λ_{blue}). The values of the fluxes and the blue-peak wavelength are listed in Table 4.2. The blue-peak position appears to have a small systematic variability with an amount of about 10 Å and a timescale of about ten days. The trend is different between in the 2013 May–June and 2013 August periods. The flux ratio also shows a small variability with an amplitude of about 10 % and a timescale of a few days. However, it appears to have no systematic trend. The flux ratio in the 2013 August period is about 20% lower than in the other periods on average.

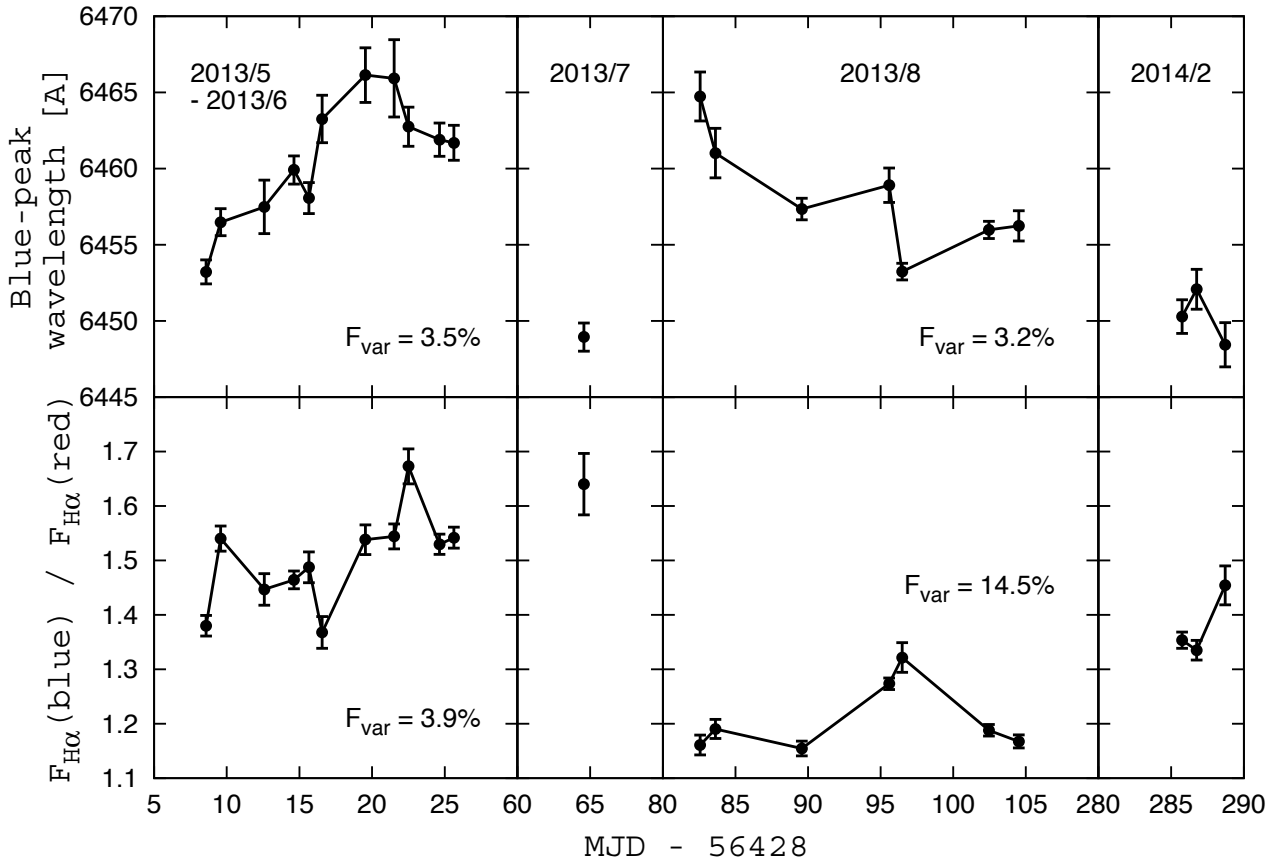


Figure 4.8: Variation of blue-peak wavelength (top) and flux ratio of blue line segment to red line segment (bottom).

We also plotted an evaluational track of the relationship between the flux ratio of blue line segment to red line segment [$F_{\text{H}\alpha}(\text{blue})/F_{\text{H}\alpha}(\text{red})$] and the blue-peak wavelength (λ_{blue}) to look for a behavior of the profile variation. Figure 4.9 shows the evaluational track each observation period. It shows a complex behavior and it looks like rather a random walk. The flux ratio

and blue-peak wavelength appear to have no clear relationship. We will compare it with the prediction from model and discuss later.

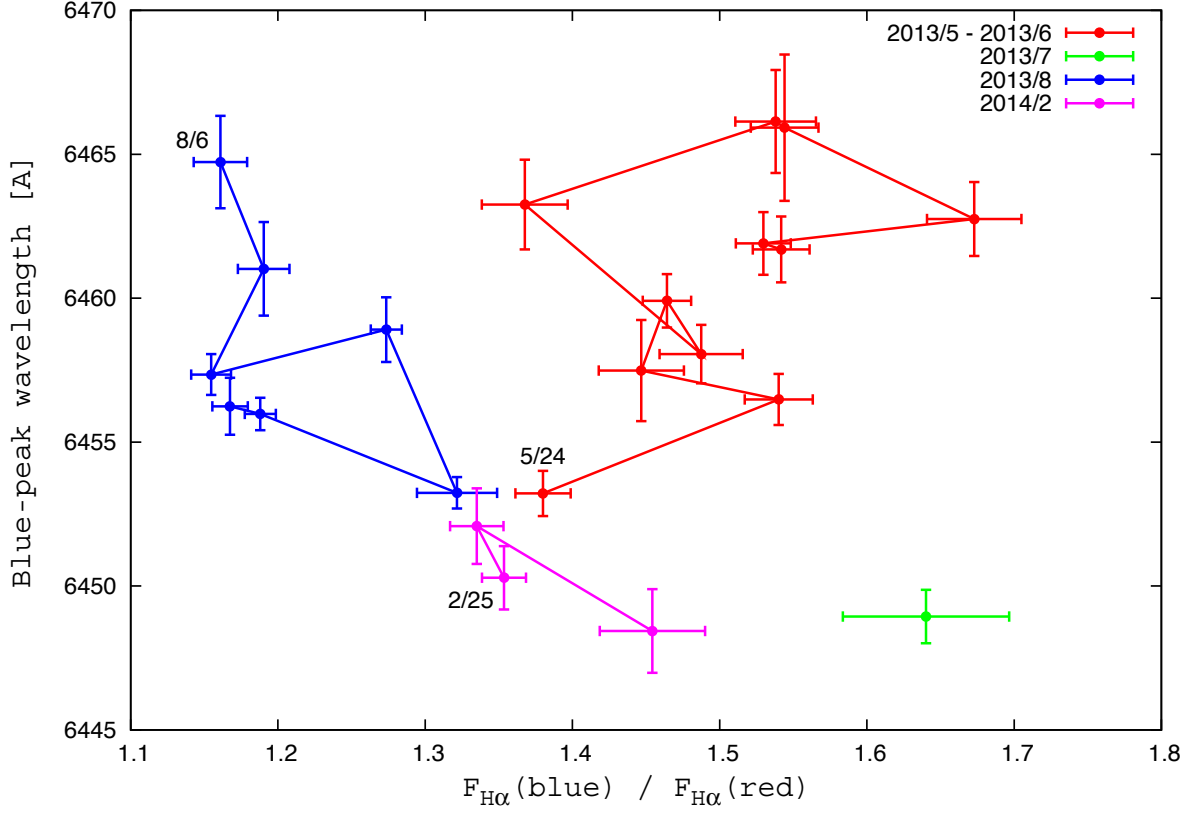


Figure 4.9: Evaluational track of relationship between flux ratio and blue-peak wavelength. The red, green, blue, and purple points present the data in the period of 2013 June, July, August, and 2014 February, respectively. The number at the end of line presents the starting date and point of each track.

Modeling of Reverberation from Accretion Disk

5.1 Line Profile of Circular Accretion Disk

We computed the double-peak line profile from a relativistic Keplerian accretion disk. Here, we present the detailed calculations of the line profile, quoting the descriptions in Eracleous et al. (1995), Chen, Halpern, & Filippenko (1989), and Chen & Halpern (1989).

At first, we assume a circular geometrically thin Keplerian disk. The geometry is depicted in Figure 5.1, which also serves as an illustration of the conventions used in the calculation.

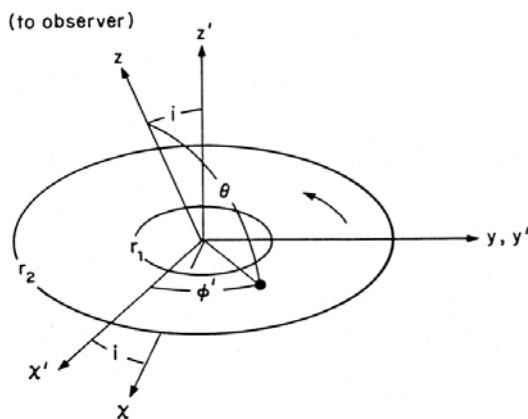


Figure 5.1: Geometry and coordinate systems used in the line profile calculations for a circular disk (Chen, Halpern, & Filippenko, 1989).

The Cartesian axes x', y', z' show the frame of the disk, chosen so that the disk lies in the (x', y') -plane. The observer's frame is indicated by the Cartesian axes x, y, z with the observer on the positive z -axis at $z = +\infty$. The line of sight (z -axis) is inclined with respect to the rotation axis of the disk (z' -axis) by an angle i , as shown in Figure 5.1. The calculation is carried out in polar coordinates (r, θ, φ) and (r', θ', φ') , where the primed angles are measured

in the frame of the disk. The plane of the disk corresponds to $\theta' = \pi/2$ and φ' is the azimuthal coordinate around the disk. The angles are related via

$$\sin \varphi' = \sin \theta \sin \varphi, \quad (5.1)$$

$$\cos \phi = \sin i \cos \varphi'. \quad (5.2)$$

The central object is assumed to be a Schwarzschild black hole of mass M , located at the origin. Throughout this calculation we use units in which $G = c = 1$ (where G is the gravitational constant and c is the speed of light), and we adopt the gravitational radius as the unit of length. Hence we define the dimensionless radial coordinate $\xi \equiv r/r_g$, where $r_g \equiv GM/c^2 = M$ is the gravitational radius.

