OPTICAL MICROVARIABILITY IN QUASARS: SPECTRAL VARIABILITY

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ABSTRACT

We present a method that we developed to discern where the optical microvariability (OM) in quasars originates: in the accretion disk (related to thermal processes) or in the jet (related to non-thermal processes). Analyzing nearly simultaneous observations in three different optical bands of continuum emission, we are able to determine the origin of several isolated OM events. In particular, our method indicates that from nine events reported by Ramírez et al., three of them are consistent with a thermal origin, three with non-thermal, and three cannot be discerned. The implications for the emission models of OM are briefly discussed.

Key words: galaxies: active – galaxies: fundamental parameters – galaxies: photometry – quasars: general

1. INTRODUCTION

Optical microvariability (OM; variations with small amplitude in time scales from minutes to hours) in quasars can be a powerful tool to constrain the energy emission models of active galactic nuclei. Some studies indicate that OM does not depend on the radio properties of quasars (see de Diego et al. 1998, hereafter PI; Stalin et al. 2004; Gupta & Joshi 2005; Ramírez et al. 2009, hereafter PII). However, the mechanism responsible for OM has not been characterized. Concerning this topic, variability studies in the optical bands acquired a particular relevance, because the optical/UV excess is identified with the emission from the accretion disk (e.g., Krishan & Wiita 1994; Lawrence 2005; Pereyra et al. 2006; Li & Cao 2008; Wilhite et al. 2008). Unfortunately, all the proposed scenarios are very complex when the emission from additional spectral components is considered.

In photometric studies, the properties of the spectral energy distribution (SED) of quasars are characterized by the spectral index, which is defined as the slope of a curve in a plane log(fν) versus log(ν), and calculated as magnitude differences at different bands (e.g., Massaro et al. 1998; Trévese & Vagnetti 2002). During variability events, changes in the shape of this SED can give us important information about the emission processes. For instance, evidence from variability studies strongly indicates that OM has non-thermal nature in both BL Lac objects and flat spectrum radio quasars (FSRQs; e.g., D’Amicis et al. 2002; Vagnetti et al. 2003; Villata et al. 2004a, 2004b; Hu et al. 2006a, 2006b, 2007), but in the case of FSRQs the contribution of a thermal component must be considered in the spectrum of these objects (e.g., Gu et al. 2006; Hu et al. 2006a; Ramírez et al. 2004). Concerning quasars, short-term variability (variations with amplitudes of tenths of a magnitude and time scales of weeks to months) might have thermal origin (e.g., Trévese & Vagnetti 2002). Nevertheless, all these studies usually employ two bands, or only the average of color values is used, thus losing information about texture of shortest variations (see Giveon et al. 1999; Webb & Malkan 2000; Trévese & Vagnetti 2002; Vagnetti et al. 2003).

In order to discern where the OM in quasars originates, we assume that emission from the accretion disk must be related to thermal processes, while the emission from the jet must be related to non-thermal processes. During OM events, the spectral component responsible for the variation may display characteristic color changes. Then, we developed a method with quasi-simultaneous observations at three optical bands to analyze these color changes that accompanied microvariability events. This paper is organized as follows: in Section 2, we shortly comment on the data treatment; in Section 3, we define a spectral variability index and how to determine the OM origin; in Section 4, we analyze the data; finally, we discuss the results in Section 5; and a summary and conclusions are given in Section 6.

2. SAMPLES SELECTION, OBSERVATIONS, AND DATA REDUCTION

Details of the selection criteria, observation strategy, and data reduction have been exposed in PI, PII, and de Diego (2010). These data consist of a sample of 22 core-dominated radio-loud quasars (CRLQ) and 22 radio quiet quasars (RQQs) observed in diverse epochs. Each object in the RQQ sample paired a CRLQ object in brightness and redshift minimizing selection effects when properties of microvariability between both samples were compared in PII. Here, we will only discuss the data corresponding to OM events reported in PII. This subsample is listed in Table 1. Four telescopes were used, which are located in Mexico and Spain. BVR filters of Johnson–Cousins series were used. The observational strategy consists of monitoring a CRLQ–RQQ couple during the same night in overlapping sequences; five images of each object in the BVR sequence are taken (~1 minute of exposure time per image, although it depends of the object brightness, the filters, and the telescope used). Each object was observed at moderated air masses, always at least 30° above the horizon. Standard stars were observed to obtain the flux level of the first data set of each object in each night. These stars were observed each time that a sequence of each pair of objects was complete. This implies that standard stars were observed each hour, approximately. All these stars are taken from Landolt (1992). In addition, these standard stars are used to perform correction by atmospheric extinction.

3. QUASAR SED AND SED VARIABILITY

In order to discern where the OM originates, the analysis is divided into two main steps: first, a SED model is fitted to the initial data set, obtaining estimations of the values of the parameters of each spectral component; then, the observed spectral variations are modeled using these values.
The simplest description of the continuum emission for quasars is given by a thermal and non-thermal emission mixture (e.g., Malkan & Sargent 1982; Malkan & Moore 1986). Thus, at any time \( t \), the flux would be determined by the expression

\[ f_{\nu t} = f_{\nu Tt} + f_{\nu Tt}, \tag{1} \]

where the sub-index \( r \) refers to the time when a particular data set was acquired; \( f_{\nu T} \) refers to the total flux; \( f_{\nu T} \) to its non-thermal component; and \( f_{\nu T} \) to its thermal component (hereafter sub-indices \( T \) and \( n \) indicate thermal and non-thermal components, respectively). Usually, thermal and non-thermal components are associated with the accretion disk and with the relativistic jet, respectively. Hereafter, we will adopt this assumption.

