EVOLUTION OF THE ACCRETION DISK AROUND THE SUPERMASSIVE BLACK HOLE OF NGC7213

JADERSON S. SCHIMOIA, THAISA STORCHI-BERGMANN
Instituto de Física, Universidade Federal do Rio Grande do Sul, Campus do Vale, Porto Alegre, RS, Brazil

CLÁUDIA WINGE
Gemini South Observatory, c/o AURA Inc., Casilla 603, La Serena, Chile

RODRIGO S. NEMME
Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Departamento de Astronomia, São Paulo, SP 05508-090, Brazil

AND

MICHAEL ERACLEOUS
Department of Astronomy and Astrophysics and Institute for Gravitation and the Cosmos, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA

The Astrophysical Journal, Version of February 2015

ABSTRACT

We present observations of the double-peaked broad Hα profile emitted by the active nucleus of NGC7213 using the the Gemini South Telescope in 13 epochs between 2011 September 27 and 2013 July 23. This is the first time that the double-peaked line profile of this nucleus – typical of gas emission from the outer parts of an accretion disk surrounding a supermassive black hole (SMBH) – is reported to vary. From the analysis of the line profiles we find two variability timescales: (1) the shortest one, between 7 and 28 days, is consistent with the light travel time between the ionizing source and the part of the disk emitting the line; and (2) a longer one of $\gtrsim$ 3 months corresponding to variations in the relative intensity of the blue and red sides of the profile, which can be identified with the dynamical timescale of this outer part of the the accretion disk. We modeled the line profiles as due to emission from a region between $\sim$ 300 and 3000 gravitational radii of a relativistic, Keplerian accretion disk surrounding the SMBH. Superposed on the disk emissivity, the model includes an asymmetric feature in the shape of a spiral arm with a rotation period of $\approx$21 months, which reproduces the variations in the relative intensity of the blue and red sides of the profile. Besides these variations, the $\text{rms}$ variation profile reveals the presence of another variable component in the broad line, with smaller velocity width $W_{\text{rms}}$ (the width of the profile corresponding to 68% of the flux) of $\sim$2100 km s$^{-1}$.

Subject headings: accretion, accretion disks — galaxies: individual (NGC 7213) — galaxies: nuclei — galaxies: Seyfert — line: profiles

1. INTRODUCTION

NGC7213 is a nearby ($z=0.005839$) Sa spiral galaxy. Its active nucleus was first classified as Seyfert 1 by Phillips (1979) based on its very broad Hα emission line (13,000 km s$^{-1}$ for the full width at zero intensity) and later was also recognized as low-ionization nuclear emission-line region (LINER) by Filippenko & Halpern (1984) based on a study of a variety of optical emission lines which were observed to have full width at half maximum (FWHM) in the range of 200 – 2000 km s$^{-1}$. Its nucleus harbors a $\sim 10^8$ M$_\odot$ supermassive black hole (SMBH) (Woo et al. 2002), producing a bolometric luminosity of $L_{\text{bol}} = 7 \times 10^{43}$ erg s$^{-1}$ (Emmanoulopoulos et al. 2012).

The nucleus of NGC 7213 has been extensively studied in X-rays. XMM-Newton/BeppoSAX observations revealed that the AGN spectrum shows no significant Compton reflection component (Bianchi et al. 2003) – what is very peculiar among bright Seyfert 1 AGN’s. Additionally, these observations also revealed the presence of a significant Fe K complex. Bianchi et al. (2008) reported the data analysis of a long Chandra HETG observation finding that the neutral iron Kα line has a FWHM of $2400^{+1100}_{-600}$ km s$^{-1}$, claiming that it was fully consistent with the Hα FWHM ($2640^{+1100}_{-600}$ km s$^{-1}$). This seems to be at odds with the previous studies that showed a much broader profile or it may indicate a strong variation of the profile. Bianchi et al. (2008) concluded that the neutral Fe K line originates in the Compton-thin Broad Line Region (BLR) to explain the absence of Compton reflection and of any relativistic component in the lines. More recently, Lobban et al. (2010) reproduced the highly ionized iron K lines with a photoionization model where gas has a column density of $N_H > 10^{23}$ cm$^{-2}$ and is likely to be located between $10^3 - 10^4$ gravitational radii ($R_g$) from the central source. The authors suggest that the inner accretion flow is radiatively inefficient (RIAF, e.g., Yuan & Narayan 2014), which would explain the photoionization spectrum and the absence of the optically thick disk component.

Although the broad Hα emission line of NGC 7213 has been reported in previous works (Phillips 1979; Filip-
penko & Halpern 1984; Storchi-Bergmann et al. 1996), there are no variability studies of its profile to date. A recent study by Schnorr-Müller et al. (2014) (see Figure 1) showed its Hα line to present a very broad double-peaked component. Very broad double-peaked lines – with velocity separation of \( \sim 10,000 \text{ km s}^{-1} \) between the blue and red peaks are thought to originate in the outer parts of an accretion disk (Schimoia et al. 2012; Lewis et al. 2010). Models of ionized gas rotating in a relativistic Keplerian accretion disk around a SMBH have been successful in accounting for such double-peaked profiles (Chen et al. 1989; Chen & Halpern 1989; Storchi-Bergmann et al. 2003; Strateva et al. 2003; Lewis et al. 2010). These models explain most of the observed features of the profiles (Eracleous & Halpern 2003) and can help to constrain the physical properties of the line emitting part of the disk, as, for instance, the inner and outer limits for the emitting region as well as its inclination relative to the plane of the sky. Although other models have been considered for the origin of the double-peaked profiles, these are much less attractive than the accretion disk model (see discussion in Eracleous & Halpern (2003); Eracleous et al. (2009)).