The total observed line flux from the disk is given by

$$F = \iiint I_\nu d\nu d\Omega, \quad (5.3)$$

where ν , I_ν , and $d\Omega$ are the frequency, specific intensity (flux per unit frequency per unit solid angle) and solid angle element respectively *as measured in the frame of the observer*. By using the invariance of the quantity I_ν/ν^3 , the specific intensity can be transformed to the frame of the emitter (denoted by the subscript "e"). The solid angle $d\Omega$ is most conveniently expressed in terms of the impact parameter b at infinity, as $d\Omega = b db d\varphi/d^2$, where d is the distance to the source. This expression allows one to deal with the difference caused by light bending between the solid angle in the frame of the disk and the solid angle in the frame of the observer. It is also necessary to express the specific intensity of a local broadening line in the emitting frame by a Gaussian function of frequency,

$$I_{\nu_e} = \epsilon(\xi) \frac{e^{-(\nu_e - \nu_0)^2/2\sigma^2}}{(2\pi)^{1/2}\sigma}. \quad (5.4)$$

The local broadening is characterized by the dimensionless quantity σ/ν_0 . We define the relativistic Doppler factor, $D = \nu/\nu_0$, where ν and ν_e are observe and emitted frequencies, respectively. In the weak-field approximation,

$$D = (1 - 3/\xi)^{1/2} (1 + \xi^{-1/2} \sin i \sin \varphi')^{-1}, \quad (5.5)$$

$\epsilon(\xi)$ is the surface emissivity that is assumed to vary with radius as a power law with index q ,

$$\epsilon(\xi) = \frac{\epsilon_0}{4\pi} \xi^{-q}. \quad (5.6)$$

The expression for the total line flux then becomes

$$F = \frac{1}{d^2} \iint I_{\nu_e} \left(\frac{\nu}{\nu_e} \right)^3 b db d\varphi, \quad (5.7)$$

where now ν_e and I_{ν_e} are the frequency and the specific intensity as measured in the frame of the emitter. The line profile itself is described by the function F_X , which is defined by $F = \int F_X dX$,

where $1 + X = \nu/\nu_0$, and ν_0 is the rest frequency of the line (X is effectively the redshift and F_X is the line flux per unit redshift interval). In general $\nu_0 \neq \nu_e$ because the line can be locally broadened (e.g., due to turbulent motions or electron scattering). It is also that $1 + X \neq D$, because the emission frequency ν_e is not identical to the rest frequency ν_0 . From equation (5.7) and the definition of F_X it follows that

$$F_X = \frac{\nu_0}{d^2} \iint I_{\nu_e} \left(\frac{\nu}{\nu_e} \right)^3 b db d\varphi. \quad (5.8)$$

In the weak-field approximation, to first order in M/r , the impact parameter b can be written as (Adler, Bazin, & Schiffer, 1975)

$$b \sim r \sin \theta + \frac{M}{2 \sin \theta} (3 - 4 \cos \theta + \cos 2\theta). \quad (5.9)$$

This expression is valid when the second term is much smaller than the first term, which is true for the disk parameters of interest here. Using the equations (5.9), (5.1), and (5.2) we have that

$$1 + X = \frac{(1 - 3/\xi)^{1/2}}{(1 + \xi^{-1/2} \sin i \sin \varphi')}. \quad (5.10)$$

Using equations (5.9) and (5.5) and expressing $d\varphi$ in terms of φ' with the help of equations (5.1) and (5.2), equation (5.8) becomes

$$F_X = \frac{2\epsilon_0 M^2 \cos i}{4\pi d^2} \frac{\nu_0}{(2\pi)^{1/2} \sigma} \int_{\xi_1}^{\xi_2} \int_{-\pi/2}^{\pi/2} \exp \left[-\frac{(1 + X - D)^2 \nu_0^2}{2\sigma^2 D^2} \right] D^3 \xi^{1-q} g(D) d\xi d\varphi', \quad (5.11)$$

where

$$g(D) = 1 + \xi^{-1} \left\{ \frac{2D^2}{D^2 \cos^2 i + \xi [D - (1 - 3/\xi)^{1/2}]^2} - 1 \right\}. \quad (5.12)$$

Figure 5.2 shows the sequences of examples of model H α line profiles of circular accretion disk. It shows the effects of selected disk parameters (inner radius r_1 , outer radius r_2 , inclination i , emissivity power-law index q , and local broadening velocity dispersion σ) on the profile shapes. In each sequence only one parameter is varied, while all other are held constant to the following values: $r_1 = 300 r_g$, $r_2 = 1500 r_g$, $i = 30^\circ$, $q = 3.0$, and $\sigma = 850 \text{ km s}^{-1}$.

5.2 Line Profile of Elliptical Accretion Disk

Eracleous et al. (1995) provided a calculation of the profiles of emission lines originating in a relativistic, *eccentric* disk, being motivated by the fact that in about one-quarter of the double-peaked emission lines observed in radio-loud AGN (for example, NGC 1097) the red peak is stronger than the blue peak, which is contrary to the prediction of relativistic circular disk model (e.g. see Figure 5.2).

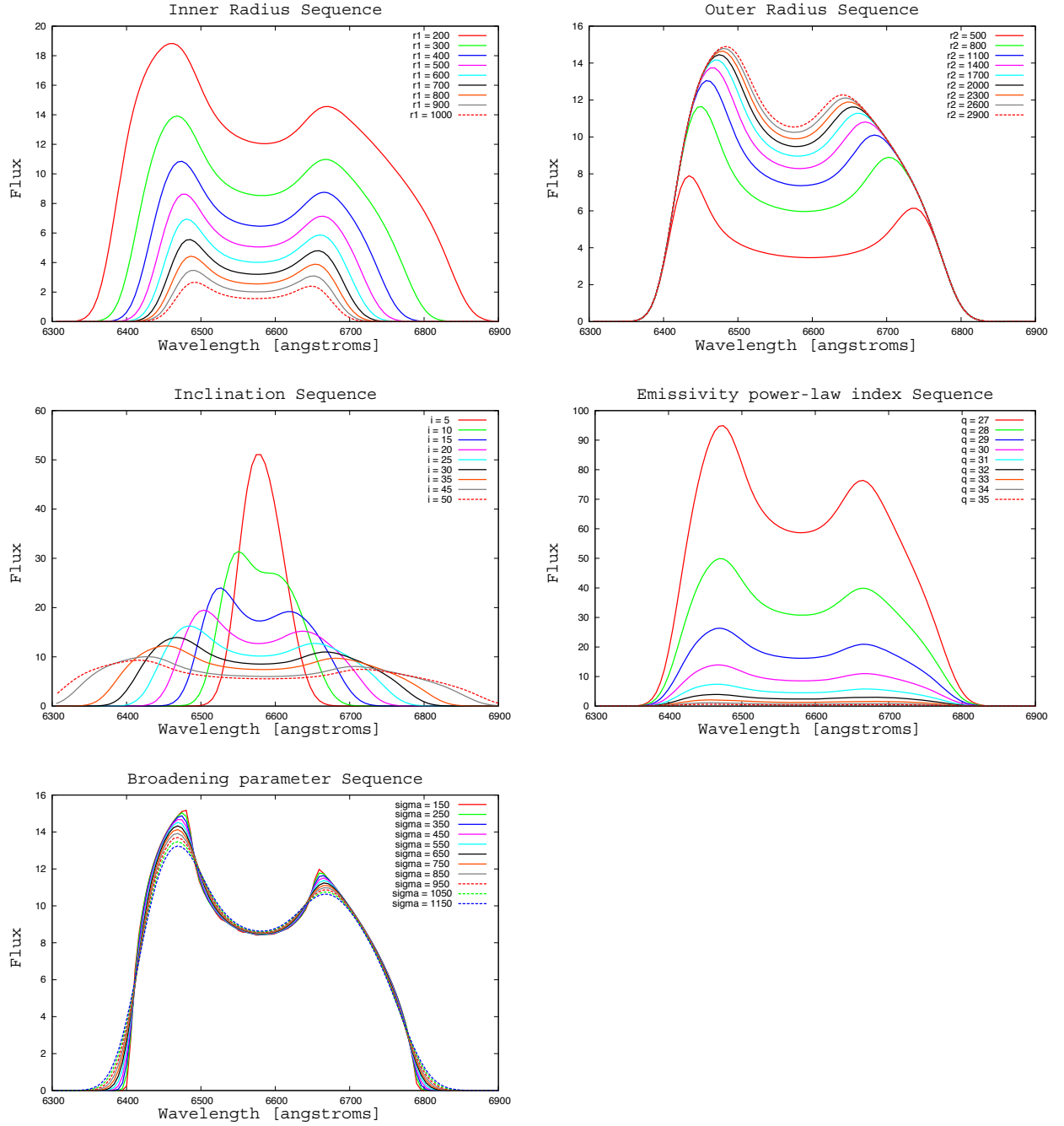
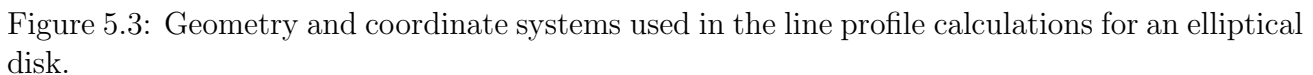


Figure 5.2: Sequences of examples of model H α profiles of circular accretion disk, showing the effects of selected disk parameters on the profile shapes: inner radius r_1 (top left), outer radius r_2 (top right), inclination i (middle left), emissivity power-law index q (middle right), and local broadening velocity dispersion σ (bottom). In each sequence only one parameter is varied, while all other are held constant to the following values: $r_1 = 300 r_g$, $r_2 = 1500 r_g$, $i = 30^\circ$, $q = 3.0$, and $\sigma = 850 \text{ km s}^{-1}$.



Assuming an elliptical accretion disk with an eccentricity e and orientation angle φ_0 as shown in Figure 5.3, the equation (5.11) becomes (Eracleous et al., 1995)

where D and $\Psi(\xi, \varphi')$ are given by

$$\Psi(\xi, \varphi') = 1 + \frac{1}{\xi} \left(\frac{1 - \sin i \cos \varphi'}{1 + \sin i \cos \varphi'} \right). \quad (5.15)$$

Figure 5.4 and Figure 5.5 show the sequences of examples of model H α line profiles of elliptical accretion disk. It shows the effects of selected disk parameters (inner radius r_1 , outer radius r_2 , inclination i , emissivity power-law index q , local broadening velocity dispersion σ , eccentricity e , and orientation angle φ_0) on the profile shapes. In each sequence only one parameter is varied, while all other are held constant to the following values: $r_1 = 300\ r_g$, $r_2 = 1500\ r_g$, $i = 30^\circ$, $q = 3.0$, and $\sigma = 850\ \text{km s}^{-1}$, $e = 0.2$, and $\varphi_0 = 270^\circ$.

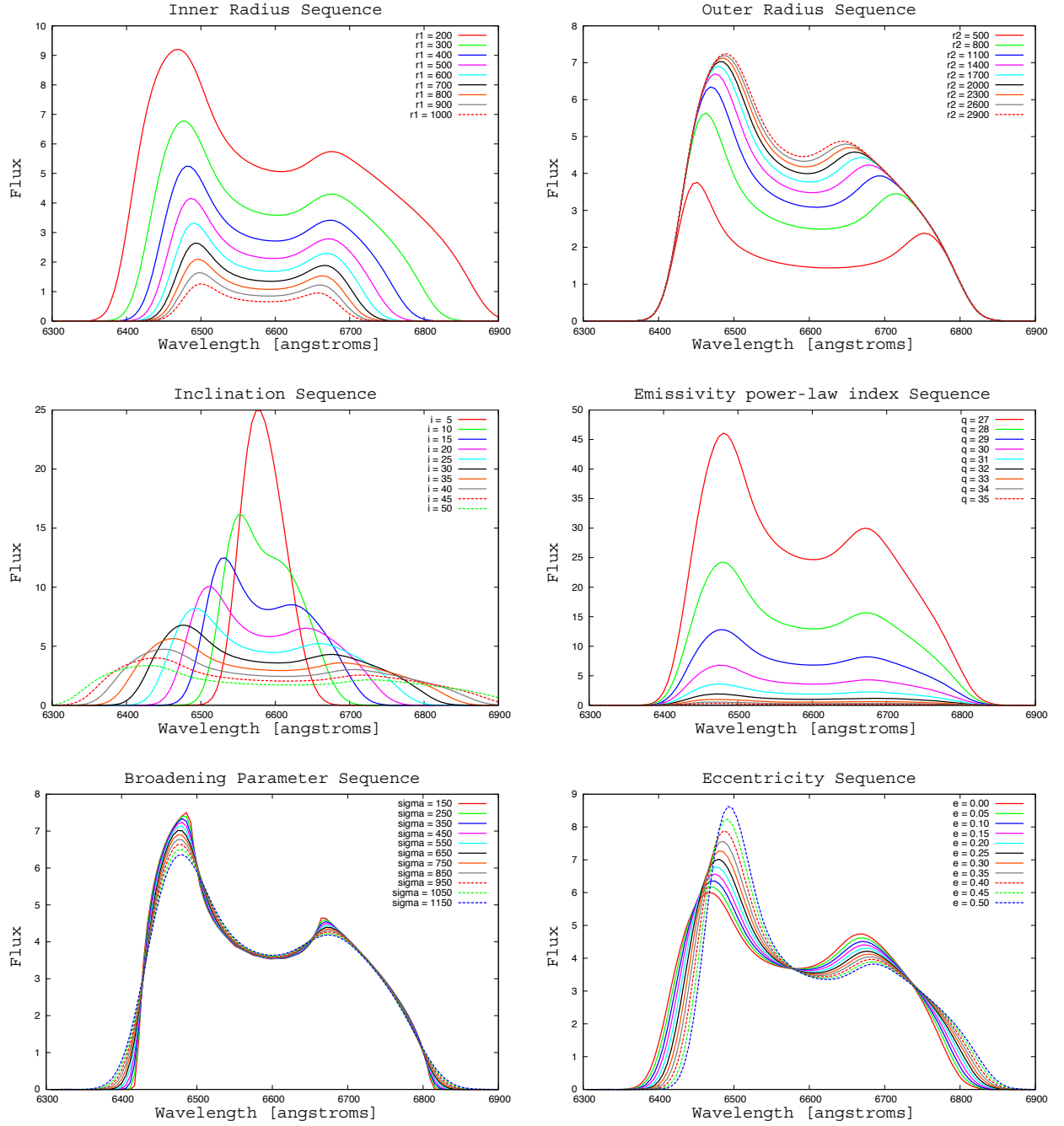


Figure 5.4: Sequences of examples of model H α profiles of elliptical accretion disk, showing the effects of selected disk parameters on the profile shapes: inner radius r_1 (top left), outer radius r_2 (top right), inclination i (middle left), emissivity power-law index q (middle right), local broadening velocity dispersion σ (bottom left), and eccentricity e (bottom right). In each sequence only one parameter is varied, while all other are held constant to the following values: $r_1 = 300$, $r_2 = 1500$, $i = 30^\circ$, $q = 3.0$, $\sigma = 850 \text{ km s}^{-1}$, $e = 0.2$, and orientation angle $\varphi_0 = 270^\circ$.