At any time \( t \), the contribution from each component to the total flux can be described as \( a_{\nu T} \equiv f_{\nu T} / f_{\nu T} \) for the non-thermal component and \( b_{\nu T} \equiv f_{\nu T} / f_{\nu T} \) for the thermal one (note that \( b_{\nu T} = 1 - a_{\nu T} \)).

In a naive description, the non-thermal emission from the jet can be described by a simple power law, while the thermal emission from the disk can be modeled by a simple blackbody. Although a simple blackbody is an over-simplification for the accretion disk, this is the simplest model that fits our data (something similar has been made previously by Malkan & Sargent 1982 and Malkan & Moore 1986, among others).

When a given object is monitored in a particular night, we can determine an initial time, \( t_0 \), which corresponds to the first data set of observations. When a variation is detected, we take the difference of fluxes between a given data set obtained at the time \( t \), and that for the first data set; then, we normalize with respect to the initial total flux. We consider that the variation is provoked by only one of the spectral components in expression (1), leading to the fact that in the difference of fluxes only the variable component survives, i.e.,

\[ \sigma_{\nu T} = \frac{\Delta f_{\nu T}}{f_{\nu T}}, \tag{2} \]

In this expression, \( f_{\nu T} (i = n, T) \) represents the variable component. Some advantages (which are easy to verify) of measuring the flux changes by this expression are: data transformation to standard photometric system is unnecessary; error propagation is diminished, and a larger accuracy is reached; correction by interstellar extinction to the first data set, while for the spectral variability description, this correction is not required.

On the other hand, we have to consider that the observed flux is related to the emission in the sources frame through the expression

\[ f_{\nu T} = (1 + z)L(1 + z)/4\pi D_L^2 \] (see Kembhavi & Narlikar 1999),

where \( f_{\nu T} \) represents the observed flux at the observed frequency \( \nu \); \( L \) the luminosity of the source; \( z \) the redshift; and \( D_L \) the luminosity distance.

In addition, we can represent the brightness amplitude of each component by means of a pair of constants: \( A_{\nu T} \) for the non-thermal component and \( A_{\nu T} \) for the thermal one. The injection of new particles with similar energy, for the non-thermal case, or changes of size of the region of emission, for the thermal case, can provoke amplitude changes.

We initially fit the observed flux at the first data set, obtaining the initial values for the temperature of the disk, the spectral index of the non-thermal component, and the contribution of each component: \( T_{\nu T}, \alpha_{\nu T}, \text{ and } a_{\nu T} \text{ and } b_{\nu T} \), respectively. Taking the initial data, we can express for the non-thermal component the ratio of fluxes between any \( t \) and \( t_0 \), i.e.,

\[ \frac{f_{\nu T}}{f_{\nu T}} = \frac{A_{\nu T}}{A_{\nu T}} \nu^{\alpha - \gamma} (1 + z)^{\alpha - \gamma}, \tag{3} \]

and from this expression we obtain

\[ \frac{f_{\nu T}}{f_{\nu T}} = \frac{A_{\nu T}}{A_{\nu T}} \nu^{\alpha - \gamma} (1 + z)^{\alpha - \gamma} a_{\nu T} f_{\nu T} 10^{-0.4 m_{\nu T}}, \tag{4} \]

where \( m_{\nu T} \) refers to the magnitude in the standard system, corrected by interstellar extinction (corrections to these initial magnitudes were carried out using values reported by the NED).
\( f_\nu \) is a constant of reference flux, corresponding to a star of zero magnitude; and \( v = v_B, v_V, v_R \), i.e., the effective frequency in the \( B, V, \) and \( R \) bands. Something similar can be done for the thermal component, leading to

\[
f_{\nu Tt} = \frac{\beta_t}{\beta_0} v^3 \nu^{-3} \left( \frac{\nu}{\nu_0} \right)^{(1+z)} - 1 e^{\left( \frac{\nu}{\nu_0} \right)^{1+z}} - 1 \times b_{\nu t} f_\nu 10^{-0.4m_{\nu t}}.
\]

(5)

Concerning the contribution from each component, we can give only \( a_{\nu t} \) or \( b_{\nu t} \), since we can write \( a_{\nu t} \) and \( b_{\nu t} \) (where \( v = v_B, v_V, v_R \)) in terms of them, i.e.,

\[
a_{\nu t} = a_{\nu 0} f_V f_\nu 10^{-0.4(m_{\nu 0}-m_{\nu t})} f_{\nu T0}.
\]

(6)

while

\[
b_{\nu t} = b_{\nu 0} f_V f_\nu 10^{-0.4(m_{\nu 0}-m_{\nu t})} f_{\nu T0}.
\]

(7)

Thus, evaluating expressions (4) and (5) at \( t = t_0 \) and replacing them in Equation (1), we can model the emission at each frequency for the first data set to get values for \( T_{t0}, \alpha_{t0}, \) and \( a_{\nu t0} \) (see Figure 1). We will test these values when we will describe the spectral variations, generating curves on a plane defined by \( \sigma Vr vs. \sigma B \) (see Figure 2). Comparing data and models on this plane, we obtain a spectral variability diagnosis plane.

3.1. Emission Models for Quasars on Diagnosis Plane for Spectral Variability

Using expression (4), i.e., a power law for the non-thermal component, expression (2) can be written as

\[
\sigma_{\nu nt} = a_{\nu t0}(n_{nt}(v + z)^{\alpha_{t0}} - 1),
\]

(8)

while using expression (5), i.e., a blackbody as the thermal component, expression (2) can be written as

\[
\sigma_{\nu Tt} = b_{\nu t0}\left( n_{Tt} \left( \frac{v}{\nu_T} \right)^3 e^{\frac{h\nu}{kTt}(1+z)} - 1 \right) \left( e^{\frac{h\nu}{kTt}(1+z)} - 1 \right).
\]

(9)

where \( n_{Tt} = \beta_t/\beta_0 \) and \( n_{nt} = A_t/A_0 \). In this way, changes in amplitude are easily obtained by varying the values of these ratios from unity, at \( t_0 \), to their final values at \( t \).

