PROFIT: a new alternative for emission-line profile fitting

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Abstract I briefly describe a simple routine for emission-line profiles fitting by Gaussian curves or Gauss-Hermite series. The PROFIT (line-profile fitting) routine represents a new alternative for use in fits data cubes, as the ones from Integral Field Spectroscopy or Fabry-Perot Interferometry, and may be useful to better study the emission-line flux distributions and gas kinematics in distinct astrophysical objects, such as the central regions of galaxies and star forming regions. The PROFIT routine is written in IDL language and is available at http://www.ufsm.br/rogemar/software.html.

The PROFIT routine was used to fit the [Fe II] λ = 1.257 μm emission-line profiles for about 1800 spectra of the inner 350 pc of the Seyfert galaxy Mrk 1066 obtained with Gemini NIFS and shows that the line profiles are better reproduced by Gauss-Hermite series than by the commonly used Gaussian curves. The two-dimensional map of the h3 Gauss-Hermite moment shows its highest absolute values in regions close to the edge of the radio structure. These high values may be originated in an biconical outflowing gas associated with the radio jet – previously observed in the optical [O III] emission. The analysis of this kinematic component indicates that the radio jet leaves the center of the galaxy with the north-west side slightly oriented towards us and the south-east side away from us, being partially hidden by the disc of the galaxy.

Keywords Galaxies: individual (Mrk 1066); Line: Profiles; Techniques: Integral Field Spectroscopy

1 Introduction

Integral Field Spectroscopy (IFS) and Fabry-Perot Interferometry are powerful tools to do a two-dimensional analysis of the physical properties of several types of astronomical objects, such as the central region of normal (e.g. Rodrigues et al. 2009; Peletier et al. 2007; Einsellem et al. 2007; Díaz et al. 2006) and active galaxies (e.g. Davies et al. 2009; Hicks et al. 2009; Riffel, Storchi-Bergmann & Nagar 2010; Riffel et al. 2009a,b, 2006; Storchi-Bergmann et al. 2009, 2010, 2007; Fathi et al. 2006), star forming regions (e.g. Blum & McGregor 2004; Barbosa et al. 2008) and young stellar objects (e.g. Beck et al. 2008; McGregor et al. 2007; Takami et al. 2007). The final result of the data reduction of the above techniques is a data cube containing hundreds to thousands individual spectra to be analyzed, thus a common problem among the studies cited above is how to extract the information from these data cubes. A manually inspection of each spectrum is an exhaustive task and demand much time, so automated methods are needed to properly measure physical parameters from the data cubes.

The most common method used to study the gaseous distribution and kinematics is based on the fitting of the emission-line profiles by Gaussian curves. Nevertheless, it is commonly reported in the literature the presence of asymmetries in the emission-line profiles, which are not well represented by Gaussian curves (e.g. Barbosa et al. 2009; Komossa et al. 2008; Riffel et al. 2009a, 2009b, 2006; Riffel & Storchi-Bergmann 2010). Several methods have been developed to fit line profiles (e.g. Sarzi et al. 2006, and IRAF FITPROFS and SPLAT tasks), but most of these methods are based on the fitting of Gaussian (or Lorentzian) functions, in which the information of the wings of the line profile can be lost. A recent developed method to extract information from data cubes is the PCA tomography, which uses...
Principal Component Analysis (PCA) to transform the system of correlated coordinates into a system of uncorrelated coordinates ordered by principal components of decreasing variance (Steiner et al. 2009). Nevertheless, in some cases the ‘traditional’ line-profile fitting method must be additionally used to properly extract the flux distribution and kinematics of the emitting gas.

In this work I present an automated line-profile fitting routine (PROFIT) to be used to extract the gaseous kinematics and flux distribution from fits data cubes. This routine is written in IDL language and allows the fit of the observed profiles by Gauss-Hermite series or Gaussian curves. The fit of Gauss-Hermite series has been chosen because it preserve the velocity information of the emitting gas by the fitting of the wing of the emission-line profiles. Such information could be lost in the fit of a single Gaussian curve for an asymmetric emission-line profile. Another advantage of the Gauss-Hermite profile is that it can be easily be implemented in an automated routine than multiple Gaussian fit – which would also preserve the velocity information.