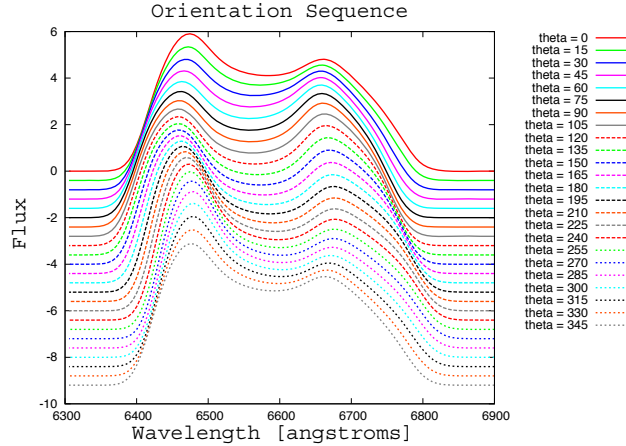


Figure 5.5: Sequences of examples of model H α profiles of elliptical accretion disk, showing the effects of orientation angle φ_0 on the profile, all other are held constant to the following values: $r_1 = 300$, $r_2 = 1500$, $i = 30^\circ$, $q = 3.0$, $\sigma = 850 \text{ km s}^{-1}$, $e = 0.2$.

5.3 Disk Parameter Fitting

We applied the elliptical accretion disk model described in the previous section to our observed mean spectra in order to derive the best disk parameters for our analysis.

To minimize the number of free parameters, we assumed a power-law index of the variation of emissivity with radius of $q = 3.0$ and a local broadening velocity dispersion of $\sigma = 850 \text{ km s}^{-1}$, which are obtained by Chen & Halpern (1989) as the best values fit to Arp 102B. The effect of value of σ on the profile fitting should be small. We adopted a black hole mass of $M = 3.5 \times 10^8 M_\odot$ for Arp 102B (Sergeev, Pronik, & Sergeev, 2000) for calculation of model line profile.

We took iterative steps to find the best parameter values effectively, reducing the range of parameter values as follows: (1) we choose several parameter values around the most probable value within some range of values, (2) find the best combination of values giving the minimum squared sum of residuals between the model and observation, calculating model line profiles for all combinations of values, (3) go back to the first step but reducing the range of values. We took three iterations to obtain the final values. For the calculation of squared sum of residuals, we used the data within a range of 6300–6900 Å, but we excluded the data within a range of 6510–6625 and 6685–6785 Å because these region is affected by an error of narrow line removal and there are an additional component (“ordinary” BLR with FWHM $\approx 3500 \text{ km s}^{-1}$) at the central part as found by Halpern et al. (1996). Table 5.1 shows the parameter values used to find the best values that fit the mean line profiles during 2013 May–June and 2013 August.

Table 5.2 shows the finally adopted parameter values for the observed mean H α line profile and the values adopted in the previous studies (Chen & Halpern, 1989; Newman et al., 1997; Gezari, Halpern, & Eracleous, 2007). Figure 5.6 shows the model line profiles with the observed mean line profile and Figure 5.7 shows the model and observed line profiles normalized with the blue-peak intensity.

Table 5.1: Parameter values used to find the best values fit observed mean line profiles

Parameters	2013 May–June Mean Profile Fitting		
	Iteration 1	Iteration 2	Iteration 3
Inner Radius (r_1)	300, 600, 900 ^a	800, 900 ^a , 1000	850 ^a , 900, 950
Outer Radius (r_2)	1500 ^a , 2000, 2500	1300, 1500, 1800, 2000 ^a	1900 ^a , 2000, 2100, 2200
Inclination (i)	30°, 40°, 50 ^{oa}	45°, 50°, 55 ^{oa} , 60°	52 ^{oa} , 55°, 58°
Eccentricity (e)	0.2 ^a , 0.4, 0.6	0.1, 0.2 ^a , 0.3	0.15 ^a , 0.2, 0.25
Orientation (φ_0)	160°, 180°, 200°, 220°, 240 ^{oa} , 260°	230°, 240°, 250 ^{oa}	245°, 250°, 255 ^{oa}
2013 August Mean Profile Fitting			
Parameters	2013 August Mean Profile Fitting		
	Iteration 1	Iteration 2	Iteration 3
Inner Radius (r_1)	300, 600 ^a , 900,	500, 600 ^a , 700	550, 600, 650 ^a
Outer Radius (r_2)	1500, 2000, 2500 ^a	2300, 2500, 2800, 3000 ^a	2900, 3000 ^a , 3100
Inclination (i)	30°, 40°, 50 ^{oa}	45°, 50 ^{oa} , 55°, 60°	48°, 50°, 52 ^{oa}
Eccentricity (e)	0.2 ^a , 0.4, 0.6,	0.1 ^a , 0.2, 0.3	0.05, 0.1, 0.15 ^a
Orientation (φ_0)	160°, 180°, 200°, 220°, 240°, 260 ^{oa}	250°, 260°, 270 ^{oa}	265°, 270°, 275 ^{oa}

^a Best values in an iteration

Table 5.2: Adopted disk parameter values to model line profile of Arp 102B

	r_1	r_2	i ($^\circ$)	q	σ (km s^{-1})	e	φ_0 ($^\circ$)
This study (2013/5–6)	850	1900	52	3	850	0.15	255
This study (2013/8)	650	3000	52	3	850	0.15	275
Chen & Halpern (1989) ^a	350	1000	32	3	850		
Newman et al. (1997) ^b	240–400	500–1000	30.8	3	1050		
Gezari, Halpern, & Eracleous (2007) ^b	325–400	700–825	31	3	1050		
Popović et al. (2014) ^c	325	825	23	3	1050		

^a Circular accretion disk model was applied.

^b Circular accretion disk + a hot spot model was applied.

^c Circular accretion disk + a hot spot model was applied, shifting enter line by -900 km s^{-1} .

We obtained a much larger inner and outer radii and inclination than the previous studies. This could be because the line profiles at our observation period has a larger blue-to-red flux ratio ($=1.5$, especially, in 2013 May–June) than before. According to Figure 5.4, a larger blue-to-red flux ratio tends to lead larger inner and outer radii, however larger inner and outer radii tend to make a narrower shape, and to match the width of shape to the observation a larger inclination is leaded. Such a large flux ratio in some epochs is already reported by several authors (Newman et al., 1997; Sergeev, Pronik, & Sergeea, 2000; Gezari, Halpern, & Eracleous, 2007; Popović et al., 2014). Newman et al. (1997) found that the circular disk model cannot provide a good fit to the profile from late 1990 through 1995 and the ratio vary sinusoidally with an amplitude of about 16 % during this period, which corresponds to a variation of flux ratio between 1 to 1.38. They found that the addition of a hot spot, which locates at a radius of $455 r_g$ and rotates with a period of 2.16 year, into the circular disk model can provide a good fit to their data. Gezari, Halpern, & Eracleous (2007) and Popović et al. (2014) also adopted a similar circular disk model with a hot spot to fit their observed line profile. Gezari, Halpern, & Eracleous (2007) reported the oscillation of flux ratio reappeared in the period of 1999–2005. They found a radius of $757 r_g$ and a period of 2.03 year as location and rotation period of hot spot for the 1999–2005 period. Thus, an axisymmetric disk model cannot provide adequate fits to the observed line profile Newman et al. (1997). To introduce an non-axisymmetry into the disk model, we adopted an elliptical disk instead of a hot spot here.

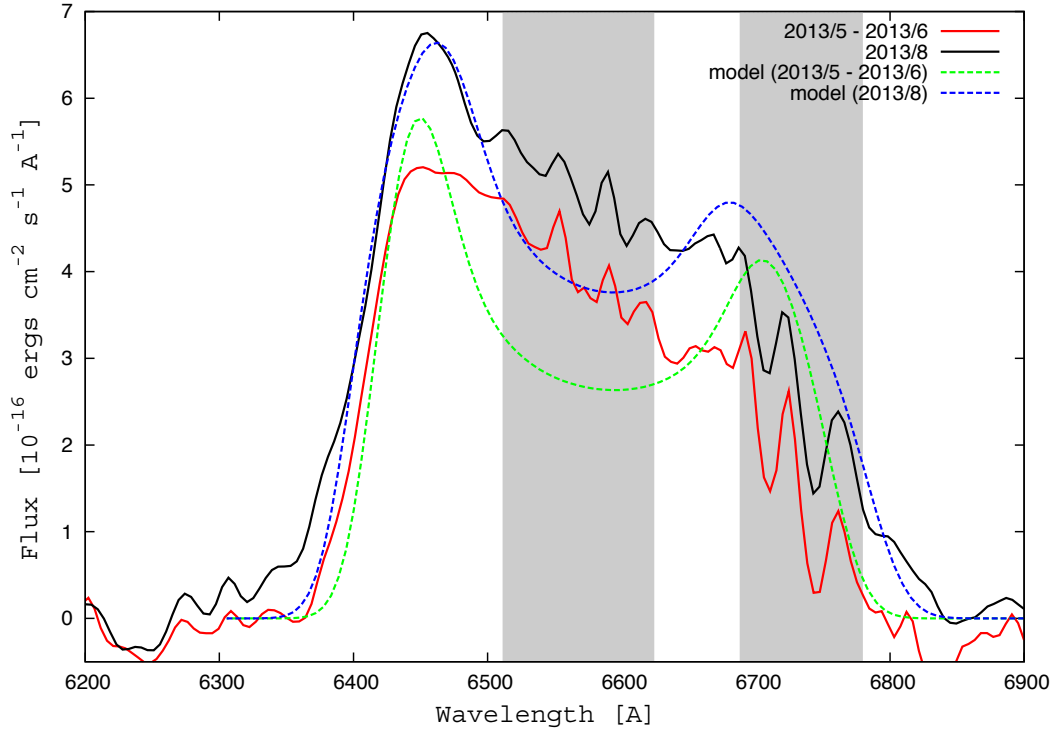


Figure 5.6: Adopted model line profiles for the observed mean line profiles. The red and black solid lines present the observed line profiles during 2013 May–June and 2013 August, respectively. The green and blue dashed lines present the model line profiles adopted for 2013 May–June and 2013 August data, respectively. Shadows present the wavelength regions not used for model fitting.