Once we get \( T_{t0}, \alpha_{t0}, \) and \( a_{\nu t0} \), changes of \( T_t \) and/or \( n_{Tt}, \) or \( \alpha_t \) and/or \( n_{nt}, \) in expression (2), generate the trajectories in the \( \sigma_{Vr} vs. \sigma_B \) plane (see Figures 2–6). Simultaneous changes in \( T_t \) and \( n_{Tt}, \) or \( \alpha_t \) and \( n_{nt}, \) can generate diagnosis trajectories with a returning behavior (see Figure 2). A similar case can happen in an expansion of the thermal component with a decrease in its temperature.

Unfortunately, for the data presented in PII it is not possible to establish a unique set of initial parameters due to the lack of data in more bands. Figure 1 shows this problem. In this figure, we present three reasonable fits for disk temperatures of 26,000 K, 20,000 K, and 30,000 K for the first data set of PKS 1510-089. For this reason, we must select the most appropriate values for \( \alpha_{t0}, T_{t0}, \) and \( a_{\nu t0}, \) based on the typical values found in the literature for similar objects. Some investigations suggest that the typical maximum disk temperature, close to the central object, should be between 20,000 K and 30,000 K, although temperatures outside of this range are not discarded (e.g., Malkan & Sargent 1982; Malkan & Moore 1986; Czerny & Elvis 1987; Pereyra et al. 2006). The spectral index of the non-thermal component might be around \( -1 \) (e.g., Malkan & Sargent 1982; Elvis et al. 1986; Brown et al. 1989a, 1989b).

On the other hand, for blazars, the non-thermal component contributes with most of the flux (e.g., Malkan & Sargent 1982).
and at low brightness levels, it is expected that both components contribute the same (e.g., Gu et al. 2006).

Nevertheless, regardless of the exact value for these parameters at $t = t_0$, we can discern the OM origin analyzing the spectral variations. The procedure consists of taking several $T_{n} - \alpha_{t} - \alpha_{V t}$ sets, trying to reproduce the spectral variations with each of them. First, the simplest component (a power law) is fitted to the initial data, obtaining $\alpha_{t}$. From this fit, we look for an explanation to the spectral variation, i.e., performing changes of amplitude, the slope, or both, in the diagnosis plane. If the explanation is satisfactory, for simplicity we consider that the OM event is consistent with changes in this unique component. Otherwise, an extra (thermal) component must be added to fit the initial data.

When this second (thermal) component is added to fit the data, two families of characterization curves are generated: one for thermal variations (as those shown in Figure 3) and one for non-thermal variations (as those shown in Figure 4). Contrasting the data with each family of curves, we can determine whether a spectral variation is consistent with a change in the thermal component (i.e., changes of $T_t$ and/or $T_{nt}$) or in the non-thermal one (i.e., changes of $\alpha_t$ and/or $n_{t}$).

After comparing the data with all the curves, we find that we can set the initial spectral index of the non-thermal component, $\alpha_{nt}$, at $\sim -1$, without affecting our conclusions. So, when we include the thermal component, we have only $T_{nt}$ and $\alpha_{V t}$ as free parameters. Then, we take this fit as representative of each family of curves, as shown in Figure 7. For this reason, the estimations for the values of $T_{nt}$, $\alpha_{nt}$, and $\alpha_{V t}$ must be considered more as a suggestion than as the actual conditions for both disk and jet.

We have explored how these assumptions can affect the discernment of the OM origin. As can be appreciated in Figures 2–6, depending on their origin, the curves show a different behavior. With different assumptions of values of $T_{nt}$, $\alpha_{nt}$, and $\alpha_{V t}$, the trajectories for non-thermal variations are very similar. For this reason, we believe that the choice of $\alpha_{nt} = -1$ has no influence on the description of the spectral variation. Expression (8) shows, in fact, that $\alpha_{V t}$, $\beta_t$, and $n_{nt}$ have more influence on the behavior of the trajectories than $\alpha_{nt}$. Additionally, it is easy to see from expression (8) that considering another power law as the second component, instead of a thermal one, does not allow us to reproduce the observed variability.

To illustrate this procedure, we have taken the case of PKS 1510-089. First, a unique non-thermal component has been fitted to the initial data. Since this fit does not describe accurately the variation, it is necessary to add the thermal emission from the disk (Figure 1). We then fixed $\alpha_{nt}$ at $-1$ and calculated the corresponding value for $T_{nt}$ for different choices of $\alpha_{V t}$. Then, we analyzed the variations of the thermal component (see Figure 2). We have used $T_{nt} \sim 26,000$ K (although we also explored the cases with 20,000 K and 30,000 K, solid thin lines in Figure 1) and a non-thermal component contribution of $\sim 60\%$.

Afterward, $\alpha_{nt}$ was fixed at different values, and the corresponding values for $T_{nt}$ and $\alpha_{V t}$ were calculated. Figures 3 and 4 show spectral variability curves for changes of the non-thermal and thermal component, respectively. Curves correspond to $\alpha_{nt} = -1$, $-0.7$, $-2$. As it can be observed in Figure 3
for a variation of the non-thermal component, the range of values used for the parameters has poor influence on the behavior of the spectral variations. On the other hand, the data have a behavior that is closer to the one expected from thermal changes of the spectral variations. On the other hand, the data have a behavior that is closer to the one expected from thermal changes of the spectral variations. On the other hand, the data have a behavior that is closer to the one expected from thermal changes of the spectral variations.