Double-peaked profiles are expected to vary. Lewis et al. (2010) and Gezari et al. (2007) studied such variation for 14 double-peaked emitters in a long-term monitoring of these sources at time intervals ranging from several months to years. They found that all profiles showed variability on timescales of years. Recently, Schimoia et al. (2012, 2015), monitored the double-peaked Hα profile of NGC 1097 on shorter timescales and found that, besides presenting variations on similarly long (1.5 years) timescales, the profile also varied on timescales as short as a week or even shorter. They concluded that there are different timescales of variability in this source, which should apply also to other double-peak emitters, including NGC 7213.

In the present paper we model, for the first time, the double-peaked Hα profile of the NGC 7213 nucleus as due to emission from the outer parts of a relativistic, Keplerian accretion disk, constraining its properties. We also present a study of its variation from spectral monitoring of the profile over a time span of almost two years, from Sep 27, 2011 to Jul 23, 2013, including one time interval as short as a week. We find that the variation of the profiles reveal that, not only the double-peaked profile varies, on short and long timescales, but there is another broad component, with a velocity width \( \sim 2100 \text{ km s}^{-1} \), that is also variable.

This paper is organized as follows: in §2 we describe the observations and the data reduction; in §3 we present the observational results, the adopted accretion disk model, and the discovery of an additional variable component to the profile; in §4 we discuss the timescales of the accretion disk variability, the interpretation and implications of the modeling to the structure of the AGN and explore a determination of the mass of the SMBH through the model. The conclusions of this work are presented in §5.

2. OBSERVATIONS AND DATA REDUCTION

We obtained a total of 13 optical spectra of the nucleus of the galaxy NGC 7213 from 2011 September 27 to 2013 July 23. The observation of 2011 September 27 was obtained with the Integral Field Unit of the Gemini Multi Object Spectrograph (GMOS-IFU) at the Gemini South telescope (Schnorr-Müller et al. 2014; Gemini project GS-2011B-Q-23). These observations consisted of two adjacent IFU fields (covering 7″ × 5″ each) resulting in a total angular coverage of 7″ × 10″ around the nucleus. The wavelength range of this observation was 5600-7000 Å in order to cover Hα+[N II] \( \lambda \lambda 6548,6583 \) Å and [S II] \( \lambda \lambda 6716,6731 \) Å observed with the grating R400-G5325, which resulted in a resolution of R \( \approx 2000 \sim 150 \text{ km s}^{-1} \)). The seeing during the IFU observations was 0′.5, what results in a spatial resolution of 58 pc, and the sampling of the final reduced cube is 0′.1×0′.1.

The remaining 12 observations were taken between 2012 July 21 and 2013 July 23 with the spectrograph GMOS of the Gemini South telescope in the longslit mode (project ID GS-2012A-Q-86). The slit used was 1″0 wide and 330″ long and was oriented at the position angle of 305° in all observations. The grating was the B600-G5323 with the central wavelength of 5700 Å chosen to cover the Hα+[N II] \( \lambda \lambda 6548,6583 \) Å and Hβ \( \lambda 4862 \) Å and give a spectral resolution of R \( \approx 1688 \sim 177 \text{ km s}^{-1} \)). The instrumental setup of the longslit observations resulted in a pixel scale of 0.14 ″/pixel. Most visits consisted of 6 exposures each, giving a total of 2700s on source. Table 1 lists the dates of the observations, the instruments, number and length of exposures on each visit. The data were reduced using the standard procedures and packages for IFU and longslit modes in IRAF\(^1\). Throughout the paper, in all figures, the spectra are shown at the rest wavelength.

| UT Date | MJD | Mode | Exposures |
|---------|-----|------|-----------|
| Sep 27 2011 | 55831.130 | IFU | 12×350 |
| Jul 21 2012 | 56129.155 | Longslit | 6×450 |
| Jul 30 2012 | 56138.422 | Longslit | 6×450 |
| Oct 15 2012 | 56215.111 | Longslit | 6×450 |
| Nov 22 2012 | 56253.047 | Longslit | 6×450 |
| Apr 13 2013 | 56953.383 | Longslit | 6×450 |
| May 11 2013 | 56423.386 | Longslit | 6×450 |
| May 20 2013 | 56432.315 | Longslit | 6×450 |
| May 30 2013 | 56442.334 | Longslit | 6×450 |
| Jun 14 2013 | 56457.399 | Longslit | 6×450 |
| Jun 30 2013 | 56473.310 | Longslit | 6×450 |
| Jul 07 2013 | 56480.218 | Longslit | 6×450 |
| Jul 23 2013 | 56496.278 | Longslit | 6×450 |

\(^{Note.} \) — Column (1) gives the date of observations while column (2) gives the Modified Julian Date (JD−2400000.5). Column (3) is the mode of observation and the column (4) gives the number of visits and the exposure time of each visit.

2.1. Subtraction of the underlying stellar population contribution

We extracted the nuclear spectra from our data using a window of 1″0×1″0 centered on the peak of the continuum emission. Within this aperture, the continuum is

\(^{1} \text{IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.} \)
dominated by the underlying stellar population. In order to isolate the AGN emission we subtracted the contribution of the stellar population. The process is illustrated in Figure 1, and is described as follows:

- First we extracted the nuclear spectrum;
- Two extranuclear spectra, also within windows of 1′×1′, were extracted at 2′ away from both sides of the nucleus;
- The two extranuclear spectra were averaged. The average spectrum was scaled to match the flux of the continuum of the nuclear spectrum, as it displays the same absorption features with the same equivalent widths to those of the nuclear spectrum. This indicates that the nuclear spectrum shows no detectable non-stellar continuum emission, only line emission (as in our previous studies of NGC 1097 Storchi-Bergmann et al. (2003); Schimoia et al. (2015)). The average extranuclear spectrum is only weakly “contaminated” by narrow emission lines which were excised by using a synthetic spectrum obtained from the application of the starlight-v04 spectral synthesis code of Cid Fernandes et al. (2005);
- The scaled and corrected stellar population template was then subtracted from the nuclear spectrum in order to isolate the AGN emission.