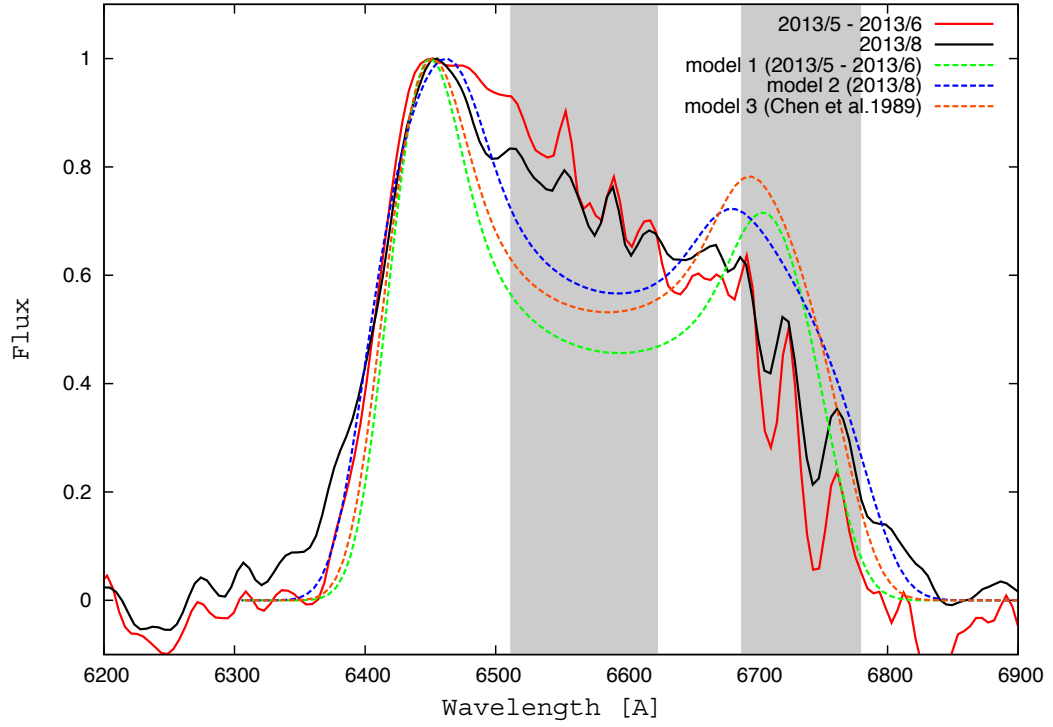


Figure 5.7: Normalized adopted model line profiles for the observed mean line profiles with the blue-peak intensity. The red and black solid lines present the observed line profiles during 2013 May–June and 2013 August, respectively. The green and blue dashed lines present the model line profiles adopted for 2013 May–June and 2013 August data, respectively. The red dashed line presents the model line profile obtained by Chen, Halpern, & Filippenko (1989) for comparison. Shadows present the wavelength regions not used for model fitting.

5.4 Response of Line Profile to Flux Variation in Central Source

Here, we present calculations of the response of the H α line profile from the adopted elliptical accretion disk to flux variations of the central ionizing source. Such a calculation was originally presented by Stella (1990) for a point-like central source, and it was extended for an extended source by Campana & Stella (1995). We consider here only a point-like central source.

Assuming that the disk emissivity responds instantaneously and depends linearly on ionizing photons and including delays by light travel time effects, the source variability can be included into the disk model by replacing equation (5.6) with a time variable emissivity given $\epsilon(\xi, \varphi', t)$ by ¹

$$\epsilon(\xi, \varphi', t) = \frac{\epsilon_0}{4\pi} \xi^{-q} S[t - \frac{r_g}{c} \xi (1 - \sin i \sin \varphi')], \quad (5.16)$$

where $S(t)$ is the intensity of ionizing source at time t .

For simplicity, we assume a step-like flare of the flux from the central ionizing source as given by

$$S(t) = \begin{cases} 1 & (t < 0) \\ 1 + f & (0 \leq t < t_d) \\ 1 & (t_d \leq t), \end{cases} \quad (5.17)$$

where f is an amplitude of flare normalized by the flux at the stationary state, and t_d is a duration time of flare.

Figure 5.8 (for the 2013 May–June model) and Figure 5.9 (for the 2013 August model) show the calculated line profiles and differences from the initial line profile for our adopted elliptical accretion disk models in the case of the duration time $t = 5$ days and the amplitude of flare $f = 1$ (corresponds to doubling of the flux from central source). For comparison, we present the calculation for the circular disk with disk parameters given by Chen & Halpern (1989) in Figure 5.10.

As described in Stella (1990), the figures present the two characteristic features (bumps) form on opposite sides of line, which owing to light travel-time effects, gradually drift from the line wings, corresponding to the innermost disk regions, to blue and red horns. We found the behavior of variability is basically independent of disk parameters. The amplitudes of bumps get larger rapidly at the line wings, and reach at the maximum just before the bumps arrive at the horns. After that, the amplitudes get smaller rapidly but somewhat slower than at raise. The time taken for the bumps to reach at the maximum is 5–7 days. The amplitudes of bumps at the maximum is about 10 % of the peak of line profile at the stationary state.

To parametrize the variation of the modeled line profile and to compare the observations, we measured the blue and red line-segment flux, the flux ratio of the blue line-segment to red line-segment, and the blue-peak wavelength. The wavelength intervals of line-segments are 6395–6502 and 6629–6775 Å, which are the same as those for the observed data (see Figure 4.5).

¹We note that the actual numerical calculations of line profiles in this section were done using a equation $\epsilon(\xi, t) = (\epsilon_0/4\pi) \xi^{-q} S[t - (r_g/c)\xi]$, instead of equation (5.16).

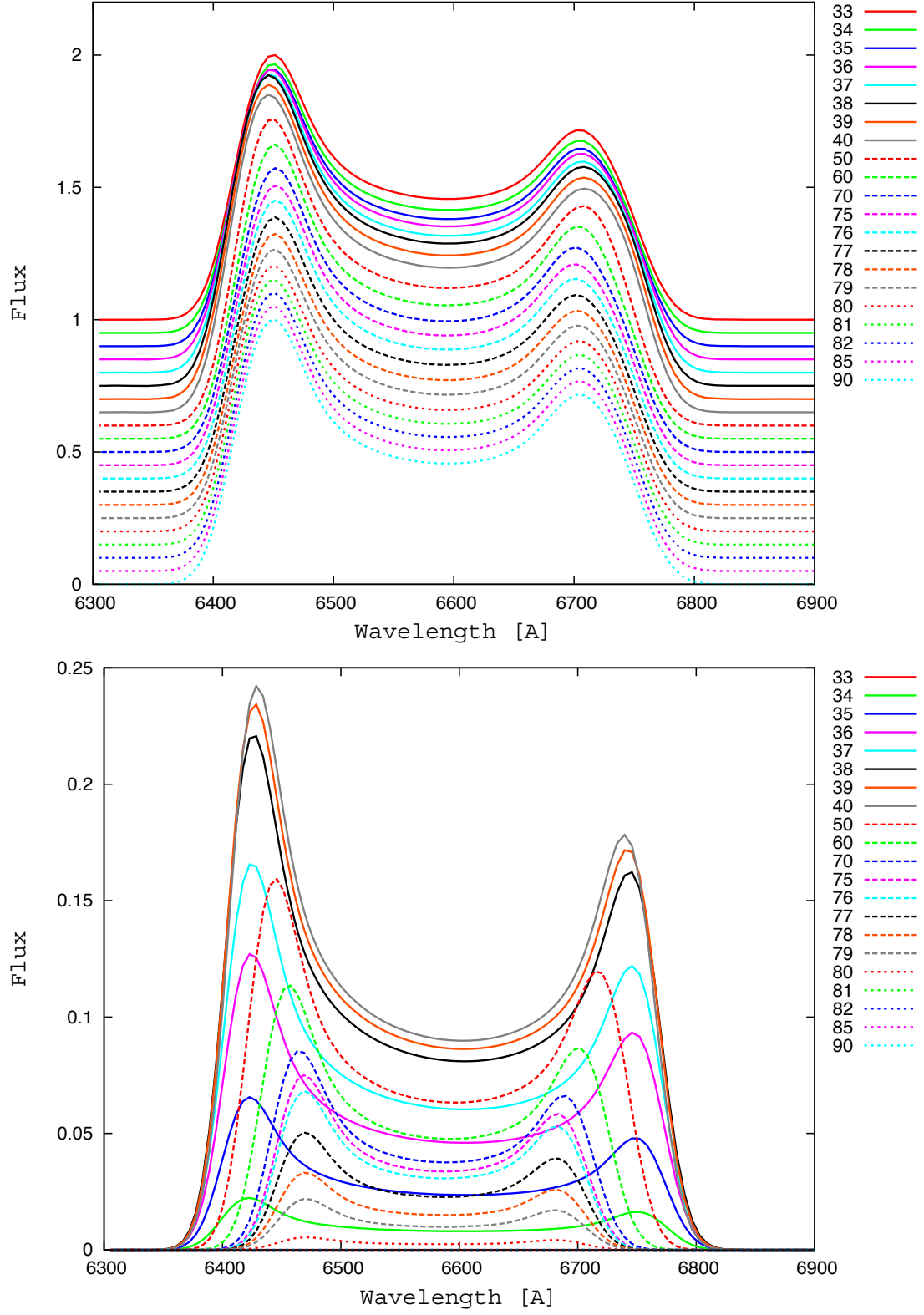


Figure 5.8: Modeled line profiles (top) and differences from initial profile (bottom) at time t (in units of day) for the elliptical disk adopted for the observed mean profile during 2013 May–June.

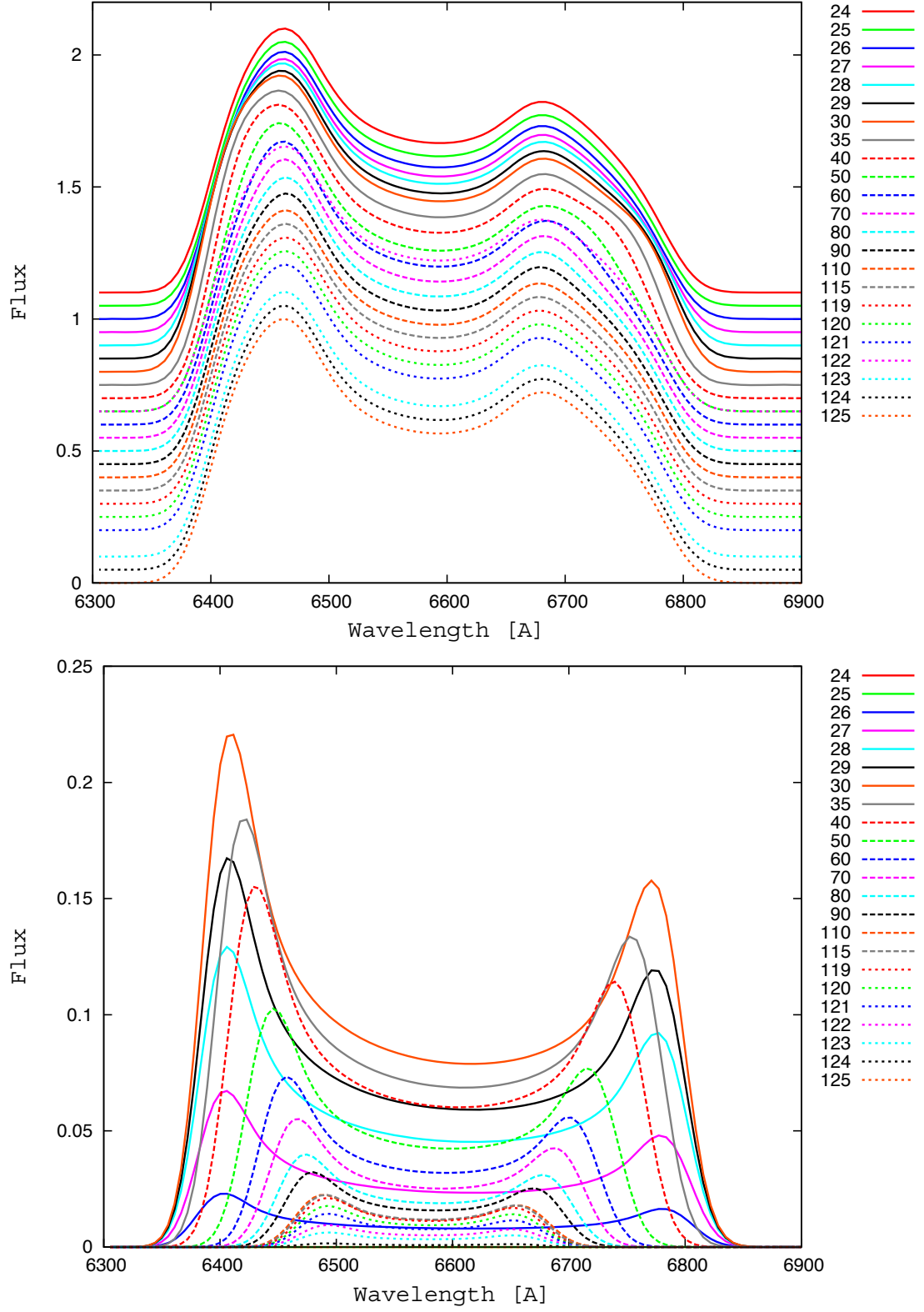


Figure 5.9: Modeled line profiles (top) and differences from initial profile (bottom) at time t (in units of day) for the elliptical disk adopted for the observed mean profile during 2013 August.