Following a different approach, \( \alpha_{V_{\text{th}}} \) was fixed at different values \( \alpha_{V_{\text{th}}} = 0.60, 0.85, 0.30 \), and the corresponding values for \( T_{\text{th}} \) and \( \alpha_{V_{\text{th}}} \) were calculated. Figure 5 shows different curves for similar changes in \( T_{\text{th}} \) and \( \alpha_{V_{\text{th}}} \), and for clarity in the figure, we have included only a curve for changes in \( \alpha_{V_{\text{th}}} \) and \( n_{\text{th}} \), since the other curves are similar (as those shown in Figure 5). Again, the spectral variation has a behavior that corresponds more to what is expected from thermal variations.

Finally, we have explored the effect of redshift on variations (Figure 6). At the same values of \( T_{\text{th}} \), \( \alpha_{V_{\text{th}}} \), and \( \alpha_{V_{\text{th}}} \), the same variation produced at different redshifts \( (z = 0.0361, 0.8, 1.5) \) causes different observable magnitude changes, but with greater effect on thermal changes than on non-thermal ones.

From this exploration, we find that variations of the non-thermal component cannot explain the data, while these are consistent with thermal variations. In such a case, the temperature of the thermal component varies at least 8000 K for the best fit.

In summary, in the case of PKS 1510-089, a change of the thermal component is the most plausible explanation for the observed variation, regardless of the exact values for \( T_{\text{th}} \), \( \alpha_{V_{\text{th}}} \), and \( \alpha_{V_{\text{th}}} \). A similar procedure has been carried out for each object reported as variable in PII. In the next section, we present the results for each object.

### 3.2. Temporal Resolution of the Spectral Variability

A problem that has to be solved when dealing with color studies refers to the time delay between optical bands (e.g., González-Pérez et al. 1996; Villata et al. 2000; Papadakis et al. 2003, 2007; Hu et al. 2006a, 2006b; Stalin et al. 2009). For spectral OM studies, it is particularly important to avoid any possibility of a time lag, because a shorter lag than the image acquisition time between bands could provoke a false spectral variation. Thus, we must observe an object at different bands in sequences that reasonably guarantee an interval duration less than the physical lags. For the blazar 0716+714, Villata et al. (2000) found that a complete sequence between the \( V \) and \( I \) bands should not exceed \( \sim 10 \) minutes. Papadakis et al. (2003) calculated a 0.4 hr time lag between \( B \) and \( I \) bands in most cases. On the other hand, Hu et al. (2006a) established a time lag of 11 minutes between the \( BATC e \) and \( m \) bands. Nevertheless there is little knowledge about the minimum temporary scales for microvariability. So, it is necessary a criterion for maximum acquisition time that help us to verify that, during a variation, each \( BVR \) sequence was make at the same level of flux. Usually, time lag could be determined by the discrete correlation function (e.g., Edelson & Krolik 1988; Hufnagel & Bregman 1992; Villata et al. 2000; Villata et al. 2004a), but for our observational strategy, we developed a time-lag criterion based on the change rate of each OM event. This criterion permits to be relatively sure that the data sets were acquired when each object was at the same flux level.

We introduce a simultaneity criterion that relates the rate of brightness change with the time of acquisition. A simultaneity
Figure 7. Fits to the first data sets and spectral variability: (a) first set of data is fitted by a power law; (b) first set of data is fitted by a power law and a blackbody mixture; continuum line represents the sum of thermal emission of accretion disk (dashed line) and non-thermal emission of the jet (dotted line). (c) The color change is fitted from the fit shown in panel (a); (d) the color change is fitted from the fit shown in panel (b); dashed lines represent thermal variations, while dotted lines represent non-thermal variations. Errors were obtained from error propagation when $\sigma_0$ is calculated from data. $t_i$ corresponds to the beginning of each monitoring) indicates the temporary sequence for the data.

Figure 8. Same as Figure 7.

index is defined by the expression

$$S_{\nu t} \equiv \frac{\Delta m}{\Delta t_{\text{obs}}} \frac{\Delta t_{\text{cap}}}{2.5\epsilon_{\nu t}} ,$$

where $\Delta m$ refers to the maximum variation amplitude; $\Delta t_{\text{obs}}$ refers to the time lasted between the observations to obtain $\Delta m$; $\Delta t_{\text{cap}}$ is the required time to take a complete sequence of BVR images; and $\epsilon_{\nu t}$ is the standard error in each group of five images. Then, it will be considered that a BVR set of observations is simultaneous when a magnitude difference larger than $2.5\epsilon_{\nu t}$ is avoided, i.e., when the measured error is smaller than a marginal variation. Thus, a set of images taken at the time $i$ is simultaneous when each $S_{\nu t} < 1$. As this criterion is applied on each sequence of observations for an object in each night, we have an average $S_{\nu}$ for the total group of observations. We will show this average in the discussion for each object when none of the $S_{\nu t}$ is greater than 1. In other case, each $S_{\nu t}$ will be showed separately.

Although this criterion requires that the variations have constant change rates, in the next analysis we will see that it is possible to make this assumption, fulfilling this condition.

