SHORT-TIMESCALE MONITORING OF THE X-RAY, UV, AND BROAD DOUBLE-PEAK EMISSION LINE OF THE NUCLEUS OF NGC 1097

Jaderson S. Schimoia1,2, Thaisa Storchi-Bergmann1,3, Dirk Grupe4,10, Michael Eracleous5,11,12, Bradley M. Peterson2,6, Jack A. Baldwin7, Rodrigo S. Nemmen8,13,14,15, and Cláudia Wingé9

1 Instituto de Física, Universidade do Rio Grande do Sul, Campus do Vale, Porto Alegre, RS, Brazil; silva.schimoia@ufrgs.br
2 Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
4 Space Science Center, Morehead State University, 235 Martindale Drive, Morehead, KY 40351, USA
5 Department of Astronomy and Astrophysics and Institute for Gravitation and the Cosmos, Pennsylvania State University, 525 Davey Lab. University Park, PA 16802, USA
6 Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 West Woodruff Avenue, Columbus, OH 43210, USA
7 Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48864, USA
8 Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, SP 05508-090, Brazil
9 Gemini South Observatory, c/o AURA Inc., Casilla 603, La Serena, Chile

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ABSTRACT

Recent studies have suggested that the short-timescale (≤7 days) variability of the broad (~10,000 km s⁻¹) double-peaked Hα profile of the LINER nucleus of NGC 1097 could be driven by a variable X-ray emission from a central radiatively inefficient accretion flow. To test this scenario, we have monitored the NGC 1097 nucleus in X-ray and UV continuum with Swift and the Hα flux and profile in the optical spectrum using SOAR and Gemini-South from 2012 August to 2013 February. During the monitoring campaign, the Hα flux remained at a very low level—three times lower than the maximum flux observed in previous campaigns and showing only limited (~20%) variability. The X-ray variations were small, only ~13% throughout the campaign, while the UV did not show significant variations. We concluded that the timescale of the Hα profile variation is close to the sampling interval of the optical observations, which results in only a marginal correlation between the X-ray and Hα fluxes. We have caught the active galaxy nucleus in NGC 1097 in a very low activity state, in which the ionizing source was very weak and capable of ionizing just the innermost part of the gas in the disk. Nonetheless, the data presented here still support the picture in which the gas that emits the broad double-peaked Balmer lines is illuminated/ionized by a source of high-energy photons which is located interior to the inner radius of the line-emitting part of the disk.

Key words: accretion, accretion disks – galaxies: individual (NGC 1097) – galaxies: nuclei – galaxies: Seyfert – line: profiles

1. INTRODUCTION

The energy emitted by active galaxy nuclei (AGNs) is provided by accretion of mass onto a supermassive black hole (SMBH), via an accretion disk, whose emission is observed in the UV continuum of Seyfert galaxies and quasars (e.g., Frank et al. 2002). The optical spectra of some AGN show extremely broad (~10,000 km s⁻¹) double-peaked emission lines that are thought to originate in the outer extension of the accretion disk. Indeed, models of ionized gas emission rotating in a relativistic Keplerian accretion disk around an SMBH have been generally successful in accounting for the 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 self-consistently most observable features of the double-peaked profiles (Eracleous & Halpern 2003). Long timescale monitoring (years to decades) has revealed variability of the double-peaked profiles in several objects, including the radio galaxy 3C390.3 (Shapovalova et al. 2010), the LINER NGC 1097 (Storchi-Bergmann et al. 2003), the radio galaxy Pictor A, and other radio-loud AGNs (Gezari et al. 2007; Lewis et al. 2010).

The variations in double-peaked profiles can provide an effective probe of disk models and lead to understanding of the physical mechanisms that cause profile variability. For this reason, we have monitored the double-peaked Hα profile in the nuclear spectrum of NGC 1097. We were fortunate enough to obtain a few Gemini-South spectra separated by less than a week, which revealed much shorter timescale profile variability than had been seen before in this source. Our observations constrain the variability timescale of the integrated flux of the profile and the velocity separation between the blue and red peaks to approximately seven days (Schimoia et al. 2012). This is the shortest timescale variability ever seen in the double-peaked profile of this object, and coincides with the estimated light travel time between the nucleus and the line-emitting region of the disk.

The short-timescale variations suggest that the line emission is driven by the central source. A number of studies have compared the available energy due to local viscous dissipation in the accretion disk with the observed luminosity of emission lines and concluded that there is indeed the need for an external
ionizing source to power the observed luminosity of the double-peaked emission lines. This has been argued by Eracleous & Halpern (1994), Strateva et al. (2006, 2008), and Luo et al. (2013). In the case of NGC 1097, Nemmen et al. (2006) have proposed that the ionizing source is a radiatively inefficient accretion flow (RIAF; Narayan & McClintock 2008) located in the center (or inner rim) of the disk. The seven-day timescale is consistent with an origin of the emission-line variability as a reverberation signal of the varying X-ray emission from the inner RIAF in the line-emitting portion of the disk.

In our previous studies of profile variability in the spectrum of NGC 1097 (Schimoia et al. 2012) we also found an inverse correlation between the flux of the line and the velocity separation between the two peaks of the profile, confirming the previous result reported by Storchi-Bergmann et al. (2003). This inverse correlation also supports the reverberation scenario: when the flux is higher, the RIAF at the center is more luminous and ionizes/ionizes farther out in the accretion disk, where the disk rotational velocities are lower (thus the profile is narrower); conversely, when the flux from the RIAF is lower, the disk emissivity is weighted more heavily toward smaller radii where the velocities are higher, hence the profile is broader. A similar behavior is also observed in 3C 390.3 by Shapovalova et al. (2001, see their Figure 4).