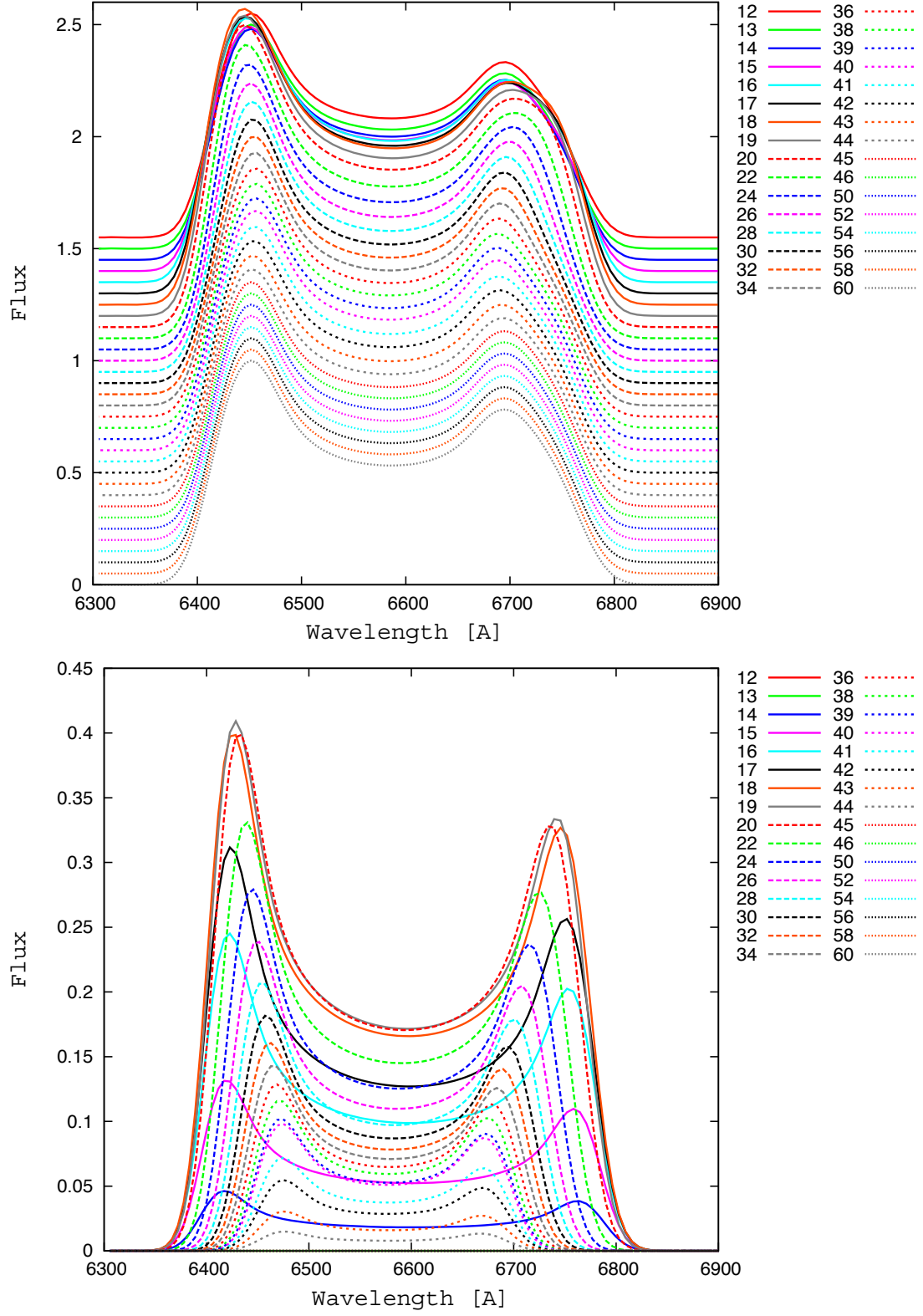


Figure 5.10: Modeled line profiles (top) and differences from initial profile (bottom) at time t (in units of day) for the circular disk with disk parameters given in Chen & Halpern (1989).

Figure 5.11 shows the variations of the blue and red line-segment fluxes, the flux ratio, and the blue-peak wavelength for the elliptical disks adopted for the observed mean profile during 2013 May–June and 2013 August. Figure 5.12 also shows the variations for the circular disk with disk parameters given in Chen & Halpern (1989). The figures show that the blue and red line-segment fluxes present a very similar variations. They raise rapidly to the maximum with a time scale of 5–7 days after the echo front of source flare reaches at the inner edge of the emitting region of disk. After they get the maximum, they decrease gradually until the final part of the source flare pass through the outer edge of the emitting region of disk. The flux ratio shows only a small amplitude of variation (0.4–1.5 %) because of similarity between variations in blue and red line-segment fluxes. The blue-peak wavelength varies by several Å. It get bluer by 3–5 Å at first rapidly, and then redder by 5–8 Å gradually until the echo front of source flare reaches at the outer edge of the emitting region of disk, and then it back to the original wavelength.

Figure 5.13 shows the evaluational track of relationship between the flux ratio and the blue-peak wavelength for the modeled variation of the adopted accretion disk models (top panel of figure). The figure shows clearly that the tracks evolve almost only along the vertical direction (peak wavelength) independently of the disk parameters, while the position of track depends on the disk parameters.

The bottom panel of Figure 5.13 shows the comparison of the evolution tracks of the modeled variation with the observations. Basically, the observed tracks have a different behavior from the model. It may imply that the observed variations does not the result in the reverberation effect from the accretion disk.

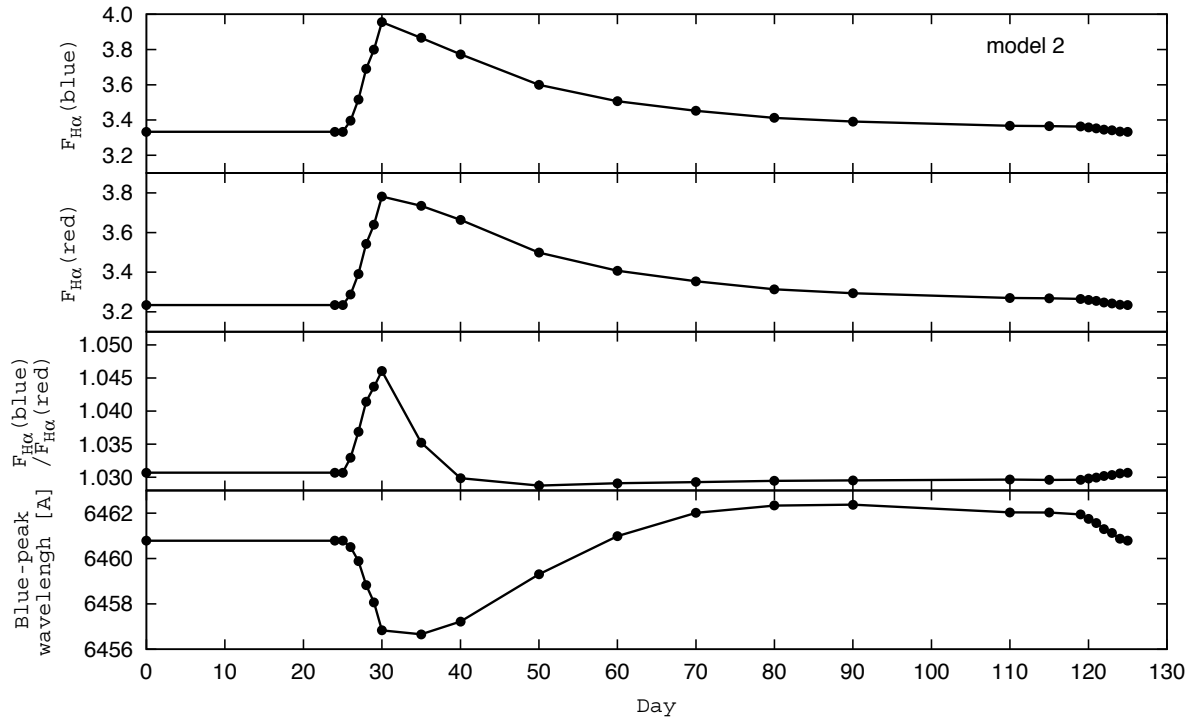
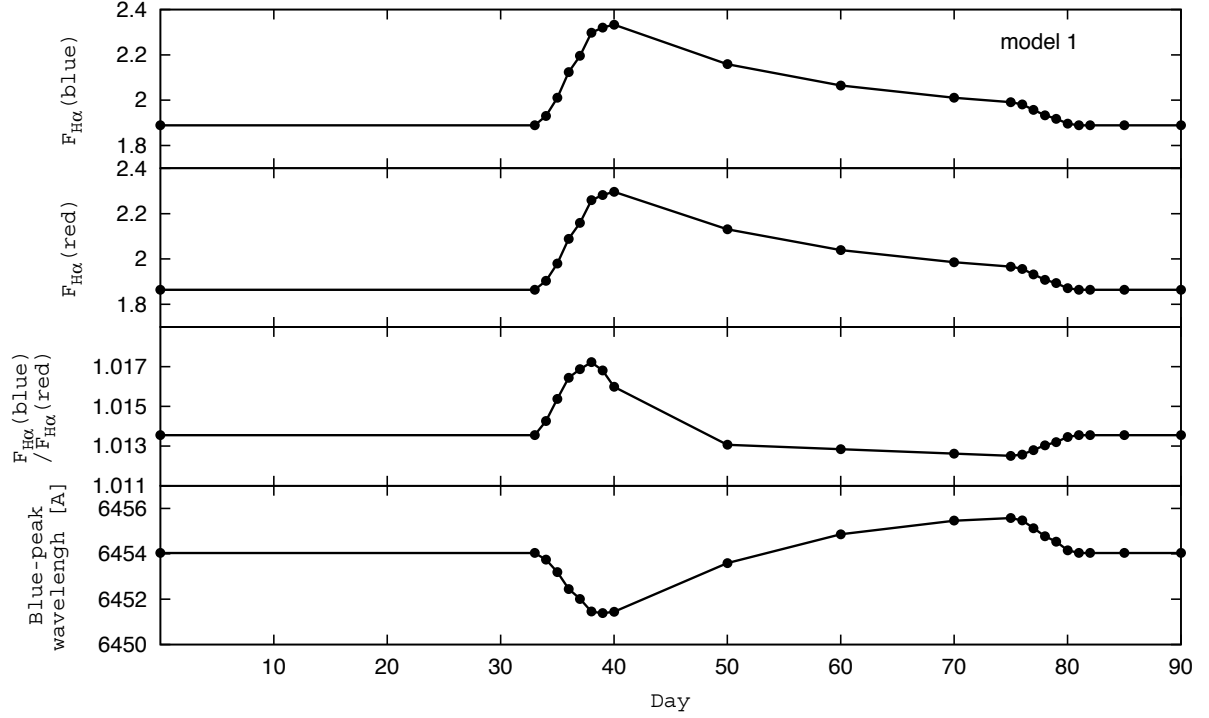


Figure 5.11: Modeled variations of blue and red line-segment fluxes, flux ratio, and blue-peak wavelength for the elliptical disks adopted for the observed mean profile during 2013 May–June (top) and 2013 August.