4. RESULTS

4.1. Model Fits and Initial Data

The results presented in this section show that it is feasible to distinguish qualitatively between thermal and non-thermal origin of some microvariation events. In those cases where both components can explain the spectral variation, for simplicity we suppose that the unique non-thermal component is responsible for the variation. This ambiguity may be eliminated by increasing the monitoring time and observing more optical bands. Figures 7–17 show the procedure described in the last section for the case of PKS 1510-089 for all the objects. The figures show the fits for a unique spectral component for each object (panel (a)). The fits for the thermal and non-thermal mixed components are shown in panel (b). Panel (c) shows a plane $\sigma_{V,R} : \sigma_B$ for the case of the fit showed in panel (a). Finally, panel (d) shows a $\sigma_{V,R} : \sigma_B$ plane for the fit shown in panel (b). In all cases, a $\chi^2$-test indicates that the fits are accurate. In panels (c) and (d), the error bars have been obtained by error propagation in the calculation of $\sigma_{\nu t}$. Additionally, time labels are shown, corresponding to $t_0$ to initial data. In all cases where
two components have been considered, a value of α₀ₙ = −1 has been set for the initial slope of the non-thermal component. Contribution to total flux refers to the V band. In the next, values for αᵥ₀ₙ will be given in percentage.

Table 1 shows the log of the observations and the results of fitting the model with one and two components. Column 1 indicates the name of the object, Column 2 the redshift, and Column 3 the date of observations. The telescope used is given in Column 4, while Column 5 shows the duration for each monitoring. The parameters for a single component are given in Columns 6–9: the magnitude in V and its error (Column 6 and 7, respectively); index αᵥ₀ (Column 8) and its error, δαᵥ₀ (Column 9). The parameters for two components are given in Columns 10–12: T₀ (Column 10); the initial contribution of the non-thermal component, αᵥ₀₀ (Column 11); and the possible cause (thermal or non-thermal) of the variation (Column 9).

4.2. Radio Loud Quasars

**3C 281.** Two OM events were detected in 2000 on March 1 and 4 (see PII).
2000 March 1. The object brightness was $m_V = 17.40 \pm 0.03$ (a little lower than the brightness reported by Sandage et al. 1965: $m_V = 17.02$) at the start of the monitoring. A single power law with $\alpha_0 = -0.03 \pm 0.01$ fits the initial data (Figure 7(a)). However, variations of this component cannot explain the OM event (see Figure 7(c)). Then, we added in the model a thermal component with temperature $T_t \approx 24,000$ K (Figure 7(b)). With this new fit, the non-thermal component contributes $\sim 46\%$ to the total emission. Still, non-thermal changes cannot explain the variation. On the contrary, thermal changes can generate a behavior as that observed (Figure 7(d)). In such a case, a temperature decrease of at least $\sim 1300$ K and an increase of the amplitude of $7\%$ ($n_{T_t} \sim 1.07$) are required. Scrutiny of the light curves (see Figure 1(a) in PII) indicates that variation developed after the second set of observations. A change of 1300 K during 2.7 hr implies a change of 700 K in 1.44 hr (i.e., between the first and second data sets). Simultaneously, the amplitude of the thermal emission would have an increase of 4% ($n_{T_t} \sim 1.04$). Such change might have been present during the observations, and not detected (see Figure 7(d)). The simultaneity criterion indicates no brightness changes during acquisition time ($S_B = 0.43$, $S_V = 0.67$, and $S_R = 0.17$). If indeed the OM event
showed constant rate, our simultaneity criterion shows that the spectral change is not due to observational artifacts.

2000 March 4. We measure $m_V = 17.40 \pm 0.02$ at the beginning of the monitoring. A power law can fit these data (see Figure 8), but with a rather low value for the spectral index $\alpha_{01} = 0.13 \pm 0.03$, with respect to that of March 1. It is possible to explain the variation without appealing to a second component. In such a case, a change of the spectral index of $\Delta \alpha = 0.031$ is required (Figure 8(c)). For the new fit has $\alpha_{01} = 36\%$ and $T_{01} = 200 \text{K}$ (Figures 10(b)). Both thermal and non-thermal changes may account for the observed behavior (Figure 9(d)). Nevertheless, the amplitude of the thermal component should increase by a rather high factor $(n_{nt} > 2.5)$, while the temperature should fall 8000 K. In such a case, the rate of variation has been $\Delta T = 1800 \text{K hr}^{-1}$ and $\Delta n_{nt} \sim 0.57 \text{hr}^{-1}$. The return observed in Figure 9(c) can be caused by a variation which is dominated first by changes in $n_{nt}$ and then by changes in temperature. This behavior might have been evident if observations had been prolonged a few hours. With a constant rate of change (as it seems to have happened; see the V-band light curve in Figure 2(c) of PII), the simultaneity criterion indicates that observations were carried out satisfying the simultaneity criterion $(S_B = 0.09, S_V = 0.22, \text{and } S_R = 0.86)$.

**PKS 0003+15.** At the beginning of the observations we measured $m_V = 15.36 \pm 0.02$, brighter than $m_V = 15.96$ reported by Barvainis et al. (2005). A single non-thermal component fits the first data set with $\alpha_{02} = 0.08 \pm 0.02$ (Figure 10(a)). However, this fit cannot describe satisfactorily the color variation (Figure 10(c)), and a second component must be added. The new fit has $\alpha_{02} = 36\%$ and $T_{02} = 19,200 \text{K}$ (Figures 10(b)).