After the subtraction of the stellar population template we adopted the spectrum of 2011 September 27 (MJD 55831) – which has the best signal-to-noise ratio (12×350 s of exposure on the source) – as the reference spectrum, and calibrated the other spectra by scaling the flux of the narrow lines [O I]λ6300 Å and [O I]λ6363 Å to match those of the reference spectrum. The [O I] lines are thought to originate in a larger region than that producing the broad double-peaked Balmer lines, thus these [O I] lines should not display significant variations in their flux during the time span of the observations, these lines are also isolated and unaffected by broad, variable emission lines. After this “intercalibration” by the [O I] emission lines we measured the flux of the narrow [S II] 6716,6731 Å lines in the different spectra finding small variations of 7 – 8% in the line fluxes. We thus conclude that the flux calibration among the spectra leads to uncertainties of 7 – 8% in the line fluxes. This uncertainty was added in quadrature to the other uncertainties in our measurements.

3. RESULTS

The resulting nuclear emission spectra, after subtraction of the underlying stellar population and calibration by the narrow emission lines, are shown in Figure 2. This figure shows that in the first observation of 2011 September 27 the blue and red peaks were very prominent in the Hα profile, with the blue peak higher than the red peak. During the second observation of 2012 July 21 (MJD 56129), taken almost ten months after the first, the profile shows less pronounced peaks, mainly the blue peak, whose flux decreased to the point of becoming lower than the red peak. The red side of the profile is now more prominent than the blue side. The overall flux of the double-peaked profile decreased from 2011 September 27 to 2012 July 21, thus showing that the time interval of ten months between these two observations is large enough to allow significant changes in the shape and flux of broad Hα double-peaked profile.

After this long time interval between the first two observations, we monitored the profile more frequently in order to look for shorter variability timescales. We found such variations. For instance, from 2012 Jul 30 (MJD 56138) to 2012 October 15 (MJD 56215), the profile changed showing mainly a decrease in flux in the red wing. In the subsequent spectra the profile continued to change, with the overall flux always lower than that of the first observation. While in the first observation one can clearly see a blue and a red peak in the profile, in most of the other observations the shape of the profile can be better described as showing a double shoulder instead of double peak.

3.1. Measurements of the flux variations of the broad double-peaked emission line

In order to measure the flux of the double-peaked line and quantify its variations, we proceeded as follows:

- We first removed the contribution of the narrow emission lines interpolating a linear effective continuum between ~6513 Å and ~6648 Å excising the emission lines Hα+[N II]λλ6548,6583 Å above this continuum. We performed the same process between ~6703 Å and ~6751 Å to remove the [S II] λ6716,6731 Å emission lines. The removed emission lines are shown as gray regions in Figure 3.
- After the removal of the narrow emission lines we defined two parameters: \( F_{\text{Blue}} \) which is the integrated flux under the blue side of the broad double-peaked profile, between 6395 Å and 6563 Å and \( F_{\text{Red}} \) which is the integrated flux under the red side of the
double-peaked profile, between 6563 Å and 6820 Å. Since we have corrected the spectra by the redshift, the definition of 6563 Å as the wavelength that divides the fluxes of the blue and red sides is equivalent to use as reference the systemic velocity of the galaxy, as 6563 Å is the rest wavelength of Hα.

F_B is illustrated as the blue region in Figure 3 while F_R is the red region in the same figure. We note that our definition is such that the wavelength range covered by the red side is wider than that of the blue side of the profile. This effect is expected due to (at least partially) the gravitational redshift, since the high velocity wings of the profile come from gas that is very close to the SMBH (~ 300 gravitational radius; see following discussion on the modelling of the profile).

- F_PP was then obtained as the sum of F_B and F_R (being thus the total integrated flux of the double-peaked line), while F_R / F_B was obtained from the ratio between F_B and F_R.

The parameters defined above are similar to those used
to quantify the variability of the double-peaked profile of NGC 1097 (Schimoia et al. 2015). The main difference is that the double-peaked profile of NGC 7213, in some epochs, does not display clear blue and red peaks, but shoulders, instead. Thus, instead of measuring the flux density and position of the blue and red peaks we rather measured the integrated flux of each side of the double-peaked line, which is more robust for this case. The values of \( F_{\text{Blue}}, F_{\text{Red}}, F_{\text{DP}} \) and \( F_{\text{Red}}/F_{\text{Blue}} \) are listed in Table 2, while the time variation of these parameters is shown in Figure 4.

3.2. Variability Timescales

From our previous studies of the broad double-peaked \( \text{H}\alpha \) profile of NGC 1097 we concluded that it shows two main variability timescales: a long one, identified as a dynamical timescale for the gas orbiting in the disk (see §4); and a shorter one that can be identified with the light travel time between the ionizing source and the emitting portion of the disk. In NGC 7213, we tentatively identify these timescales as follows:

- **Long variability timescale**: significant changes in the integrated flux of the double-peaked profile can occur on timescales of a few months. For instance, from 2012 July 21 (MJD 56129) to 2012 November 22 (MJD 56253) \( F_{\text{DP}} \) decreased by \( \sim 30\% \) in approximately 4 months. During the same period, the relative intensity of the red and blue sides of the profile, \( F_{\text{Red}}/F_{\text{Blue}} \), also changed by 46%. But we also note that between 2013 April 13 (MJD 56395) and 2013 July 23 (MJD 56496) – a time interval of \( \sim 100 \) days – \( F_{\text{Red}}/F_{\text{Blue}} \) almost did not vary, keeping a value of \( \sim 1.5 \). We thus conclude that the timescale of the \( F_{\text{Red}}/F_{\text{Blue}} \) variations is \( \gtrsim 3 \) months.