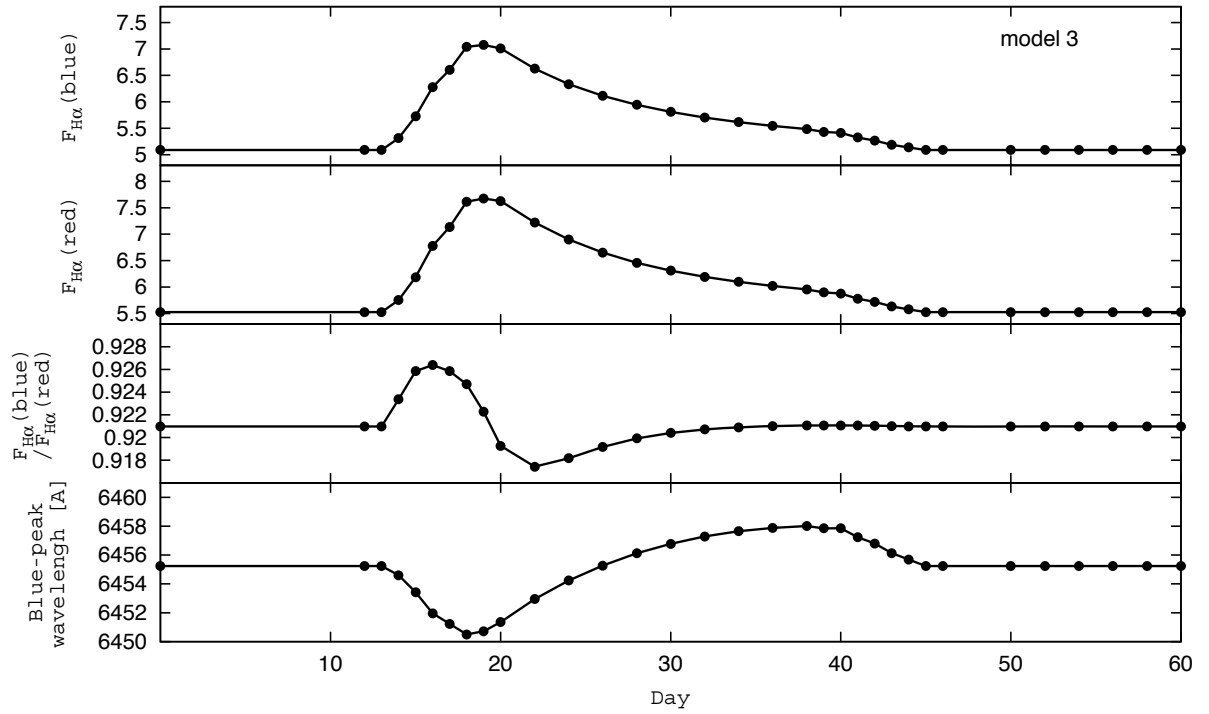


Figure 5.12: Modeled variations of blue and red line-segment fluxes, flux ratio, and blue-peak wavelength for the circular disk with disk parameters given in Chen & Halpern (1989).

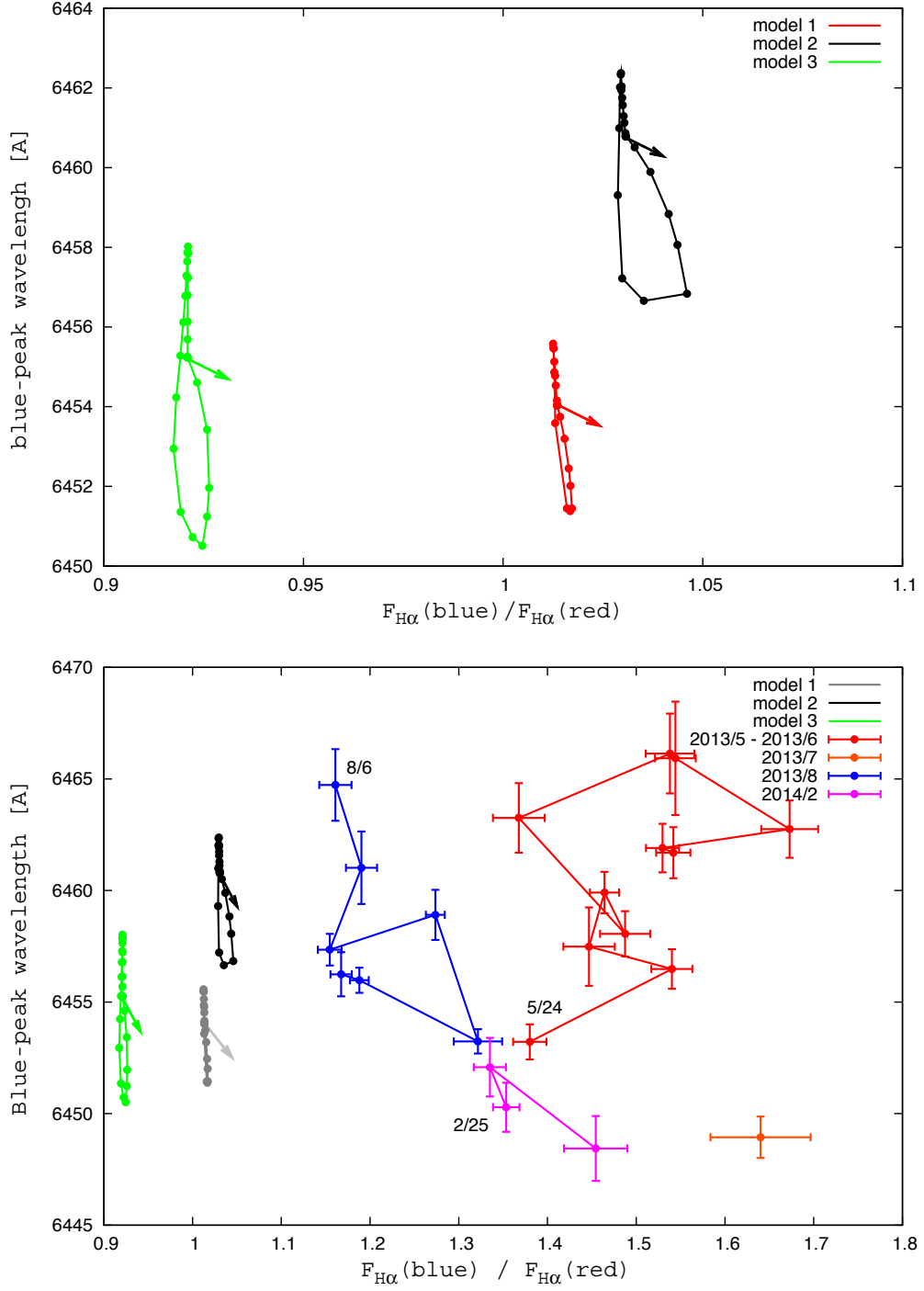


Figure 5.13: Evaluational track of relationship between flux ratio and blue-peak wavelength for modeled accretion disk (top) and comparison with the observed tracks (bottom). The red, green, blue, and purple points present the data in the period of 2013 June, July, August, and 2014 February, respectively. The number at the end of line presents the starting date and point of each track. The model 1, 2, and 3 indicate the modeled tracks of our adopted elliptical disk model for 2013 May–June and 2013 August mean profiles, and circular disk model given in Chen & Halpern (1989).

Chapter 6

Discussion

6.1 Reverberation from the Accretion Disk

We performed the high-frequency spectroscopic monitoring of the double-peaked H α profile of Arp 102B, and tested the presence of the reverberation from the accretion disk as predicted by Stella (1990) by modeling the evaluational track of the relationship between the blue-to-red flux ratio and the blue-peak wavelength. We have detected a small rapid variability of the double-peaked profile with a time scale of a few or ten days as changes in both the blue-to-red flux ratio (about 10 %) and the blue-peak wavelength (about 10 Å). However, our reverberation model predicts the constancy of the blue-to-red flux ratio against the change in the blue-peak wavelength, and this prediction is inconsistent with our observed evaluational track.

We adopted an elliptical accretion disk for modeling of the double-peaked line profile and reverberation effects from it. The elliptical accretion model leads to much large inner and outer radii, and a much larger inclination angle compared to the previous modeling by other authors. (Newman et al., 1997) mentioned that the elliptical disk model provided an excellent fit to the line profiles with a large blue-to-red flux ratio, however much poorer fits to the line profiles with a small blue-to-red flux ratio were achieved, and only then by allowing the eccentricity to vary from 0.1 to 0.59, the power law index q to vary from 2.2 to 3, and inclination i to vary from 28° to 31.5° , all simultaneously. They indicate such variations are more or less unrealistic. Therefore, our disk parameters adopted for the reverberation calculations could not well reproduce the actual disk geometry and dimensions. However, the basic behavior of the evaluational track of the relationship between the blue-to-red flux ratio and the blue-peak, namely, the constancy of the blue-to-red flux ratio against the change in the blue-peak wavelength, is almost independent of the disk parameters, as mentioned in the previous section. The constancy of the blue-to-red flux ratio is mainly due to mirror symmetry of disk geometry between bluer and redder sides of double-peaked line. Therefore, the model with a hot spot onto the accretion disk may predict some change in the blue-to-red flux ratio.

The calculations of reverberation from an accretion disk by Stella (1990) and us predict the two drifting features (bumps) on the wings of the line profile, which move towards the line center on time scales (5–7 days in our calculations) shorter than the light-crossing time of the disk (about 20 days for the inner and outer radii in our model), assuming a step-like variation

of the ionizing radiation from the central source. We could not find such a drifting feature in our observed spectral profile, although it is difficult to detect such a feature in the red region because there are several random spike-like features mainly due to error of removal of narrow-line components in this region. The absence of drifting features also supports that the observed variability of double-peaked profile is not the result of the reverberation from the accretion disk.

Gezari, Halpern, & Eracleous (2007) reported the rapid change in shape of the profile of Arp 102B during the small amplitude, rapid flare with a period of less than 9 days in 1989 July. They detected a narrower and stronger blue-peak, and a dramatically weaker red wing during this flare. This feature resembles the narrower and stronger blue peak in our observed profile at May 25 in 2013 during the small amplitude, rapid flare of flux, which disappeared soon after a few day. Although a weaker red wing was not seen at the same time in our observation, it may be the same phenomena. They also observed a similar profile change during the long flare in 1998. The flare in 1998 occurs over a much longer time scale than the light-crossing time. Therefore, they concluded the reverberation effect are unlikely to be causing the changes in the profile shape during both flares. They also mentioned that rapid flare temporarily fully ionize the inner regions of the disk, causing an increase in the effective inner radius of the line-emitting portion of the disk or a flatter emissivity law at small radii, and then resulting a decrease of in the strength of the wings, a shift of the peaks to lower velocities, and decrease in blue-to-red flux ratio. They mentioned that the increase of blue-to-red flux ratio during the flares is not compatible with this reverberation scenario.

As mentioned by Eracleous & Halpern (1993), a necessary requirement for the specific reverberation effects predicted by Stella (1990) is that the source of the ionizing radiation exhibit sharp, large-amplitude flares on time scales shorter than the light-crossing time of the light-emitting portion of the accretion disk. Our model calculations predict the amplitudes of bumps due to the reverberation effect is about 10 % of the peak of line profile at the stationary state in the case that a rapid flare with an amplitude of 100 % occurs in the central source. Therefore, the absence of reverberation effects with an amplitude above our detected variation level of 10 % indicates that the central source ionizing the accretion disk of Arp 102B had not a large rapid flare with a time scale of shorter than about ten days and an amplitude of above 100 % during our observation period.