In order to test the hypothesis that the Hα variability is a reverberation response to variations of the X-ray and UV continuum emitted by the inner RIAF, we undertook a campaign to monitor the X-ray and Hα emission in NGC 1097. From 2012 August to 2013 February, we monitored the emission from the nucleus of NGC 1097 in three different wavelengths bands. The high-energy continuum (presumably emitted by the RIAF) was monitored with the Swift satellite, using the X-ray telescope (XRT) telescope to obtain X-ray fluxes and the UVOT(M2) to obtain the UV fluxes. The spectral monitoring of the Hα double-peaked profile was performed using the GOODMAN spectrograph at the SOAR telescope. In this contribution, we report on the results of this campaign. In Section 2, we describe the observations and the data reduction and, in Section 3, we present the measurements of the properties of the Hα double-peaked profile and the flux measurements of X-ray/UV bands as well as the main results from our monitoring campaign. In Section 4, we discuss the results and their physical implications to the reverberation scenario and the emitting structure of the double-peaked profile. Our conclusions are summarized in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. X-Ray and Ultraviolet Observations with Swift

Observations were made with X-ray and ultraviolet (UV) telescopes on Swift between 2012 July 26 and 2013 January 30 (MJD\textsuperscript{16} 56134 to 56327).

The Swift XRT (Burrows et al. 2005) was operated in photon counting mode (Hill et al. 2004). The data were reduced by the task xrtpipeline version 0.12.6, which is included in the HEASOFT package 6.12. Source counts were measured inside a circle of radius 47″ and the background was determined from a source-free region of radius of 235″ using the task xselect (version 2.4b). Auxiliary response files were created using the XRT task xrtmkarf. The spectra were rebinned with 20 counts per bin using the task grppha and the response files swxpc0to12a6_20010119v013.rmf were applied. The rebinned spectra were modeled over the range 0.3–10 keV in XSPEC v.12.7 with a single power law and correction for Galactic absorption corresponding to a hydrogen column density $N_H = 2.03 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005), which is very close to the value of $N_H = 2.3 \times 10^{20}$ cm$^{-2}$ determined from a Chandra observation by Nemmen et al. (2006).

We analyzed all available data obtained with the Swift UV/Optical Telescope (UVOT; Roming et al. 2005) during this period. We restrict our attention to data obtained through the UVM2 (2246 Å) filter as it is the cleanest of the UVOT filters (Breeveld et al. 2010). We employed the UVOT software task uvotsource to extract counts within a circular region of 3′0 radius for the nucleus of NGC 1097 and used 20″ radius to determine the background. The UVOT count rates were aperture corrected and then converted into magnitudes and fluxes based on the most recent UVOT calibration as described by Poole et al. (2008) and Breeveld et al. (2010). The flux measurements were corrected for Galactic reddening ($E_{B-V} = 0.027$ mag) following the corrections given by Roming et al. (2009), based on standard reddening correction curves from Cardelli et al. (1989). X-ray and UV measurements from Swift are given in Table 1.

2.2. Optical Observations with SOAR

The Hα region of the optical spectrum was monitored at the SOAR Telescope using the Goodman High-Throughput Spectrograph in long-slit mode. Observations were obtained approximately every 7 days in queue mode from MJD56147 to MJD56319 for a total of 22 epochs (Program SO2012B-020). A few scheduled observations were lost to poor weather so the actual mean interval between observations is ∼7.5 days. A log of observations appears in Table 2.

The observations employed a 600 1 nm$^{-1}$ grating, yielding a dispersion of 0.065 nm pixel$^{-1}$ in the “Mid” mode. A GG455 filter was used to block second-order contamination. This setup provides wavelength coverage 450–725 nm and spectral resolution of ∼0.55 nm, measured as the FWHM of the lines in the arc spectrum. The spectrograph slit was set to a projected width of 1.03 (∼80 pc at the galaxy), because it is usually larger than the average seeing during the observations. The same slit width was used in our previous observations (SB03), which allows us to scale the new spectra to match the narrow emission line fluxes observed in our previous studies. This allows us to “normalize” the spectra to a common flux scale.

2.3. Gemini Data

Motivated by the low Hα flux in the SOAR spectra obtained early in this campaign compared to what had been observed previously (Schimoia et al. 2012), a single long-slit spectrum was obtained with the Gemini-South Multi-Object Spectrograph on MJD56173. This observation was obtained as part of an active “Poor Weather” project on the Gemini-South telescope (Program GS-2012A-Q-86). For this observation, we used a slit width of 1′0, the B600 grating, and a GG455 filter. The resulting spectrum covers the range from 510 nm to 800 nm with a resolution of ∼0.45 nm. The data were reduced using the standard procedures in the IRAF\textsuperscript{17} software package.

\textsuperscript{16} For brevity, we use only the five least-significant digits of the modified Julian Date (MJD); MJD56134 refers to JD 2456134.

\textsuperscript{17} IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The resulting GMOS spectrum demonstrated that despite the low Hα flux, the double-peaked profiles obtained at SOAR were sufficiently reliable for detailed analysis.
have not varied since our 1991 observation because of the long light travel time across the region as well as the long recombination time at low densities (although these assumptions may not hold for higher-ionization narrow lines, see Peterson et al. 2013). Hereafter we refer to the flux-calibrated starlight-corrected nuclear emission spectra simply as the “nuclear emission spectra.”