- **Short variability timescale**: from 2013 April 13 to 2013 July 23 we obtained more frequent observations, separated by time intervals of a week to a month. The shortest time interval between consecutive observations is 7 days (from 2013 June 30 to 2013 July 07). On this timescale \( F_{\text{DP}} \) did not display changes larger than the uncertainties in the measurements. During the period from 2013 April 13 (MJD 56395) to 2013 May 11 (MJD 56423) \( F_{\text{DP}} \) changed from 409.8±22.1 to 461.6±25 ×10\(^{-15}\)erg s\(^{-1}\)cm\(^{-2}\) thus by 10% in a time interval of 28 days. We can thus only put limits on the shortest timescale: it is probably longer than a week but shorter than 28 days. We note that this week-to-28 days for the shortest timescale of variability was obtained for our specific set of observations. Since we did not sample the profile in a time interval shorter than 7 days we may have missed possible stochastic variations that may have occurred on a shorter timescale.

3.3. The \( \text{rms} \) spectrum

Figure 2 shows that the broad double-peaked profile clearly varies with time. Variations in the illumination of the disk and/or the presence of structures eventually developing in the disk can explain these variations. In order to investigate which regions of the profile show more variations, we have calculated the root mean square (\( \text{rms} \)) spectrum – \( F_{\text{RMS}}(\lambda) \) – which can reveal if there are specific regions in the velocity space in which the flux varies more. The \( \text{rms} \) spectrum, \( F_{\text{RMS}}(\lambda) \), is calculated as the \( \text{rms} \) variation of the flux at each wavelength covered by the double-peaked profile. As discussed in §3.1, significant changes in \( F_{\text{DP}} \) and in the shape of the double-peaked profile are only seen on timescales \( \gtrsim 30 \) days. Thus, in order to calculate the \( \text{rms} \) spectrum, we selected spectra that are separated by time intervals of the order of 30 days, namely: 2011 September 27, 2012 July 21, 2012 October 15, 2012 November 22, 2013 April 13, 2013 May 20, 2013 June 14, 2013 July 07.

The resulting \( \text{rms} \) spectrum is shown in Figure 5. The largest variations in the profile are observed in three “peaks”: two of them coinciding in wavelength with the blue and red peaks of the double-peaked profile and a third peak observed in between the two peaks, centered at a velocity close to zero (adopted as the velocity of the narrow \( \text{H}\alpha \) component). The double-peaked structure is expected for variable emission in an accretion disk, but the central hump reveals that there is significant variation also in a lower velocity structure, resembling another broad component with a velocity width of \( \approx 2100 \text{km s}^{-1} \) (see discussion below). Some residual variation is also observed at the wavelengths of the narrow lines, but this is due to the estimated uncertainties of the “intercalibration” of the data, as discussed previously.

The blue and red peaks of the \( \text{rms} \) spectrum support the origin of the double-peaked emission and its variability, from gas emission in an accretion disk with variable...
The Accretion Disk Model

We modeled the double-peaked Hα profiles using the accretion disk model described by Gilbert et al. (1999), Storchi-Bergmann et al. (2003), and Schimoia et al. (2012, 2015). In this formulation, the broad double-peaked emission line originates in a relativistic Keplerian disk of gas surrounding the SMBH. The line-emitting portion of the disk is circular and located between an inner radius $\xi_1$ and an outer radius $\xi_2$ — where $\xi$ is the disk radius in units of the gravitational radius $r_g = G M_\bullet / c^2$, $c$ is the speed of light, $G$ is the gravitational constant, and $M_\bullet$ is the mass of the black hole. The disk has an inclination angle $i$ with respect to the plane of the sky.

In order to take into account the observed asymmetries on the double-peaked profile we adopted the “saturated spiral model” (Schimoia et al. 2012) for the total emissivity of the accretion disk. In this formulation, there is an enhancement of the emissivity in the form of a spiral arm, which is superposed on the underlying emissivity of the circular accretion disk. The details of the emissivity law are described in Storchi-Bergmann et al. (2003) and Schimoia et al. (2012). Here we briefly describe the physical meaning of the different parameters which are relevant for our modeling.

The parameter $\xi_2$ is the radius of maximum emissivity, or saturation radius, at which the emissivity law changes; $q_1$ is the index of the emissivity law for $\xi_1 < \xi < \xi_2$; $q_2$ is the index for $\xi_2 < \xi$. The presence of the spiral arm enhances the emissivity of the gas where it is located, thus the parameter $A$ represents the brightness contrast between the emissivities of the spiral arm and the underlying disk. The emissivity of the spiral arm decays as a function of the azimuthal distance $\phi - \psi_0$ from the ridge line to both sides of the arm, assumed to be a Gaussian with an azimuthal width of $\delta$. Furthermore, $\phi_0$ is the azimuthal angle of the spiral pattern, $p$ is the pitch angle, and $\xi_{in}$ is the innermost radius of the spiral arm (cf. Schimoia et al. 2015 for more details).

We kept the emissivity index for radii larger than the break radius as $q_2 = 3$, as proposed by Dumont & Collin-Souffrin (1990): after the saturation radius the emissivity of the disk is expected to be proportional to $\xi^{-3}$. We tested many values for the emissivity index for the region between the inner and the saturation radius, $\xi_1 < \xi < \xi_2$,
and concluded that \( q_1 = -0.2 \) gave the best fits; this small value for \( q_1 \) is required because, as can be seen in Figure 2, the broad double-peaked profile displays very extended wings. The presence of extended wings means that the inner parts, with higher projected velocities, are important for the emissivity of the disk and the value \( q_1 = -0.2 \) implies that the emissivity increases slowly until the break radius, which makes the inner parts of the accretion disk important with respect to the outer parts. We also tested different values for the inner and outer radii, \( \xi_1 \) and \( \xi_2 \), and the inclination angle, \( i \), and found that the set of values that best reproduced all the data together are \( \xi_1 = 300 \pm 60 \), \( \xi_2 = 3000 \pm 90 \) and \( i = 47^\circ \pm 2^\circ \), so in the analysis below, we keep these values for these parameters.