4.3. Radio Quiet Quasars

**MC3 1750+175.** For this object, we measure $m_V = 16.18 \pm 0.02$ at the beginning of the observations, i.e., brighter than the value reported by Véron-Cetty & Véron (2001) ($m_V = 16.60$). A power law with $\alpha_{00} = 0.64 \pm 0.02$ fits this first data set (Figure 11(a)). However, a second component is necessary to reproduce the observed spectral variation (Figure 11(c)). A mix of thermal and non-thermal components fits the data with $T_{00} \sim 33,700 \text{K}$ and $\alpha_{02} \sim 27\%$ (Figure 11(b)). Non-
thermal changes cannot explain this variation. Nevertheless, changes in thermal component only can explain the $BV$ data set (Figure 11(d)). As it happened in the case of PKS 0003+15, a variation should be observed in the $R$ band. A variation in the thermal component requires a temperature fall of $\sim 5600$ K, while the amplitude should increase by 44% ($n_{T_0} \sim 1.44$) as it is suggested from the data in the upper panel of Figure 11(d). In such a case, the simultaneity criterion indicates the reliability of the spectral evolution ($S_B = 0.01, S_V = 0.21$, and $S_R = 0.10$); however, this variation is something much more complicated to describe with our toy model, as it is easy to see in the Figure 11(d).

**CSO 21.** For this object, we measure a brightness of $m_V = 17.02 \pm 0.03$ at the beginning of the observations, which is similar to the value reported by Véron-Cetty & Véron (2001), $m_V = 17.0$. This first set of data is fitted with $\alpha_{V_0} = -0.67 \pm 0.11$ (Figure 12(a)). The variation detected can be explained by an increase of 0.002 of the spectral index and a decrease in amplitude of $\sim 4\%$ (Figure 12(c)). It is possible that the OM detected for the $V$ and $R$ bands is also present in the $B$ band, but the variation in this band was not detected due to observational errors. The simultaneity criterion indicates that the level of brightness had not changed during observations of a $BVR$ set (Figure 11(d)). As it happened in the case of PKS 0003+15, a single non-thermal component fits these data, while $n_{Tt} \sim 1.10$. For the case of variations of the non-thermal component, the spectral index stays constant, and the amplitude increases to $n_{Tt} \sim 1.02$.

**1628.5+3808.** The magnitude of this quasar was $m_V = 16.78 \pm 0.02$ at the beginning of the observations, i.e., similar to the reported brightness $m_V = 16.80$ by Véron-Cetty & Véron (2001). A single non-thermal component fits these data, with $\alpha_{V_0} = -1.75 \pm 0.02$ (Figure 13(a)). However, the spectral variation cannot be reproduced by changes in this component (Figures 13(c)). Then, a thermal component is added to model the data with $T_0 \sim 10,000$ K and $\alpha_{V_0} = 78\%$ (Figure 13(b)). A variation of non-thermal origin can explain marginally the spectral evolution. On the contrary, a thermal variation can reproduce more accurately the observed behavior (Figure 13(d)). In such a case, $T$ would have fallen by $\sim 760$ K, while $n_{Tt} \sim 1.48$. According to the simultaneity criterion, the spectral variation should be real ($S_B = 0.16, S_V = 0.12$, and $S_R = 0.14$).

**US 3472.** When this object was observed, its brightness was $m_V = 16.25 \pm 0.01$, i.e., brighter than that reported by La Franca et al. (1992) and Véron-Cetty & Véron (2001) ($m_V = 16.99$). Initial data were fitted by a power law with $\alpha_{V_0} = 0.48 \pm 0.01$ (Figure 14(a)). Nevertheless, with this arrangement we cannot give an explanation for the color variation shown in the Figure 14(c). The mixture of a blackbody with $T_0 \sim 27,900$ K and a non-thermal component with $\alpha_{V_0} \sim 29\%$ can also fit the data (Figure 14(b)). While a change of the non-thermal component cannot explain the observed variation, a thermal variation can do it (Figure 14(d)). However, the changes in $T$ and $n_T$ should be larger in $V$ than in $R$. In $V$, the temperature would have changed $\sim 2000$ K with $n_{Tt} \sim 0.87$, while in $R$ the change would be of only $\sim 1200$ K and $n_{Tt} \sim 0.92$. According to the changes of brightness in the $V$ band, the rate of the change would be of $\sim 600$ K hr$^{-1}$. The observations between $R$ and $B$ bands were obtained with a difference of $\sim 8$ minutes; then, the temperature difference would be $\sim 80$ K. Considering the first and the second data sets: $S_B = 1.12$ and $S_R = 1.26$. In such a case, the temperature discrepancy would be explained. The simultaneity criterion indicates that observations were not performed at the same level of brightness (considering the first and last data sets: $S_B = 0.05, S_V = 0.53$, and $S_R = 0.96$), because the variation in $R$ is very quick, leading to a spurious spectral variation. In spite of this lack of simultaneity, the spectral microvariation possesses thermal characteristics. This is evident taking into account that the $B$ and $V$ bands data comply with the simultaneity criterion.

**Mrk 830.** This quasar showed variations in three different nights. Its brightness was similar during the three nights ($m_V \sim 17.6$), and close to the brightness reported by Stepanian et al. (2001; $m_V = 17.29 \pm 0.03$) and by Chavushyan et al. (1995) ($m_V = 17.62$). A unique component marginally fits to the data of this object (Figures 15(a), 16(a), 17(a)). Although a thermal component can be added with $T \sim 10,000$ K, contrary to the case of 1628.5+3808, the non-thermal component is sufficient to explain the spectral variation. Then, the addition of a second component is avoided.

1999 August 17. At the beginning of the night the brightness of this quasar was $m_V = 17.55 \pm 0.01$. But as the first $R$ data set was lost (see PII), the second group was used to fit the model. A single non-thermal component fairly fits the data, with $\alpha_{V_0} = -3.06 \pm 0.49$ (Figure 15(a)). This value was used for the initial data of $B$ and $V$ bands to predict the $R$ value. It is possible to explain a microvariation event as observed with changes in this non-thermal component (Figure 15(c)). The spectral index would have increased $9.8 \times 10^{-4}$, between the first and the third data set, while $n_V$ would have stayed constant. The simultaneity criterion indicates that observations were taken at the same level of brightness ($S_B = 0.09, S_V = 0.35$, and $S_R = 0.02$).