As we noted earlier, the broad Hα flux is lower than it had been in our earlier observations, and consequently some of the spectra are noisy. This leads to some ambiguity in measuring profile parameters (as described in the next section) such as the wavelengths of the red and blue peaks. We therefore smoothed the spectra with a Gaussian function. We experimented with Gaussian smoothing functions between one and five times the spectral resolution (i.e., FWHM between 5.5 and 27.5 Å), finally settling on FWHM = 11 Å. This resulted in much better defined profile parameters for noisier spectra without altering the measurements for the less noisy spectra.

3.1.2. Salient Features of the Hα Profile Variations

The smoothed nuclear emission spectra are shown in Figure 2. The most conspicuous characteristics of the evolution of the profile during the monitoring campaign are:

1. The double-peaked profile remained asymmetric, although the relative intensity of the blue and red peaks changed during the campaign. At the beginning of the observations, MJD56147, the maximum flux of the blue peak, $F_B$, was slightly stronger than the maximum flux of the red peak, $F_R$. The profile changed gradually until the red peak was much stronger than the blue peak by MJD56194. After that, the blue peak became increasingly prominent, becoming stronger than the red peak by MJD56277. This is similar to the results of our previous studies that showed that the relative intensity of the blue and red peaks changes on a timescale of months (Storchi-Bergmann et al. 2003; Schimoia et al. 2012).

2. Besides the changes in the relative intensity of the peaks, the integrated flux of the broad Hα line, $F_{\text{broad}}$, also varied significantly. The first remarkable rise in $F_{\text{broad}}$ occurred in the interval MJD56187–56194, when it changed from $62.5 (\pm 6.9) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ to $107.9 (\pm 4.4) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, an increase of $\sim 70\%$ in just six days. A second, even larger, flux increase of $\sim 90\%$ occurred in the interval MJD56285–56290, when the Hα flux increased from $43.8 (\pm 8.2) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ to $83.4 (\pm 5.3) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ in only five days.

3. After MJD56277, the red peak became less well-defined, with a shape more like a “plateau.” Similar behavior is seen on the blue side of the profile in the observation of MJD56310. By the final observation of the campaign on MJD56319, the double-peaked nature of the profile is barely discernible.

3.1.3. Model-independent Parameterization of the Double-peaked Profile

Prior to making measurements to parameterize the broad Hα profile, we must first remove the very strong narrow emission lines that are still present in the spectrum. We attempted to remove these features by simultaneously fitting three Gaussians to the Hα narrow component and the [N ii] λλ6548, 6584 lines and two more Gaussians to the [S ii] λλ6717, 6731 doublet. After removing the narrow components, we made the following measurements: $\lambda_i$ is the initial wavelength, defined as the wavelength at which the flux of the blue side reaches zero intensity within the uncertainties. Similarly, $\lambda_f$ is the final wavelength where the flux of the red side of the profile reaches zero intensity. Together these two parameters define the wavelength range of the double-peaked profile. $F_B$ is the maximum intensity of the blue peak (or blue side) of the profile and $\lambda_B$ is the wavelength where this maximum occurs, while $F_R$ is the maximum intensity of the red peak (or red side) of the profile and $\lambda_R$ the wavelength where it occurs. We obtained the integrated flux in the broad component of Hα $F_{\text{broad}}$ by integrating the flux underneath the profile from $\lambda_i$ to $\lambda_f$. Figure 3 illustrates all these properties, including the results of fitting and subtracting the contribution of the narrow lines. The resulting measurements are listed in Table 3. For most spectra,
Figure 2. Resulting spectra of each epoch after the subtraction of the stellar population contribution and calibration through the fluxes of the narrow emission lines (which do not vary on such short timescales). For each frame the vertical axis is flux in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ while the horizontal axis is wavelength in units of Å. The red solid line is the best fit of the accretion disk model to the data (see Section 4.1 for details).
it was possible to make reliable measurements of the properties described above. However, the irregular profiles in the final observations (from MJD56285 on) preclude characterization of the blue and red peaks.

### 3.2. Time-series Analysis

In this section, we characterize the variability of the X-ray and UV continuum and the integrated flux $F_{\text{broad}}$ of the broad H$\alpha$ profile. Figure 4 shows the corresponding light curves obtained over the complete monitoring campaign.

The mean cadence of the observations during the monitoring campaign was based on the results from Schimoia et al. (2012). In this previous work, we did not observe any significant H$\alpha$ variations within a time interval of seven days. We therefore planned the monitoring campaign to obtain an optical spectrum with SOAR once every 8 days. As the X-rays usually show shorter variability timescale than the optical in AGNs, we requested a Swift observation once every four days whenever possible.

For the high-energy continuum emission, 45 Swift observations were obtained in each of two bands, the XRT (0.3–10 keV) and UVOT/M2 band (\$\lambda_0\approx 2246\ \AA, FWHM \approx 510\ \AA), with a mean time interval of \~4.2 days and minimum and maximum time intervals of \~3 and 8 days, respectively. The H$\alpha$ light curve comprises 23 observations with a mean time interval between them of \~7.5 days, with minimum and maximum time intervals between two consecutive observations of \~1 and 20 days, respectively.