In order to reproduce the double-peaked profile variations, namely, in the relative intensity of the blue and red sides of the double-peaked profile and the broadening/narrowing of the profile, we first modeled the reference spectrum (with the best signal-to-noise ratio), from 2011 September 27; and after finding the best parameter values for this epoch, we allowed only 3 parameters to vary: \( \phi_0 \), \( A \) and \( \xi_1 \). The parameters that define the shape of the spiral arm were kept fixed at \( p = 13^\circ \), \( \delta = 75^\circ \) and \( \xi_{sp} = \xi_1 \). Among these parameters, the pitch angle is the least uncertain because it regulates the curling of the spiral arm, and in the case of NGC 7213, a small pitch angle (\( p = 13^\circ \)) is required to curl the spiral arm close to the inner radius and give relative more importance to the inner regions of the disk, and consequently, better reproduce the wings of the profile. Figure 6 shows the best fit for each epoch while the corresponding parameters are listed in Table 3. Surface emissivity maps corresponding to the models are shown in Figure 7.

### 3.5. The central broad component (CBC)

Figure 6 shows that the accretion disk model can reproduce the broad double-peaked emission line in our observations, and we thus confirm that its emission originates from gas rotating in a relativistic Keplerian disk with very high projected velocities (e.g., \( \sim 8,550 \text{ km s}^{-1} \)) is the velocity separation between the blue and red peaks of the double-peaked profile of 2011 September 27).

But the rms spectrum of Figure 5 shows that, besides the broad double-peaked component there is another varying component that appears as an excess variation above that attributed to the gas that is rotating in the accretion disk, observed at lower project velocities. We have called this component CBC (Central Broad Component). The CBC is not easily seen in the profile because of the blended narrow emission lines \( \text{H}_\alpha + [\text{NII}] \) that sit “on top” of it. It cannot be due to the narrow lines because the observed variation is larger than the estimated 8% variations attributed to the uncertainties in the intercalibration using the narrow lines.

We inspected the IFU data in order to check if the CBC and the broad double-peaked line were detectable outside the nucleus, considering our spatial resolution of 58 pc. We did not find evidence for the presence of the CBC neither the double-peaked line beyond this 58 pc region, concluding that both of them are unresolved, consistent with an origin in the outer parts of the accretion disk or in the BLR.

In order to measure the contribution of the CBC in each epoch and characterize its profile, it is necessary to separate the CBC from the narrow lines. We have used the following method to do this:

- We first subtracted the modeled double-peaked profile from each spectrum, and then fitted the narrow emission lines \([\text{SII}] \lambda 6716, 6731\). These lines
were fitted with two Gaussian components each, as the use of only one Gaussian did not fit well the base of the lines. Each Gaussian component was constrained in velocity space to have the same central velocity and width in the two lines of the [SII] doublet. An example of the fit to the [SII] lines is shown in the left panel of Figure 8. The broader of the two narrow components of [SII] λλ6716, 6731 has typical central velocity of 66±17 km s\(^{-1}\) and velocity dispersion of 329±17 km s\(^{-1}\); the other narrow component has central velocity and velocity dispersion of 41±8 and 159±5 km s\(^{-1}\), respectively.

- Since the narrow emission line components of H\(\alpha+[\text{NII}]\) λλ6548, 6583 are superposed on the H\(\alpha\) CBC that we want to characterize, in order to decrease the degeneracy in the fit, we adopted the physically motivated assumption that these components originate in the same region as the [SII] lines, thus fixing the centroid velocities and widths of the Gaussians to the corresponding values of the [SII] lines. The flux of the lines was allowed to vary, only constraining the flux of [NII] λ6583 to be 2.87 times the flux of [NII] λ 6548 (Osterbrock & Ferland 2006).

- Once we constrained the center and dispersion velocities of the H\(\alpha+[\text{NII}]\) narrow components, (and the flux constraints above) we fitted the H\(\alpha\) CBC together with these lines. For the fit of the CBC we used three Gaussian components. An illustration of the result of this fit is shown in the right panel of Figure 8. The magenta line represents our fit for the CBC, whose flux accounts for a significant part of the total broad H\(\alpha\) line (comprising the contributions of the double-peaked component plus the CBC).

After fitting the broad double-peaked H\(\alpha\), the narrow emission lines H\(\alpha+[\text{NII}]\)λλ6548,6583 and the CBC, we calculated the mean, \(\text{rms}\) and minimum spectra from our 8 modeled observations, as well as of the modeled profiles.

The top panel of Figure 9 shows the mean spectrum we have calculated from our data. This spectrum displays double-shoulders, with the maximum flux density of the blue side of the profile slightly higher than that of the red side, which is well modelled by our mean accretion disk model, shown as the green dotted line. In addition we note that the CBC \(\text{H}\alpha\) component also contributes strongly to the mean overall broad \(\text{H}\alpha\) emission.

Before calculating the \(\text{rms}\) spectrum we subtracted the contribution of the narrow emission lines, and the result is shown in the middle panel of Figure 9. The \(\text{rms}\) spectrum, for both the data and the models (red line), shows that, as discussed before, the most variable portion of the spectrum shows a profile with three peaks: a blue peak centered around 6487 Å, a red peak centered around 6684 Å, in agreement with the expected variations in the accretion disk plus a central peak corresponding to variations in the CBC. The similarity between the black (observations) and red (model) profiles shows that the variations in the broad profile can be well reproduced by the \(\text{rms}\) profile of our accretion disk model (green dotted line) plus the CBC (modelled via the fit of three gaussians to each profile).