From the above discussion, we conclude that the reverberation effect from the accretion disk does not dominate our observed rapid variability of the double-peaked profile. However, we could not completely exclude the possibility to detect the reverberation effect from accretion disk. In our observation period, the double-peaked line have been unusually faint, which is an half in flux compared to that in the bright state. The fainter the double-peaked line is, the less dominant its variability compared to other time-variable components, and it makes the detection of reverberation effect more difficult. To detect the reverberation effect from accretion disk, we suggest the observations of Arp 102B when the double-peaked line becomes bright again and the further high-frequency monitoring observations for other objects with a bright double-peak line such as 3C 390.3.

We assumed a point-like source as the ionizing light source of accretion disk. However, in the double-peaked broad emission line AGN such as Arp 102B, the extended central source such as an ion torus (Chen & Halpern, 1989) and a radiatively insufficient accretion flow (RIAF; Nemmen

et al., 2006; Quataert, 2001; Narayan et al., 1998) is expected theoretically and observationally from their SEDs. It is also suggested that the double-peaked lines arise at an outer region of an accretion disk by illuminated with an inner, geometrically thick RIAF (Nagao et al., 2002). Therefore, the models with a point-like illuminating source might be inappropriate to test the reverberation effect from accretion disk in the double-peaked broad emission, and the calculation of reverberation effect in case of extended illuminating source, which is presented by Campana & Stella (1995), might be required. Recently, Wilkins & Fabian (2013) found that the central X-ray source of Seyfert 1 galaxy 1H 0707–495 is extending radially outwards to around $35 r_g$ and at a height of $2 r_g$ above the plane of accretion disk from the reverberation studies with X-ray emission. In the X-ray region, there are some evidence of the reverberation from the accretion disk (See review by Uttley et al., 2014) and more advanced and realistic analysis with such Fourier analysis techniques to extract the reverberation effect from randomly fluctuated light curves. The further analysis with the above techniques will be required to check the detectability and to characterize the reverberation effect in the double-peaked broad emission line AGN.

6.2 Origin of Small Rapid Variability

Halpern et al. (1996) found that there are an additional component with $\text{FWHM} \approx 3500 \text{ km s}^{-1}$ at central part of double-peak $\text{H}\alpha$ line profile of Arp 102B. This component is a possible origin of the observed rapid variability of flux. It is thought to be an broad emission line from the ordinary BLR usually shown in the normal broad-line AGN. The broad emission lines in normal AGN show a small variability of a few percent level both in flux and shape of profile (e.g. Barth et al., 2015). Although we could not separate this component from the observed spectra because the shape of this emission line is unknown, it is likely to be a origin of observed variability because the normal broad-line emission can also vary rapidly in a few days time scale, responding to change of the central ionizing continuum source flux.

Another possible origin is an outflow in the BLR. Popović et al. (2014) reported the presence of an outflow in the BLR of Arp 102B. They found a bump in the blue part of the $\text{H}\alpha$ line around -2500 km s^{-1} during some periods in their monitoring term from 1987 to 2013. Figure 6.1 shows the bump in the $\text{H}\alpha$ line profile in years when it is most intensive. The presence of outflow is expected by Couto et al. (2013). They found a two-armed nuclear spiral recently, as shown in Figure 6.2. They estimated a mass outflow rate along the east arm of $0.26\text{--}0.32 M_\odot \text{ yr}^{-1}$, which is between one and two orders of magnitude higher than the mass accretion rate to the active nucleus, implying that there is mass-loading of the nuclear outflow from circumnuclear gas.

Figure 6.1 shows the monthly averaged line profiles of our observed spectra overlaid on the data of Popović et al. (2014) to check the presence of the bump. The mean line profiles of our observed spectra show no clear evidence of presence of an outflow around -2500 km s^{-1} . It may imply the activity of outflow is basically low in our monitoring period.

Figure 6.3 and Figure 6.4 show the daily line profiles and the differences from the mean line profiles during the 2013 May–June and August monitoring periods, respectively. An excess around -3000 km s^{-1} is seen on the line profile at 2013 August 6. This excess decreases gradually and almost disappeared after an half of month. It may suggest a rapid variability of the outflow component. However, there are no clear excess except this.

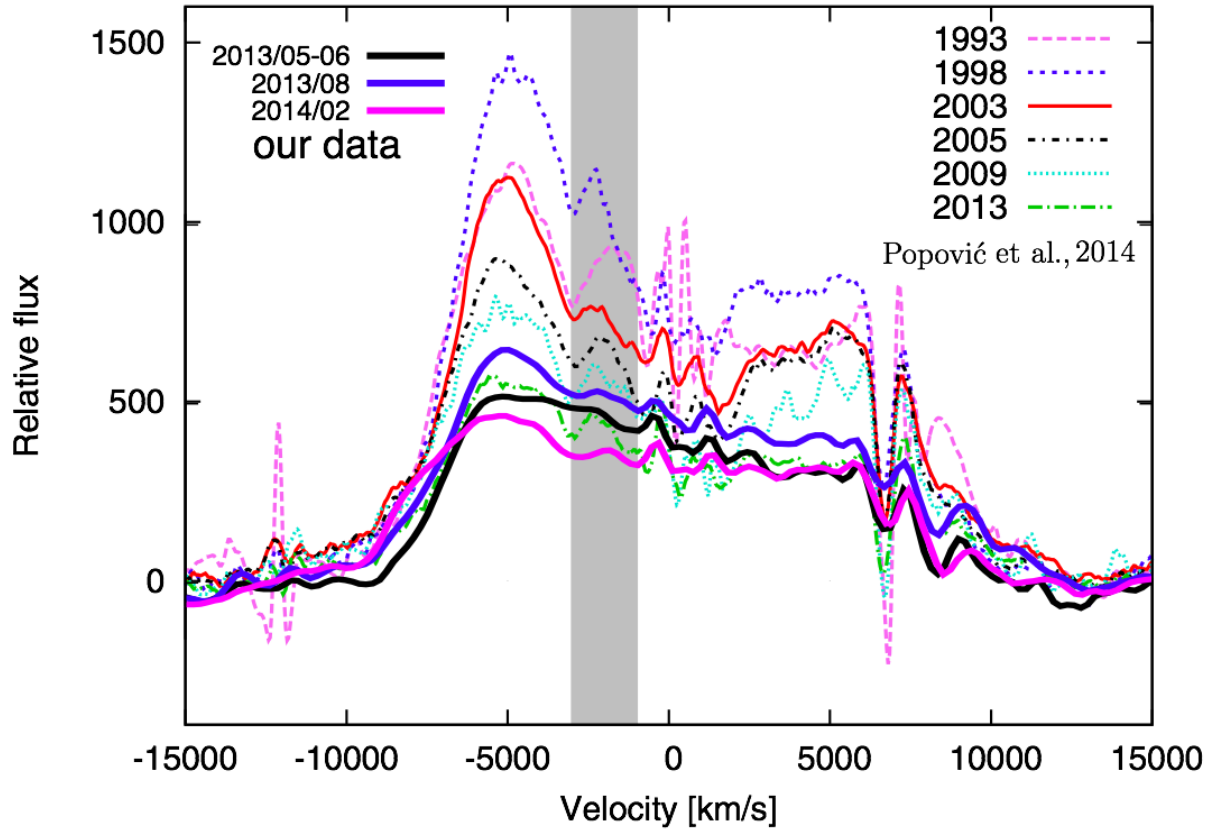


Figure 6.1: Bump in the $H\alpha$ line profile of Arp 102B at $\sim -2500 \text{ km s}^{-1}$ found by Popović et al. (2014). Mean line profiles of our observed spectra are overlaid to check the presence of the bump in our spectra.

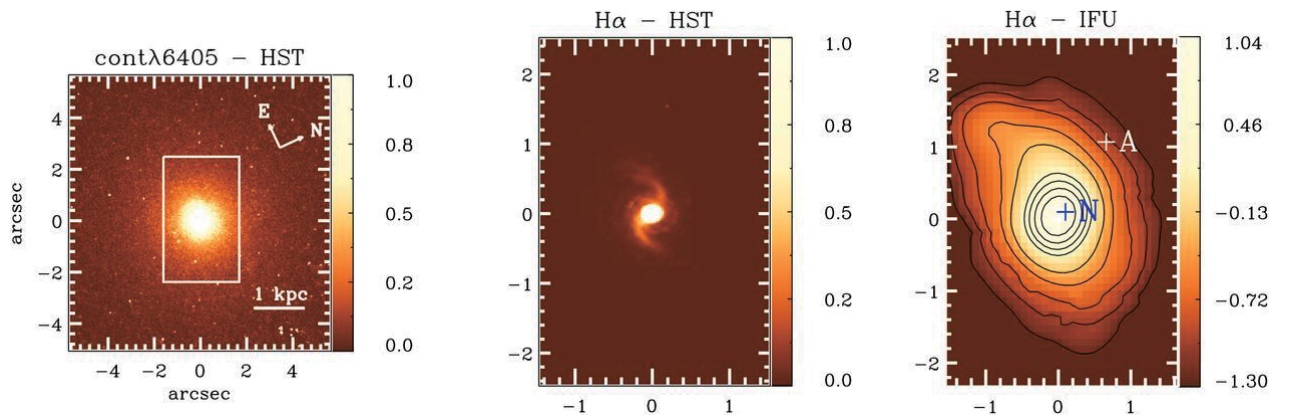


Figure 6.2: Left: $6405\text{\AA}$ continuum map of Arp 102B obtained with the HST-ACS camera. The rectangle shows the GMOS IFU FOV. Center: $H\alpha$ flux map obtained with ACS within the IFU FOV. Right: $H\alpha$ flux map from the IFU spectroscopy (Couto et al., 2013).

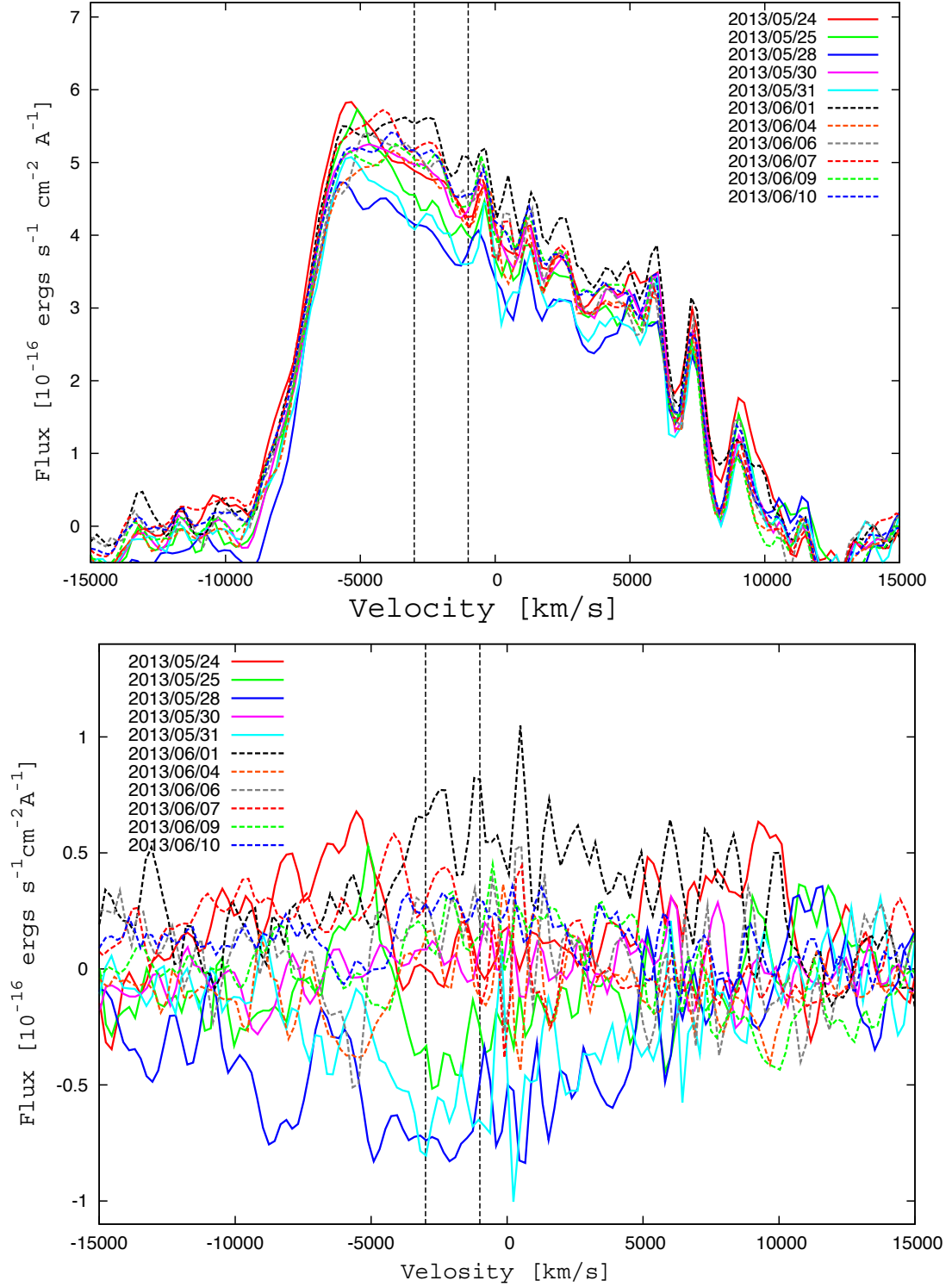


Figure 6.3: Observed daily line profiles (top) and differences (bottom) from mean line profile of Arp 102B during the 2013 May–June monitoring period. Dashed lines show a region from -3000 to -1000 km s^{-1} .