We characterize the variability of each light curve using the same parameters as O'Brien et al. (1998). The results are given in Table 4, where \$N\$ is the number of epochs, \$\overline{F}\$ and \$\sigma_F\$ are, respectively, the mean flux and standard deviation, and \$\Delta\$ is the mean measurement uncertainty. The parameter \$F_{\text{var}}\$ is an estimate of the amplitude of the variability.
Figure 4. Light curves. Top: integrated flux of the Swift/XRT X-ray band, 0.3–10 keV. Middle: UV integrated flux, from the M2 band (∼2246 Å) of Swift/UVOT. Bottom: integrated Hα broad-line flux. The largest average variation was observed for the Hα profile, of 20%, followed by the X-rays, which varied by 13%, while the UV did not show significant variation.

### Table 4

| Feature        | N  | \(F\) | \(\sigma_F\) | \(\Delta\) | \(F_{\text{var}}\) (%) | \(R_{\text{max}}\) |
|----------------|----|--------|--------------|-----------|------------------------|---------------------|
| XRTa           | 45 | 3.54   | 1.1          | 1.0       | 13.18                  | 4.18                |
| \(F(M2)b\)    | 45 | 9.44   | 0.52         | 0.62      | INDEF                   | 1.26                |
| \(F_{\text{broad}}b\) | 23 | 6.72   | 2.01         | 1.43      | 20.44                  | 3.52                |

Notes.

a \(F\), \(\sigma_F\), and \(\Delta\) are in units of \(10^{-12}\) erg s\(^{-1}\) cm\(^{-2}\).
b \(F\), \(\sigma_F\), and \(\Delta\) are in units of \(10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\).

relative to the mean flux, corrected by the uncertainties in the measurements, i.e.,

\[
F_{\text{var}} = \frac{\sqrt{\sigma_F^2 - \Delta^2}}{F}.
\]

The parameter \(R_{\text{max}}\) is the ratio between the maximum and minimum fluxes in the light curve.

#### 3.2.1. X-Ray

The X-ray variations (Figure 4) were of very low amplitude, with \(F_{\text{var}} \approx 13\%\). There were two periods of large changes, a large decrease followed by a large increase in flux around MJD56150 and another increase followed by a rapid decrease around MJD56194. These variations imply that the X-ray emitting structure must be smaller than four light days. We note that there is an ultra-luminous X-ray source (ULX) located approximately 27″ away from the nucleus, as pointed out by Nemmen et al. (2006). As the Swift measurements employ an aperture of 47″ radius, this source is included in our measured X-ray flux. We have used the information provided by Nemmen et al. (2006) to estimate an upper limit of \(\sim 8\%\) to the flux contributed by this ULX to our measurements. If we correct our measurements by this constant contribution, we expect that \(F_{\text{var}} \approx 15\%\).

#### 3.2.2. UV

The \(F_{\text{var}}\) parameter for the M2 Swift band is undefined because the variations in the UV flux are smaller than the uncertainties of these measurements.

Nemmen et al. (2006) have used an Hubble Space Telescope STIS UV/optical spectrum of the nucleus of NGC 1097 as part of the nuclear spectral energy distribution (SED). With data from radio wavelengths to X-rays, they then modeled the nuclear SED as originating in a RIAF plus the contribution from a radio jet, including also the continuum of the part of the disk which emits also the double-peaked line. Besides these components, it is also necessary to include the contribution of a nuclear starburst (Storchi-Bergmann et al. 2005) to reproduce the UV spectral range. The derived contributions of each of these structures to the luminosity at 2246 Å are \(L_{\text{RIAF}} = 1.26 \times 10^{40}\) erg s\(^{-1}\) from the RIAF, \(L_{\text{jet}} = 2.57 \times 10^{39}\) erg s\(^{-1}\) from the radio jet, \(L_{\text{disk}} = 5.25 \times 10^{34}\) erg s\(^{-1}\) from the thin disk, and \(L_{\text{star}} = 2.04 \times 10^{40}\) erg s\(^{-1}\) from the compact nuclear starburst. We thus conclude that, in the observed UV band, the nuclear starburst, which has a projected distance to the nucleus smaller than 9 pc (Storchi-Bergmann et al. 2005), dominates the luminosity. As the light from the starburst does not vary on the timescales we are considering, it can be concluded that any eventual variation...
of the AGN in this band is probably heavily diluted by the starburst continuum and cannot be detected.

### 3.2.3. The Hα Emission Line

As we can see in Figure 2, the Hα profile and flux have varied on the shortest timescales probed by the observations. The broad-component flux $F_{\text{broad}}$ varied overall by approximately $\sim 20\% (F_{\text{broad}} = 20.44\%)$ with respect to the mean. The two most remarkable increases in $F_{\text{broad}}$ occurred in the interval MJD56187–56194 and MJD56285–56290, when the line flux increased by $\sim 70\%$ in 7 days and by $\sim 90\%$ in 5 days, respectively, as seen in Figures 2 and 4. We conclude that a substantial portion of the broad-line luminosity comes from a region that has a size less than 5 light days.