The minimum spectrum was constructed by selecting, at each wavelength, the minimum flux from all spectra. This minimum spectrum represents a base profile which is common to all profiles, and is shown at the bottom panel of Figure 9. In the scenario in which the emission arises from a circular accretion disk with an emissivity enhancement (such as a spiral arm, as we have considered in our modelling), the minimum spectrum would be that of the underlying accretion disk. Figure 9 shows that the minimum spectrum also displays two shoulders, consistent with the above assumption. Individually or taken together, the mean, \(\text{rms}\) and minimum spectra all support the scenario where the origin of the broad,

**Fig. 7.—** Emissivity maps corresponding to the accretion disk models fitted to the double-peaked profiles of Figure 6. The yellow to white represents regions with the highest surface emissivity while the dark red represents the regions with the lowest surface emissivity. The non-axisymmetric part of the emissivity has the shape of a spiral arm rotating in the accretion disk. The observer sees the disk from the bottom of the figure and the spiral arm rotates clockwise. The epoch of observation is written in the top left corner of each frame.
Fig. 8.— *Left*: Fit of the narrow emission lines [SII] \( \lambda \lambda 6716, 6731 \). Each narrow line was fitted using two Gaussian components which are represented by the blue and green dashed lines. The central velocity and velocity width of each component were constrained to have the same values as the [SII] lines. The red solid line is the best fit to the lines and represent the sum of the individual components, and the black dashed line is the residual from the fit. *Right*: Fit of the H\( \alpha \) CBC and narrow components of H\( \alpha \)+[NII] \( \lambda \lambda 6548, 6583 \). The narrow components were constrained to have the same velocities as the [SII] lines. The fitted components to the narrow lines are shown as dashed blue lines. The CBC was fitted with three Gaussian components; the sum of the three is shown as a continuous magenta line and the individual components are shown in green, yellow and cyan. The solid red line is the sum of all components and the residual (observed - modeled) is shown as a black dashed line.

Fig. 9.— *Top*: The black dashed line is the mean spectrum calculated from our observations, while the solid black line is the mean spectrum calculated after subtracting the contribution of the H\( \alpha \)+[NII] \( \lambda \lambda 6548, 6583 \) narrow lines. The green dotted line is the mean model spectrum of the accretion disk. The solid red line is the mean spectrum of the total broad H\( \alpha \) emission calculated from the accretion disk models + the fitted CBC. *Middle*: the rms variations of the observed and modeled spectra. *Bottom*: the minimum observed and modeled spectra.

3.5.1. Properties of the CBC

We have measured three properties of the CBC: the integrated flux, \( F_{\text{CBC}} \), the peak velocity, \( V_{\text{peak}} \), which is the velocity corresponding to the wavelength of maximum flux and the median velocity, \( V_{\text{50}} \), which corresponds to the wavelength at which the integrated flux under the profile corresponds to 50% of the total flux. As the profile is not fitted by only one Gaussian and contain asymmetries, we adopted as velocity dispersion the velocities above and below the median velocity that encompass 34% of the flux under the profile, \( \pm \sigma_v \). We list these measurements in Table 4.

We note that the CBC flux \( F_{\text{CBC}} \) is usually \( \sim 50 - -100\% \) higher than the flux of the double-peaked component, \( F_{\text{DP}} \) (the only exception being the first epoch). However, during the campaign, the amplitude of the variations of the \( F_{\text{CBC}} \) was lower than that of the \( F_{\text{DP}} \): while \( F_{\text{DP}} \) varied between minimum and maximum fluxes of 410 and \( 802 \times 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \), respectively, \( F_{\text{CBC}} \) varied between minimum and maximum fluxes of 803 and \( 921 \times 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \), respectively. This behavior is also evident from a comparison of the top and middle panels of Figure 9: the CBC is much more pronounced in the mean spectrum than in the rms spectrum. We define a proxy for the velocity width of the CBC as:

\[
W_{68} = +\sigma_v - (-\sigma_v) \tag{1}
\]

which represents the velocity width of the line that contains 68% of the total line flux around \( V_{50} \). The values of \( W_{68} \) are listed in the last column of Table 4. The average value of the parameter \( W_{68} \) is \( 2100 \pm 73 \text{ km s}^{-1} \) which represents the average velocity width of the CBC.

4. DISCUSSION

4.1. Low-state of the double-peaked profile
the SMBH) and the radius of maximum emission, we can adopt as approximately coinciding with the location of \( \sim 17 \) – the middle between these two limits – as the light-

\[ V = 5 \times 10^5 \text{km s}^{-1} \]

Considering that this radius could be in the range between the lower and upper limits of 7 and 28 days, respectively, the result for the radius of maximum emission of the line emitting disk. When we performed the stellar population synthesis with *starlight-v04* we used the simple stellar population templates of Bruzual & Charlot (2003) and allowed the fit of the stellar kinematics. The value we obtained for the velocity dispersion was \( \sigma = 219 \text{km s}^{-1} \). We have corrected this value for the instrumental resolution, \( \sigma_{\text{inst}} \), and the resolution of the template spectra, \( \sigma_{\text{base}} \), as follows:

\[ \sigma^2 = \sigma^2 - \sigma_{\text{inst}}^2 + \sigma_{\text{base}}^2 \]  

The B600 grating that we used in the longslit GMOS observations has an instrumental resolution of \( \sigma_{\text{inst}} = 177 \text{km s}^{-1} \), while the Bruzual & Charlot (2003) base of simple stellar population spectra has a resolution of \( R = 2000 \), thus \( \sigma_{\text{base}} = 150 \text{km s}^{-1} \), in the wavelength range 3200 Å to 9500 Å. We thus obtain a stellar velocity dispersion of \( \sigma_\star = 198 \text{km s}^{-1} \), which via Equation 2 gives \( M_\star = 1.29 \times 10^8 M_\odot \) in very good agreement with the value we have obtained via the estimated light travel time between the nuclear ionizing source and the radius of maximum emission of the line emitting disk.

This value that we have obtained for the stellar velocity dispersion is also very close to the value \( \sigma_\star = 185 \text{km s}^{-1} \) previously obtained by Woo et al. (2002), who also used the \( M_\star - \sigma_\star \) relation (Tremaine et al. 2002) to estimate the mass of the SMBH as \( M_\star = 9.77 \times 10^7 M_\odot \). Considering that there is an intrinsic scatter of \( \sim 0.3 \text{dex} \) (a factor \( \sim 2 \)) in the \( M_\star - \sigma_\star \) relation, we conclude that both our determinations of the mass of the SMBH are in good agreement with this previous determination, supporting this value.