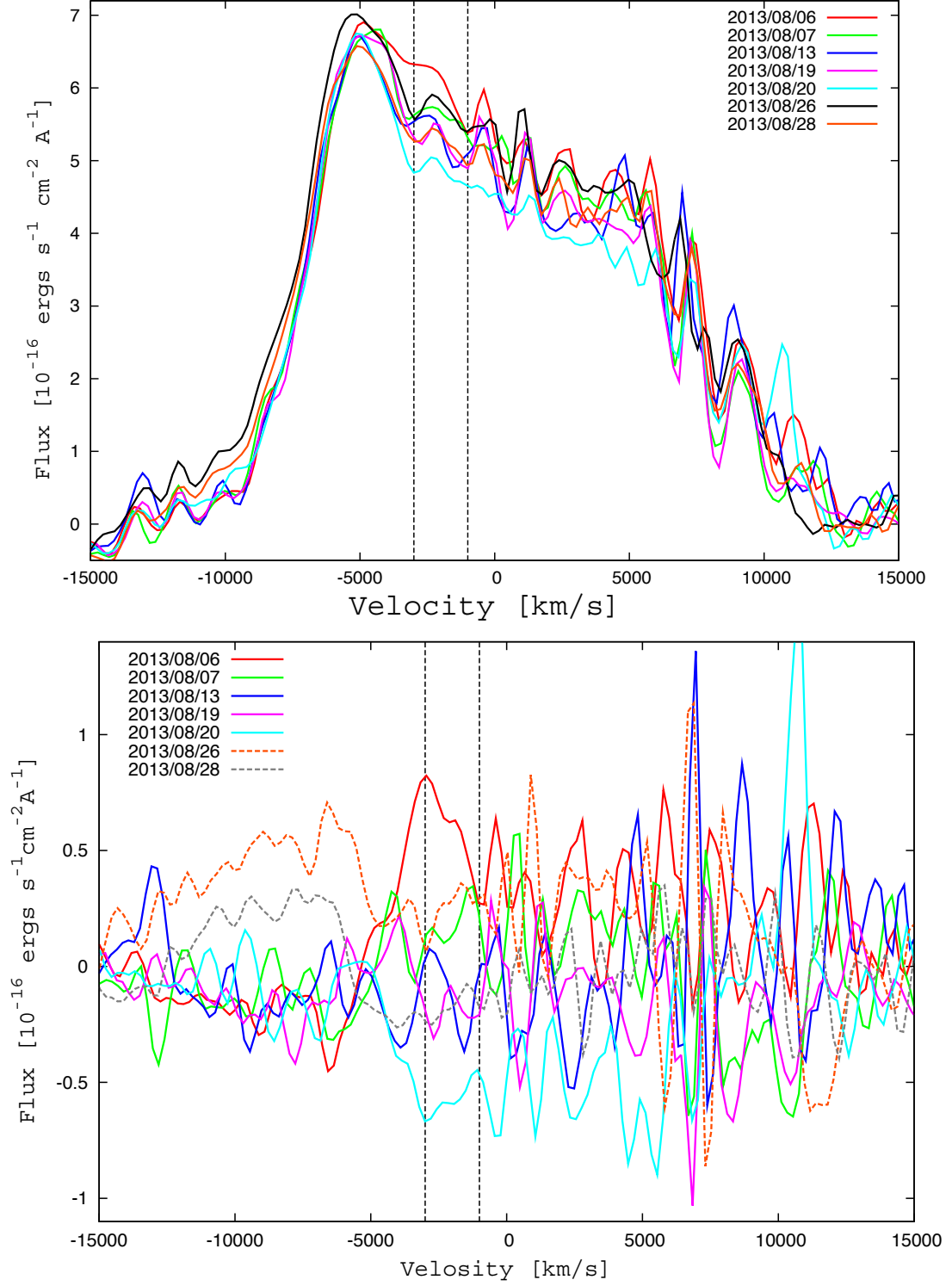


Figure 6.4: Observed daily line profiles (top) and differences (bottom) from mean line profile of Arp 102B during the 2013 August monitoring period. Dashed lines show a region from -3000 to -1000 km s^{-1} .

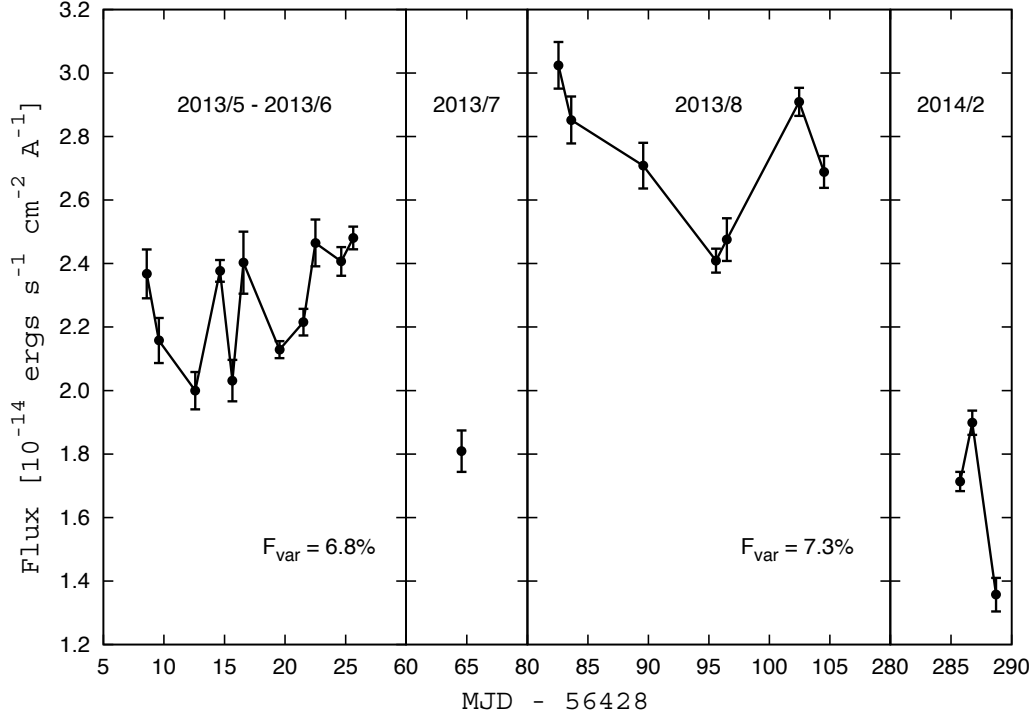


Figure 6.5: Light curve of flux integrated over the velocity range of -3000 to -1000 km s^{-1} for our observed $\text{H}\alpha$ line profile.

Figure 6.5 shows the light curve of flux in the velocity region of -3000 to -1000 km s^{-1} and the net amount of variability (F_{var}). The net amount, which is $F_{\text{var}} = 6.8$ and 7.3 for 2013 May–June and August, respectively, is comparable to or slightly larger than the net amount of variability in the blue line-segment. It might indicate that the variable component more dominates in this region than in the blue line-segment region, although it is unclear because the difference is not so large.

Assuming there are an outflow component in this velocity region, we estimate a lower limit of emitted energy by outflow. From the net amount of variability, it is estimated to be about $5 \times 10^3 L_{\odot}$ ($= 1.9 \times 10^{37} \text{ erg s}^{-1}$) in both the periods. This is about 0.015 – 0.06 % of a kinetic power for the outflow of 0.3 – $1.3 \times 10^{41} \text{ erg s}^{-1}$ estimated by Couto et al. (2013).

Chapter 7

Conclusions

The detection of reverberation effects from an accretion disk in an active galactic nucleus (AGN), which is predicted by Stella (1990) for the double-peaked line AGN, can illuminate the structure and kinematics of the broad-line region (BLR) and permit a measurement of the central mass and the size of the extended ionizing central source such as a radiatively insufficient accretion flow (RIAF). In order to test the presence of the reverberation effects from an accretion disk in the double-peaked AGN, we performed a high-frequency imaging and spectroscopic monitoring of the double-peaked $H\alpha$ line of Arp 102B with a short interval of a day.

To enable us to achieve such a high-frequency monitoring observations, we newly developed a visible imager and spectrograph, Nayoro Optical Camera and Spectrograph (NaCS) for the 1.6-m Pirka telescope of the Hokkaido University. This instrument has a CCD with quite a high quantum efficiency over a wide wavelength range (440–920 nm) and it is designed to enable to switch the observation modes quickly between the imaging and spectroscopy modes to improve the observing efficiency. The combination of this high efficient instrument and the Pirka telescope, which is focusing on monitoring observations, enables us to do high-frequency monitoring observations efficiently.

The monitoring observations of Arp 102B were carried out during 2013 May–June, 2013 August, and 2014 February over a month each period, and we succeed in obtaining 25 spectra of Arp 102B. We found that the double-peaked $H\alpha$ line of Arp 102B was unusually faint, which is an half of the flux at the past bright state, during our observation period. Nevertheless, we detected a small rapid variability of the double-peak $H\alpha$ line of Arp 102B with 5–10 % in flux, about 10 Å in blue-peak wavelength, and about 10 % in blue-to-red flux ratio, with a time scale of a few to ten days.

To test the presence of the reverberation effects from an accretion disk in the observed variations, we modeled the double-peak line profile with an elliptical accretion disk and computed the response of the $H\alpha$ line profile from the accretion disk to a step-like flux variation of the central ionizing source. As a result, we found that the model predicts the constancy of the blue-to-red flux ratio against the change in the blue-peak wavelength and that this behavior is almost independent of the disk parameters of accretion disk model. This predicted behavior is inconsistent with our observed behavior of the flux ratio and blue-peak position. We also could not find any drifting bumps that move from the wings of the line profile towards the line center with a time scale of 5–7 days, which is predicted as a result of light travel-time effects of

the echo front of the source flux variation. Therefore, we conclude that the reverberation effect from the accretion disk does not dominate our observed rapid variability of the double-peaked profile. It may imply that the central source ionizing the accretion disk of Arp 102B had not a large rapid flare with a time scale of shorter than about ten days and an amplitude of above 100 % during our observation period. We suggest that the observed small rapid variability is possible to originate from the variability of an ordinary broad-line or outflow components in the BLR of Arp 102B. Long-term high-frequency spectroscopic monitoring observations with a short interval of a day scale over a month are much important to construct the model of AGN including the RIAF and accretion disk in detail.

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