### 4. DISCUSSION

The double-peaked Hα profile of NGC 1097 has been monitored by our group for more than 20 yr (Storchi-Bergmann et al. 1993, 1995, 1997, 2003). Recently we reported the discovery of short-timescale variability (Schimoia et al. 2012) of $\lesssim 7$ days, consistent with the shortest timescale variations detected here of $\lesssim 5$ days. Another previous finding was an inverse correlation between $F_{\text{broad}}$ and the velocity separation between the blue and red peaks, $\Delta V = V_B - V_R$. This inverse correlation supports the reverberation scenario: when the ionizing flux is low, the innermost parts of the accretion disk are relatively more important and the profile becomes weaker and broader, when the ionizing flux is high the inner disk becomes more highly ionized, therefore the bulk of the Balmer line emission moves to larger radii (Dumont & Collin-Souffrin 1990) and the profile becomes both stronger and narrower.

Figure 5 shows, in the left panel, a comparison of the measurements of $F_{\text{broad}}$ and $\Delta V$ of the present and previous works. The right panel shows three typical profiles for each of the three epochs we have collected the data.

The left panel of Figure 5 shows that in the current campaign, the broad Hα flux $F_{\text{broad}}$ reached historically low levels and remained low throughout the campaign, with variations comparable to or just barely larger than the uncertainties in the measurements. The separation $\Delta V$ between the blue and red peaks was also at the largest values we have ever observed in this source, what is still consistent with the reverberation scenario.

We now investigate the significance of the inverse correlation between the integrated flux of the Hα double-peaked line and the velocity separation of the blue and red peaks. Figure 5 (left) shows that there is a distinct behavior between the data from Storchi-Bergmann et al. (2003) (red triangles)—taken between 1991 and 2002, and that from our more recent studies, corresponding to the period between 2010–2013, including both the data from Schimoia et al. (2012) and that of the present work (blue circles and green squares).

Between these two data sets there is a temporal gap of approximately 7–8 yr. The right panels of Figure 5 show that in the first data set (1991–2002) the profile showed large variations, both in flux and peak separation, with a strong inverse correlation between the two. In the more recent observations that begun in 2010, the profiles became broader. In order to investigate the significance of the inverse correlation, we have grouped the data as follows: (1) only the data from Storchi-Bergmann et al. (2003); (2) only the most recent data of Schimoia et al. (2012) + that of this work; and (3) all the data together. The resulting linear regressions are shown as dashed lines in Figure 5.

We have calculated the correlation coefficient and respective significance for the three different groups of data above:

1. For the data from Storchi-Bergmann et al. (2003) alone we found a linear correlation coefficient $r = -0.823^{+0.034}_{-0.038}$, which implies significance levels from 99.95% to 99.99%.
2. For the data from Schimoia et al. (2012) plus that of this work we found a correlation coefficient $r = -0.343^{+0.049}_{-0.050}$ which gives significance levels from 89.25% to 97.17%.
3. For all data together we found a correlation coefficient of $r = -0.354^{+0.029}_{-0.029}$, and the respective significance levels are 97.05% and 99.06%.

Thus we conclude that for any set of data there is an inverse correlation with a significance level $\gtrsim 90\%$, while for the complete data set the correlation is $\sim 97\%$. The data are thus consistent with a low-flux state corresponding to the widest separation between the two peaks, which leads us to the conclusion that the overall data are consistent with the reverberation scenario.
4.1. An Accretion Disk Model

In order to test further the scenario we have proposed for the accretion disk (Schimoia et al. 2012), we modeled the Hα profiles using the accretion disk model described by Gilbert et al. (1999), Storchi-Bergmann et al. (2003), and Schimoia et al. (2012). In this formulation, the broad double-beaked 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 $r_g = GM_{\text{BH}}/c^2$, $c$ is the speed of light, $G$ is the gravitational constant, and $M_{\text{BH}}$ is the mass of the black hole). The disk has an inclination $i$ relative to the line of sight (i.e., zero degrees is face-on). Superimposed on the axisymmetric emissivity of the circular disk, there is a perturbation in the form of a spiral arm. We adopted the “saturated spiral model” (Schimoia et al. 2012) for the total emissivity of the accretion disk, as it best reproduces the data. This emissivity law is given by

$$
\epsilon(\xi, \phi) = \epsilon(\xi) \left\{ 1 + \frac{A}{2} \exp \left[ -\frac{4 \ln 2}{\delta^2} (\phi - \psi_0)^2 \right] + \frac{A}{2} \exp \left[ -\frac{4 \ln 2}{\delta^2} (2\pi - \phi + \psi_0)^2 \right] \right\}, \tag{2}
$$

where

$$
\epsilon(\xi) = \begin{cases} 
\epsilon_0 e^{-q_1}, & \xi_1 < \xi < \xi_q \\
\epsilon_0 e^{-(q_1-q_2)\xi-\xi_1}, & \xi_q < \xi < \xi_2 
\end{cases} \tag{3}
$$

is the axisymmetric emissivity of the disk. The parameter $\xi_q$ 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 $\xi_1 < \xi < \xi_q$; $q_2$ is the index for $\xi_q < \xi < \xi_2$. $A$ is the brightness contrast between the spiral arm and the underlying disk, and the expression between square brackets represents the decay of the emissivity of the arm 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 function with FWHM $= \delta$ (azimuthal width).

The relation between the azimuthal angle $\phi_0$ and the angular position $\psi_0$ of the ridge of emissivity on the spiral arm is given by

$$
\psi_0 = \phi_0 + \frac{\ln(\xi/\xi_{sp})}{\tan p}, \tag{4}
$$

where $\phi_0$ is the azimuthal angle of the spiral pattern, $p$ is the pitch angle, and $\xi_{sp}$ is the innermost radius of the spiral arm.