### 4.3. Variability timescales

The two shortest variability timescales of standard accretion disk data are the *light travel timescale*, \( \tau_l \), and the *dynamical timescale*, \( \tau_{\text{dyn}} \) (Frank et al. 2002):

\[ \tau_l = 6 M_\odot \xi_3 \text{days} \]  

\[ \tau_{\text{dyn}} = 6 M_\odot \xi_3^{3/2 \text{months}} \]  

where \( M_\odot \) is the mass of the SMBH in units of \( 10^8 M_\odot \) and \( \xi_3 = \xi/10^{-3} \). Adopting the mass of the SMBH in NGC 7213 as \( M_\star = 1.29 \times 10^8 M_\odot \) and considering the best model inner and outer radius of the accretion disk, \( 0.3 < \xi_3 < 3 \), we obtain a range for the variability timescales of:

- \( \tau_l: 2.3 - 23 \text{days} \)
- \( \tau_{\text{dyn}}: 1.3 - 40 \text{months} \)

The evolution of the model parameter \( \phi_0 \) – the azimuthal angle of the spiral pattern, with time is shown in Figure 10. A linear fit to the data gives an angular velocity of \( \alpha \approx -0.58^\circ \text{day}^{-1} \), which implies a rotation period of \( \sim 620 \text{days} \) or 21 months, within the expected range of the dynamical timescale above. Considering this period of rotation as a dynamical timescale of the accretion disk, it suggests that the asymmetric feature of the

---

### Table 4

*NGC 7213 CBC Properties*

| UT Date       | MJD   | \( F_{\text{CBC}} \) | \( V_{\text{peak}} \) | \( V_{50} \pm \sigma_V \) | \( W_{68} \) |
|--------------|-------|---------------------|---------------------|---------------------|-------------|
| Sep 27 2011  | 55831.130 | 921.74+72 | 253 | 274.1046 | 1966 |
| Jul 21 2012  | 56129.155 | 936.75+75 | 211 | 148.1048 | 2049 |
| Oct 15 2012  | 56215.111 | 891.71+71 | 253 | 274.1046 | 2175 |
| Nov 22 2012  | 56253.047 | 803.64+64 | 253 | 274.1046 | 2049 |
| Apr 13 2013  | 56395.383 | 829.66+66 | 253 | 274.1046 | 2049 |
| May 20 2013  | 56432.315 | 831.67+67 | 253 | 274.1046 | 2133 |
| Jun 14 2013  | 56457.399 | 889.71+71 | 253 | 274.1046 | 2174 |
| Jul 07 2013  | 56480.218 | 904.72+72 | 253 | 274.1046 | 2174 |

Note. — Column (1): date of observations; column (2): Modified Julian Date (JD−2400000.5); column (3): integrated flux of the CBC in units of \( 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \) and the uncertainties are \( \pm 8\% \) of the measured flux; column (4): peak velocity of the line; column (5): median velocity of the line plus/minus the velocities corresponding to \( \pm 3\% \) of the integrated flux; column (6): velocity width of the CBC that contains \( 68\% \) of the total line flux around \( V_{50} \). Velocity units are \( \text{km s}^{-1} \).
accretion disk has completed almost one full rotation. The observed precession period of the spiral pattern is also in good agreement with the theoretical predictions for n=1 modes in massive, Keplerian disks by Adams, Ruden & Shu (1989) and Shu et al. (1990).

From Figure 4 it can be further concluded that variations in the relative intensity of fluxes of the red and blue sides of the profile, \( F_{\text{red}}/F_{\text{blue}} \), occur in the timescale of a few months. For instance: \( F_{\text{red}}/F_{\text{blue}} \) varied from 1.09 (2011 September 27) to 1.33 (2012 July 21) in almost 10 months and also varied from 1.33 (2012 July 21) to 1.67 (2012 November 22) in approximately 4 months. This variation is also within the range of the dynamical timescale, and compatible with the rotation period of the spiral arm in the accretion disk discussed above.

Regarding the shortest variability timescale, although our relatively sparse monitoring did not allow us to put strong constraints on its value, the range we have estimated, between 7 and 28 days is approximately consistent with the light travel time.

4.4. The CBC

The mean velocity width of the CBC, \( \overline{V}_{50} = 2100 \pm 73 \text{ km s}^{-1} \) suggests it is located at larger distances from the SMBH than the disk. Estimating its variability timescale from the line flux – considering typical uncertainties of \( \sim 8\% - \) we obtain \( \sim 120 \) days, \( \sim 6 \) times the outer radius of the disk. The central velocity of the CBC of \( V_{50} = 260 \pm 40 \text{ km s}^{-1} \) is much larger than the gravitational redshift at the above distance, that suggests the presence of a bulk motion of this region.

The presence of a CBC together with disk-like profiles have been also found by other authors Ho et al. (1997) and Storchi-Bergmann et al. (2016). Their methodology for subtracting the contribution of the narrow lines and fitting the broad central component is very similar to the methodology adopted in the present work. These authors found mean values of the FWHM for the broad component of \( \sim 2000 \text{ km s}^{-1} \) (Ho et al. 1997) and \( \sim 1500 \pm 500 \) (Storchi-Bergmann et al. 2016), which are consistent with the value of \( \overline{V}_{50} = 2100 \pm 73 \text{ km s}^{-1} \) we found for NGC 7213.