1999 August 18. The brightness was at the same level as for August 17, $m_V = 17.56 \pm 0.03$. The first set of observations at the beginning of the session can be fitted by a non-thermal component with $\alpha_{V_0} = -2.51 \pm 0.35$ (Figure 16(a)). The variation can be described by changes in this component. In such a case, the spectral index would have decreased by a factor of $\times 10^{-3}$ and the amplitude would have increased by a factor of $1\%$ ($n_{SV} \sim 1.01$) (Figure 16(c)). The simultaneity criterion indicates that the spectral variation is reliable ($S_B = 0.27, S_V = 0.39$, and $S_R = 0.15$). However, although the model predicts that the variation could be observed in the $B$ band, it also predicts that a variations should be observed also in the $R$ band, which is not the case.

2001 June 14. The brightness during this night, $m_V = 17.66 \pm 0.01$, was a tenth of a magnitude weaker with respect to the values measured in 1999 August. Initial data can be described by a power law, with $\alpha_{V_0} = -1.81 \pm 0.04$ (Figure 17(a)). The microvariability event can be marginally explained with a variation in the spectral index of $\sim 0.001$ while the amplitude stays constant (Figure 17(c)). The simultaneity criterion establishes that observations have been taken without a change in brightness ($S_B = 0.17, S_V = 0.50$, and $S_R = 0.37$); therefore, the color change is considered real.

Although the continuum emission can be fitted in all cases by a unique non-thermal component, in many of them the broadband spectral variation may require the assumption of the
presence of a second component. Additionally, considering a unique component we have that $\alpha_v > 0$, which indicates that more spectral components must be acting.

5. DISCUSSION

From nine OM detections reported in PII (the two possible variations are excluded), our method can determine that three events are consistent with a thermal variation and three with a non-thermal origin. The other three variations are undetermined, i.e., may be associated with either thermal or non-thermal processes (the cases of PKS 0003+15, MC3 1750+175, and US 3472), but with partial characteristics of thermal variations.

In agreement with de Diego et al. (1998) and Ramírez et al. (2009), the results presented in Section 4 show that microvariability does not depend on radio properties of quasars. Moreover, our study shows that OM related to non-thermal processes might be detectable not only in radio-loud quasars (RLQ; e.g., 3C 281/2000/Mar/04) but also in RQQ (e.g., Mrk 830/2001/Aug/18), and that OM related to thermal processes might be detected in both kinds of objects, RQQ (e.g., 1628.5+3808) and RLQ (e.g., PKS 1510-08).

There are several explanations to account for spectral variability originating either in the jet or the accretion disk. On the one hand, microvariability can be explained by the jet because of its physical conditions and because time scales of OM coincide with jet dynamics (e.g., Tingay et al. 2001; Wiita 2006). If all quasars can generate a relativistic jet, as suggested by the observational reports (Blundell & Rawlings 2001; Blundell et al. 2003; Ghisellini et al. 2004), it is not surprising to find the manifestation of non-thermal microvariability in RQQ. However, in the case of a jet, brightness temperatures exceeding the critical temperature, $T \sim 10^{12}$ K, are required (e.g., Tingay et al. 2001; Wiita 2006 and references therein; Fuhrmann et al. 2008). Although this problem may be overcome if large Doppler factors are considered (e.g., Tingay et al. 2001; Fuhrmann et al. 2008).

The correlation between bands represents an additional problem for the jet thesis, because correlated variations between optical/UV and higher frequencies should be observed (e.g., Nandra et al. 2000; Peterson et al. 2000; Shemmer et al. 2001; Gaskell 2006), which is not the general rule (e.g., Edelson et al. 2000).

On the other hand, variations of diverse time scales, including OM, can be produced in accretion disks (Webb & Malkan 2000; Trèvese & Vagnetti 2001, 2002; Pereyra et al. 2006; see also Mangalam & Wiita 1993; Fukue 2003; Wiita 2006; Gu et al. 2006). Some of these variations may be associated with disk dynamics, or time scales associated with thermal and sound crossing time phenomena (minutes and hours; e.g., Wiita 2006). Changes in the accretion rate can modify the temperature of the disk, altering the flux level and producing short-term variations (e.g., Webb & Malkan 2000; Pereyra et al. 2006; Wiita 2006). Perturbations on the accretion disk can also produce variations with time scales of weeks, days, and even hours (e.g., Webb & Malkan 2000; Wiita 2006). Recently, Chand et al. (2010) have suggested that rather than the OM being produced by processes related to the jet, then a smaller FWHM is expected of the emission lines in quasars with positive detection than in those without OM detection. These authors found no such behavior. Additionally, Goyal et al. (2010) have reported that the microvariability detected in radio intermediate quasars has a duty cycle similar to that detected in RQQs and RLQs by Ramírez et al. (2009) and Stalin et al. (2004). All these results suggest that variations involving the accretion disk play an important role.

Trèvese & Vagnetti (2002) developed a method to analyze the color changes in variability events. They determined that short-term variations in quasars may be originated by thermal processes related to changes in accretion rate and hotspots in the accretion disk (see also Vagnetti et al. 2003). The same conclusion was obtained by Webb & Malkan (2000) for variability of quasars and Seyfert galaxies. However, although periodic or quasi-periodic variations are attributed to circling and auto-occulted hotspots in the disk (e.g., Carrasco et al. 1985; de Diego & Kidger 1990), most variations do not display this characteristic. Nevertheless, non-periodicity might be the result of the combination of hotspots and geometric changes, such as if the orbits in the disk are not Keplerian (e.g., Fukue 2003).