The specific intensity from each location in the disk, in the frame of the emitting particle is calculated as

$$
I(\xi, \phi, v_r) = \frac{\epsilon(\xi, \phi) e^{-\left(v_r-v_0\right)^2/2\sigma^2}}{4\pi \left(2\pi\right)^{1/2} \sigma}, \tag{5}
$$

where $v_r$ is the emission frequency and $v_0$ is the rest frequency corresponding to Hα 25656.4 and $\sigma$ is the local “broadening parameter” (Chen & Halpern 1989).

We fixed the following model parameters: $q_1 = -2.0$, $q_2 = 3.0$, $\xi_{sp} = \xi_1$, $p = 50^\circ$, $\delta = 70^\circ$ and $i = 34^\circ$, which are the same values adopted in previous works (Storchi-Bergmann et al. 2003; Schimoia et al. 2012). Thus, the only parameters we allowed to vary are $A$, $\xi_q$ and $\phi_0$. In practice, $\xi_q$ regulates the width of the profile: when $\xi_q$ is closer to $\xi_1$ the profile is broader, when $\xi_q$ is closer to $\xi_2$ the profile becomes narrower; $\phi_0$ is the orientation of the spiral pattern and by allowing this parameter to increase monotonically, we can reproduce the variation of the relative intensity of the blue and red peaks as due to the rotation of the spiral arm.

For direct comparison with the scenario proposed by Schimoia et al. (2012), we adopt their derived angular velocity of the spiral arm, of $\phi_0 \sim 0.680$ day$^{-1}$, which corresponds to a rotation period of $\sim 18$ months. Using this prescription, we estimate the value of $\phi_0$ for the first optical observation (MJD56147) as $775^\circ$, which means that the spiral arm should have completed one rotation since the last observation of Schimoia et al. (2012) for which $\phi_0 = 400^\circ$. The best-fitting models are compared with the observed line profiles in Figure 2, and the corresponding parameter values are listed in Table 5. The disk emissivity for each epoch is illustrated in Figure 6.

As can be seen in Figure 2, the model can indeed reproduce the observed variations of the double-peaked profile. We have tested many values for $\xi_q$ in the range between the inner and outer radius, $\xi_1 = 450$ and $\xi_2 = 1600$. However, we achieved the best fits by keeping $\xi_q$ close to the inner radius, in the range $\xi_q \sim 500–600$. This is consistent with the fact that during the monitoring campaign we observed the broadest profiles ever seen for this object.

In order to improve the fitting we also had to apply an overall blueshift of about $-250$ km s$^{-1}$ to all model profiles. Such a velocity shift has been noted in our previous studies (Storchi-Bergmann et al. 2003; Schimoia et al. 2012), in which they were attributed to possible winds from the accretion disk. Another

### Table 5

| UT Date  | MJD  | $\xi_q$ | $\phi_0 - 760^\circ$ | $A$   |
|---------|------|--------|----------------------|-------|
| 2012 Aug 7 | 56147.356 | 550   | 15                   | 0.2   |
| 2012 Aug 9 | 56149.368 | 570   | 20                   | 0.2   |
| 2012 Aug 10 | 56150.360 | 580   | 20                   | 0.2   |
| 2012 Aug 24 | 56164.349 | 580   | 30                   | 0.5   |
| 2012 Aug 31 | 56171.388 | 570   | 35                   | 0.5   |
| 2012 Sep 3 | 56173.305 | 550   | 35                   | 0.8   |
| 2012 Sep 8 | 56179.370 | 550   | 40                   | 0.8   |
| 2012 Sep 16 | 56187.222 | 540   | 45                   | 2.0   |
| 2012 Sep 23 | 56194.256 | 580   | 50                   | 2.5   |
| 2012 Sep 27 | 56198.175 | 570   | 50                   | 1.5   |
| 2012 Oct 12 | 56213.316 | 525   | 60                   | 1.5   |
| 2012 Oct 18 | 56219.316 | 500   | 65                   | 1.5   |
| 2012 Oct 25 | 56226.048 | 545   | 70                   | 0.3   |
| 2012 Oct 28 | 56229.229 | 515   | 75                   | 0.5   |
| 2012 Nov 2 | 56234.086 | 545   | 75                   | 0.2   |
| 2012 Nov 12 | 56244.074 | 560   | 80                   | 0.2   |
| 2012 Nov 23 | 56255.068 | 530   | 90                   | 0.0   |
| 2012 Dec 8 | 56270.206 | 515   | 100                  | 0.0   |
| 2012 Dec 15 | 56277.142 | 520   | 105                  | 0.0   |
| 2012 Dec 23 | 56285.097 | 515   | 110                  | 0.0   |
| 2012 Dec 28 | 56290.074 | 570   | 115                  | 0.0   |
| 2013 Jan 17 | 56310.047 | 545   | 130                  | 0.0   |
| 2013 Jan 26 | 56319.067 | 510   | 135                  | 0.0   |

Notes. The date of observations are given in Column 1 while Column 2 gives the Modified Julian Date (JD−2400000.5). The resulting parameters of the modeling are given in the following columns: Column 3 gives the radius of maximum emissivity of the accretion disk, Column 4 gives the azimuthal orientation of the spiral arm, and Column 5 gives the contrast between the spiral arm and the underlying disk.
Figure 6. Image showing the disk emissivity utilized to model the double-peaked profile for each epoch of observation of Figure 2. White represents the brightest regions, and the observer is to the bottom. The disk parameters for these epochs are listed in Table 5. On each frame the axis is expressed in terms of $\xi = 10^{-3} \xi_3$. 
possible explanation for the velocity shifts is the presence of the spiral pattern, since the spiral arm also slightly modifies the velocity field. We note that some epochs require blueshifts somewhat higher or lower than −250 km s$^{-1}$; however, the corresponding improvements in the fit are smaller than the uncertainties. Thus, we adopt the mean blueshift value of $−250$ km s$^{-1}$.