5. CONCLUSIONS

We have presented 13 new optical spectra of the broad H\( \alpha \) profile of the AGN in NGC 7213 over a time span of 22 months, with observations sparsed by time intervals from a week to a few months. The main results of this paper are:

- It is the first time that variability is reported for the broad \( \sim 8550 \text{ km s}^{-1} \) for the velocity separation of the blue and red peaks) H\( \alpha \) line of this AGN, that shows a double-peaked profile, typical of gas rotating in an accretion disk around a SMBH;
- The relative intensity of the integrated flux of the blue and red sides of the double-peaked profile displayed significant variations on a timescale \( \gtrsim 3 \) months, consistent with the dynamical timescale of gas rotating in an accretion disk around a \( 10^8 \text{ M}_\odot \) SMBH;
- The total flux of the broad line showed variations on a timescale between 7 and 28 days, consistent with the light travel timescale between the ionizing source and the emitting part of the disk;
- The rms variation spectrum reveals that the most variable part of the broad H\( \alpha \) line shows three peaks: a blue and a red peak consistent with an origin in the accretion disk plus an additional central peak which we attribute to a “central broad component” (CBC), showing similar amplitude to those of the two other peaks;
- We successfully modeled the broad double-peaked profile as due to gas emission from a region of a Keplerian and relativistic accretion disk with inner and outer radii of \( \xi_1 = 300 \pm 60 \text{ and } \xi_2 = 3000 \pm 90 \) (in units of gravitational radii), respectively, and inclination angle of \( i = 47^\circ \pm 2^\circ \) relative to the plane of the sky. We also found that the disk harbors a spiral arm with varying contrast relative to the underlying disk;
- The variations in the relative intensity of the blue and red sides of the profile were modeled as due the rotation of the spiral arm, with a period of \( \sim 21 \) months. This arm completed almost one full rotation in the accretion disk and faded (decreased its contrast) over the approximately two years spanned by the observations;
- The profile of the CBC was modelled via the fit of three Gaussians; it shows an average width velocity (proxy for the velocity dispersion) of \( \overline{V}_{50} = 2100 \pm 73 \text{ km s}^{-1} \), which suggests that the gas of this component is located at larger distances from the SMBH than the outer radius of the disk;
- Using the fit of the stellar absorption features with the starlight-v04 code we obtained a velocity dispersion of the bulge of \( \sigma_\ast = 188 \text{ km s}^{-1} \), what implies a mass for the SMBH of \( M_\ast = 1.29 \times 10^7 \text{ M}_\odot \) via the \( M_\ast - \sigma_\ast \) relation, in agreement with previous determinations;
- We also estimated the mass of the SMBH using a representative velocity of the gas in the disk and
the light travel time between the SMBH and the disk. We find that the SMBH mass is in the range $5 \times 10^7 < M_\bullet < 2 \times 10^8 M_\odot$, also in agreement with the previous and our above estimate.

In summary, our proposed scenario for the origin of the broad H$\alpha$ profile of NGC 7213 is the following: the broad double-peaked emission arises from a Keplerian and relativistic accretion disk, inclined by 47 degrees relative to the plane of the sky from a region with inner and outer radii of $\approx 300$ and $3000$ gravitational radii, respectively. This disk orbits a SMBH with a mass in the range $5 \times 10^7 \leq M_\bullet \leq 2 \times 10^8 M_\odot$. The relative intensity of the flux of blue and red sides of the double-peaked profile changes due to the rotation of a spiral arm with a rotation period of 21 months. The contrast between the arm and underlying disk decreased gradually during the approximately two years of observations, leading to ever smaller asymmetries between the heights of the blue and red sides of the double-peaked profile. An additional component, the CBC, also contributes to the variable broad H$\alpha$ profile as a central “hump” observed at velocities close to systemic, with a velocity width of 2100 km s$^{-1}$. We propose that this component originates in gas that is also orbiting the black hole but is either at larger radii in the accretion disk or not coplanar with the disk.

J.S.S. acknowledges CNPq, National Council for Scientific and Technological Development - Brazil. R.N. acknowledges support from FAPESP.

REFERENCES

Adams F. C., Ruden S. P., Shu F. H., 1989, ApJ, 347, 959
Bianchi S., Matt G., Balestra I., Perola G. C., 2003, The origin of the iron lines in NGC 7213, A&A, 407, L21
Bianchi S., La Franca F., Matt G., Guainazzi M., Jimenez Bailón E., Longinotti A. L., Nicastro F., Pentterruci L., 2008, MNRAS, 389, L52
Brusa N., Charlot S., 2003, MNRAS, 344, 1000
Chen K., Halpern J. P., & Filippenko A. V., 1989, ApJ, 339, 742
Chen K., & Halpern J. P., 1989, ApJ, 344, 115
Cid Fernandes R., Mateus A., Sodré L., Stasińska G., & Gomes J. M., 2005, MNRAS, 358, 363
Dumont A. M., Collin-Souffrin S., 1990, A&A, 229, 313
Emmanoulopoulos D., Papadakis I. E., McHardy I. M., Arévalo P., Calvelo D. E., Uttley P., 2012, MNRAS, 424, 1327
Eracleous M., & Halpern J. P., 2003, ApJ, 599, 886
Eracleous M., Lewis K. T. & Flock H. M. L. G., 2009, New Astr. Rev. 53, 133
Filippenko A. V., Halpern J. P., 1984, ApJ, 285, 458
Frank J., King A., Raine D. J., 2002, apa..book, 398
Gezari S., Halpern J. P., Eracleous M., 2007, ApJS, 169, 167
Gilbert A. M., Eracleous M., Filippenko A. V., & Halpern J. P., 1999, ASPC, 175, 189
Ho L. C., Filippenko A. V., Sargent W. L. W., Peng C. Y., 1997, ApJ, 112, 391
Lewis K. T., Eracleous M., & Storchi-Bergmann T., 2010, ApJS, 187, 416
Lobban A. P., Reeves J. N., Porquet D., Braito V., Markowitz A., Miller L., Turner T. J., 2010, MNRAS, 408, 551
Narayan R., & McClintock J. E., 2008, NewAR, 51, 733
Osterbrock D. E., Ferland G. J., 2006, Astrophysics of gaseous nebulae and active galactic nuclei, agna.book,