On the other hand, the contribution of each component to the total flux would play an important role to describe the spectral variations (Vagnetti et al. 2003 and Gu et al. 2006 arrived at a similar conclusion). We need two components to explain several spectral variations. In addition, when data are fitted exclusively with a non-thermal component, we have several cases where $\alpha_v > 0$ (3C 281, PKS 003+15, MC3 1750+175, US 3472). Since such a behavior is strange for the average SED of quasars (e.g., Elvis et al. 1986), this result supports the idea that in general a better fit is obtained when a second component is added. Cases like those of PKS 1510-089 indicate that the largest changes of color are due to thermal variations. If a disk–jet relationship exists (e.g., Falcke et al. 1995), more complex variations can be produced by perturbations in the disk that are propagated to the jet (e.g., Wiita 2006). Thus, our results are in agreement with Vagnetti et al. (2003), who reported that BL Lac objects do not show spectral variability as large as quasars for which the thermal component contribution is larger.

Our description of the disk emission by a single blackbody may be inadequate to explain observations; however, more complicated models still produce unsatisfactory explanations even for the simplest variations. For example, the standard accretion disk model predicts time lags between optical bands (e.g., Lawrence 2005; Pereyra et al. 2006; Wiita 2006 and references therein) that are not always observed.

Because for spectral microvariability variable and non-variable components should be considered, some spectral components that have not been considered by our model can change the value of $\alpha_v$. These additional components can generate spectral variations not contemplated in our model; for instance, the contribution from a line in only one of the three bands (maybe, this can give an explanation to variations as those of 3C 281 (2000 March 4), PKS 0003+15, and MC3 1750+175).

In blazars, there are evidences that the spectral variations are larger for low flux levels (Vagnetti et al. 2003; Ramírez et al. 2004; Gu et al. 2006). This can be understood if at low flux levels the thermal and non-thermal components have a comparable contribution to the optical flux (e.g., Ramírez et al. 2004). In the case of the archetypical object BL Lacerta, some OM events have been detected in which the object turned bluer when it increases its brightness (e.g., Nesci et al. 1998; Speziali & Natali 1998; Clements & Carini 2001; Papadakis et al. 2003; Villata et al. 2004b; Hu et al. 2006b). These variations should be generated by a non-thermal component (e.g., Racine 1970; Gear et al. 1986; Massaro et al. 1998; Vagnetti et al. 2003; Villata et al. 2004b; Hu et al. 2006b). On the other hand, the spectral changes in FSRQs seem to be larger than in BL Lac objects, because the latter do not have a remarkable contribution from the thermal component (Gu et al. 2006; Ramírez et al. 2004).
Then, a difference between the two blazar types may arise: the thermal component and its influence on spectral changes.

The time-lag criterion that we developed is based on the change rate of each OM event for our observational strategy. Although this criterion permits to be relatively sure that the data sets were acquired at the same flux level, it requires that the variations have constant change rates. It should be noticed that the light curves with a jump, as that of PKS 1510-089 reported in PII, can be in fact the result of continuum and gradual variations that show such jump because the observational strategy. The odd spectral variations observed in PKS 0003+15, MC3 1750+175, and US 3472 might be caused by the violation of the simultaneity criterion. The emission from additional components would also have unexpected repercussions on the color changes.

The importance of orientation on variations originated in the jet is not discarded, but processes such as those taking place in the disk should be considered. Thermal component becomes indispensable to generate the observed variations, even in blazars (particularly at low activity), because the accretion disk in these objects must be face-on.

Although variations presented in Section 4 were classified as microvariability, we cannot rule out that they can be part of a variation of a trend with a larger characteristic time. For example, an alteration in the temperature of the accretion disk can show a variation with time scales of days or even hours, which might presents a trend that we can observe during one night, and interpreted it as microvariability.

6. SUMMARY AND CONCLUSIONS

The optical microvariations in RQQ and RLQ reported by Ramírez et al. (2009) were analyzed to determine whether their origin is thermal or non-thermal. We suppose that while thermal variations are related to the accretion disk, non-thermal variations are related to the relativistic jet.

With such a purpose, we developed a method to discriminate between color changes by thermal and non-thermal processes in quasars during an OM event. This method consists in modeling the optical broadband continuum of quasars considering thermal and non-thermal components, and comparing the observed color changes with spectral variations derived from this model. The main result of this work is the possibility to distinguish between thermal and non-thermal origin of an optical microvariation event in quasars.

We identified that some events are consistent with a thermal origin, while some others with a non-thermal one. In other cases, either component can give an explanation to the detected variation. Thus, another important contribution of this research is that, analyzing the spectral microvariability, we have found that the OM might be generated in either the disk or the jet, regardless of the radio classification of the quasars, CRLQ or RQQ. Additionally, some variations in RLQs are consistent with thermal OM and vice versa. Thus, our results indicate that microvariability in both quasar type might originate under similar conditions.

In addition, although the continuum emission can be fitted in all cases by a unique non-thermal component, the broadband spectral variation may require the assumption of the presence of a second component of thermal origin. The relative contribution of each component is an important parameter that should be taken into account for the description of spectral variability. Additional studies must be carried on to investigate the effects of these contributions on the type of quasar that we observe, and if this can be expended to the blazar class.

This result agrees with the discovery of small relativistic jets in RQQs (Blundell & Rawlings 2001) and explains previous results (de Diego et al. 1998; Ramírez et al. 2009). Although this method yields interesting results applied to our data, it is desirable to have a monitoring with a better temporal resolution, as well as to observe in more bands. More realistic models are also necessary.

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