Modeling the present data revealed that the parameter $ξ_q$—the “break” radius, corresponding to the region with strongest emission in the disk—must be kept close to the inner radius in order to reproduce the observed double-peaked profiles. This result is consistent with the scenario in which the central ionizing source is faint and able to power just the innermost region of the accretion disk. The mean value of $ξ_q$ over all the observations is $ξ_q = 545 \pm 25$. Assuming the black hole mass is $M_{BH} = 1.2 \times 10^8 M_\odot$ (Lewis & Eracleous 2006), at this radius the dynamical timescale of the accretion disk is $τ_{dyn} \approx 3$ months and the rotation period ($2πτ_{rot}$) is $\sim 18$ months, which is consistent with the estimated rotation period for the spiral arm. A property of the double-peaked profile that varies on this timescale is the relative intensity of the blue and red peaks: for instance, from MJD56194 to MJD56277 (see Figure 2) the profile changed from a dominant red peak to a dominant blue peak in $\sim 3$ months. We note that the light travel timescale, at $ξ_q = 545$ is just 4 days, which is consistent with the upper limit of $\sim 5$ days for the timescale for the H$\alpha$ flux variations.

### 4.2. Correlation Between X-Rays and H$\alpha$

In order to look for a direct reverberation signal between the X-rays (presumably emitted by the RIAF) and the response of the line-emitting portion of the disk, we applied the interpolated cross-correlation function method (Gaskell & Peterson 1987; White & Peterson 1994; Peterson et al. 1998, 2004) between the X-ray and H$\alpha$ light curves. Unfortunately, we are unable to constrain the lag between the X-ray and H$\alpha$ light curves. We are similarly unable to constrain any possible lag between the X-rays and the UV continuum. The main reason that the time-series analysis fails to yield results is primarily the absence of strong flux variations in every band in this campaign. It also seems apparent that, at least in this low-luminosity state, the time sampling was not frequent enough. This conclusion is supported by the fact that we could detect significant variations in the X-rays and H$\alpha$ light curves on time intervals as short as our mean sampling time interval.

In order to take into account the effect of the uncertainties of the flux measurements in the correlation, we proceeded as follows. Before calculating the correlation coefficient, we scattered each flux measurement using a Gaussian probability distribution in which the mean value of the Gaussian corresponded to the value of the flux measurement and the root mean square of the Gaussian corresponded to the mean squared value of the lower and upper uncertainties. We repeated this process $10^5$ times and calculated the median value for the distribution of values of the correlation coefficient as $τ = 0.253^{+0.105}_{−0.133}$. The upper and lower limits correspond to $\pm 34.1\%$ of the distribution around the median. The lower and upper limits for the correlation coefficient imply a significance level of 56.8%–98.4%.

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We can thus conclude that there is a marginal correlation between the X-ray and H$\alpha$ flux variations; the variations are not completely random. Nevertheless the correlation is not tight enough to confirm that the two fluxes vary together. The weakness of the correlation is almost certainly attributable to the low amplitude of the variations during the monitoring campaign. The lack of variability in the UV precluded any similar analysis in that band.

### 4.3. Comparison with other Objects and Accretion Disk Models

Monitoring of “double-peaked” emitters have been used as a probe for testing accretion disk models and to understand what are the physical mechanisms responsible for the observed changes in the double-peaked profiles. In this subsection we make a comparison between the observed properties of the NGC 1097 double-peaked profile and two other also very well studied double-peaked emitters: Arp 102B and 3C390.3.

In the case of 3C 390.3, many works have reported spectroscopic long-term monitoring (years to decades) (Shapovalova et al. 2001; Sergeev et al. 2002; Shapovalova et al. 2010) or short-term monitoring (a few months) (Dietrich et al. 2012) of the AGN optical continuum around 5100 Å and the variations of the broad Balmer double-peaked emission lines, H$\alpha$ and H$β$.

Common to these works is the conclusion that the broad double-peaked Balmer lines flux variations do follow the optical continuum variations with time delays of $τ(H\alpha) \gtrsim 56$ days and $τ(H\beta) \gtrsim 44$ days. Also, Dietrich et al. (1998) found that the flux variations of the Balmer lines of Arp 102B seems to be correlated with the X-ray flux variations with a time delay of $\sim 20$ days. However, for the case Arp 102B the variations of the flux of the Balmer broad double-peaked emission lines do not appear to be strongly correlated with the variations of the AGN optical continuum (Shapovalova et al. 2013). In spite
of the weak correlation, the authors estimate a time delay of \( \tau (H_\beta) \sim 20 \text{ days} \).

In the case of NGC 1097, we were never able to detect the AGN optical continuum (Storchi-Bergmann et al. 1993, 2003; Schimoia et al. 2012), and this was the motivation for us to look for the continuum in X-rays and UV. Unfortunately, the variations were small during our campaign, but in Section 4.2 we have nevertheless shown that the profile variations are weakly correlated with the X-ray continuum variations, indicating that the X-rays could indeed be the driver of the double-peaked profile.

In the case of Arp 102B the variations of the relative intensity of the blue and red peaks were first modeled by Newman et al. (1997) in the context of a relativistic accretion disk in which the non-axisymmetric emissivity part of the disk has the shape of a hot spot that rotates in the disk around the central SMBH in the dynamical timescale. In the case of 3C90.3 the hot spot model have been used to explain the observed flux “outbursts” of the blue peak of the profile (Jovanović et al. 2010). Lewis et al. (2010) have reported a long-term monitoring of a few radio galaxies in which the double-peaked profiles display small flux bumps that move in the velocity space and are attributed to hot spots in the accretion disk. Nevertheless, in almost all cases the hot spots are short lived: they have been observed to appear and are more likely to last from several months to a few years. In contrast, the alternating relative intensity of the blue and red peaks of NGC 1097 have lasted for more than 20 yr, suggesting that the features producing the variation of the relative intensity of the blue and red peaks are longer lived than the hot spots observed in other double-peaked emitters. The variations in the relative intensity of the blue and red peaks in NGC 1097 have been clearly observed both when the flux of the broad line is in a high state (higher line flux and narrower profile) as well as when the flux is in a low state (low line flux and broader profile). On the other hand, we note that the emissivity of the saturated spiral model adopted in our modeling is not that different from that of a hot spot, in the sense that the spiral arm + broken power-law emissivity component can effectively concentrate the non-axisymmetric emissivity in a structure very similar to a hot spot (see Figure 6, MJD56194). Nevertheless, we favor the scenario of the saturated spiral model for NGC 1097 due the fact that the fast timescale variations of the profile, namely in the velocity separation of the peaks and integrated flux of the broad profile, occur in timescales of a few days to a few weeks. At these short timescales, these variation can only be attributed to changes in the illumination/ionization of the disk, which have been modeled by changing the break radius, \( \xi_q \), while the rotation of the non axisymmetric pattern allow us to simultaneously model the variations of the relative intensity of the blue and red peaks.

Finally, we point out that at some epochs there is a flux excess in the high velocities of the blue wing of the double-peaked profile (see Figure 2, for instance MJD56194 and 56290), that was also observed in previous works (Storchi-Bergmann et al. 2003; Schimoia et al. 2012). The origin of this excess is not completely understood. In Storchi-Bergmann et al. (2003) it was proposed that it could be due to the presence of a wind emanating from the disk, what is not taken into account in the model.

5. CONCLUSIONS

We monitored the AGN in NGC 1097 for \(~6\) months, from 2012 August to 2013 February, in three spectral bands: in the X-ray (0.3–10 keV), using the Swift/XRT, in the UV, using the Swift/UVOT telescope, and in the double-peaked H\(\alpha\) profile, with data from the SOAR and Gemini-South telescopes. Our main conclusions are:

1. The X-ray fluxes varied on the shortest timescale probed by the observations, 4 days, indicating that the emitting structure has a size smaller than 4 light days; the maximum variation observed between two consecutive dates was 97\%, but the average variation over the whole period was only 13\%.

2. The H\(\alpha\) flux also varied on the shortest timescale probed by the observations, \(~5\) days. The maximum variation observed was 90\%, but the average variation over the whole period was 20\%.

3. To within the uncertainties, the UV flux did not vary. This can be due to the contribution of the compact nuclear starburst previously found within the inner 9 pc, that dominates the UV continuum emission, and is probably diluting the contribution of a variable source.

4. Although we have not found a clear reverberation signal in our most recent data, when we consider this data together with the previous ones from epochs 1991–2001 and 2010–2012, they are consistent with the reverberation scenario, as we can still observe, in the overall data, an inverse correlation between the H\(\alpha\) flux and the separation between the red and blue peaks of the H\(\alpha\) profile, as noted in previous studies.

5. We were able to reproduce the variations of the double-peaked profile using the same accretion disk model of Schimoia et al. (2012); in particular, we kept the same inner and outer radii, as well as the 18 month rotation period for a spiral arm in the disk, that, combined with variations in the contrast of the spiral arm, successfully reproduces the variation of the relative intensity of the blue and red peaks.

6. The small range of variation of the width of the double-peaked profiles was reproduced by keeping the \( \xi_q \) values (radius of maximum emissivity) close to the inner radius. This radius corresponds to a rotation period of 18 months and a light travel time of \(~4\) days, in agreement with the shortest variation timescales observed.

7. We find only a marginal correlation between the X-ray and H\(\alpha\) flux variations, although the analysis reveals the need for more frequent monitoring of this source, particularly when it is in such a low-luminosity state.

The presence of some correlation between the X-ray flux and the broad H\(\alpha\) profile, even though we could get only an upper limit on the shortest variation timescale, leads us to the conclusion that the variations of the broad H\(\alpha\) line profile do follow the variations of the X-ray flux. But we also note that the H\(\alpha\) flux remained at the lowest levels we have ever observed, and the blue and red peaks of the double-peaked profile remaining at the widest separation. This indicates that we have caught the AGN in NGC 1097 in a very low activity state, in which the ionizing source was very weak and capable of ionizing just the innermost part of the gas in the disk. Nonetheless, the data presented here still support the picture in which the gas that emits the double-peaked Balmer lines is illuminated/ionized by a source of high-energy photons which is located interior to the inner radius of the line-emitting part of the disk.

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