The paper is organized as follows. In Section 2 I present the formalism of the Gauss-Hermite and Gaussian functions; Sec. 3 presents the PROFIT routine and in Sec. 4 I discuss an application of the routine for the Seyfert galaxy Mrk 1066. Sec. 5 presents the final remarks of the present work.

2 Gauss-Hermite versus Gaussian

The Gauss-Hermite series can be written as (e.g. van der Marel & Franx 1993; Gerhard 1993; Cappellari & Emsellem 2004):

\[ GH = \frac{A \alpha(w)}{\sigma} \sum_{j=0}^{n} h_j H_j(w) \]

where

\[ w = \frac{\lambda - \lambda_c}{\sigma} \]

and

\[ \alpha(w) = \frac{1}{\sqrt{2\pi}} e^{-w^2/2}, \]

\[ H_j(w) \]

\[ A \]

is the amplitude of the Gauss-Hermite series, \( \lambda_c \) is the peak wavelength, \( h_j \) are the Gauss-Hermite moments and \( H_j(w) \) are the Hermite polynomials.

\( \text{Fig. 1} \) Comparison of Gaussian curves (dotted lines) with Gauss-Hermite series (continuous lines) for the \( h_3 \) and \( h_4 \) values shown at the top-left corner of each panel. The amplitude, central wavelength and \( \sigma \) are the same for both functions and have arbitrary values.

If the emission-line profile is similar to a Gaussian we can truncate the sum on \( n = 4 \) and assume \( h_0 = H_0(w) = 1, h_1 = h_2 = 0 \) (van der Marel & Franx 1993). This is a good approximation if the emission-line presents an asymmetric profile, such as the blue or red wings frequently observed for the line emission from ionized gas in the narrow line region of active galaxies (Riffel, Storchi-Bergmann & Nagar 2010; Riffel et al. 2009a; Komossa et al. 2008). Using the approximation above, the Eq.1 can be written as

\[ GH = \frac{A \alpha(w)}{\sigma} \left[ 1 + h_3 H_3(w) + h_4 H_4(w) \right], \]

where

\[ H_3(w) = \frac{1}{\sqrt{6}} (2\sqrt{2} w^3 - 3\sqrt{2} w) \]

and

\[ H_4(w) = \frac{1}{\sqrt{24}} (4w^4 - 12w^2 + 3). \]

The \( h_3 \) Gauss-Hermite moment measures asymmetric deviation from a Gaussian profile, such as blue or red wings, while the \( h_4 \) moment quantify the peakiness of the profile, with \( h_4 > 0 \) for a more peaked and \( h_4 < 0 \) for a broader profile than a Gaussian

\footnote{http://www.ittvis.com/}
curve. A particular case of Eq. 4 is $h_3 = h_4 = 0,$ when it becomes a Gaussian curve. In Figure 1 I present a sample of profiles for Gauss-Hermite series with distinct $h_3$ and $h_4$ values (continuous lines) and Gaussian curves (dotted lines). The amplitude, central wavelength and $\sigma$ are the same for Gaussian and Gauss-Hermite functions and have arbitrary values. The $h_3$ and $h_4$ moments are shown at the top-left corner of each panel and have values typically observed for the narrow line region of active galaxies (e.g. Riffel & Storchi-Bergmann 2010). The comparison of observed emission-line profiles, such as those of Mrk 1066 from Riffel, Storchi-Bergmann & Nagar (2010) (see Sec. 4), with the profiles shown in Figure 1 suggests that the observations are better reproduced by Gauss-Hermite series than by Gaussian curves in most cases.

3 The PROFIT routine

The model of each emission-line profile is constructed by the sum of Eq. 2 with a linear equation, in order to represent the underlying continuum emission. The resulting equation contains seven free parameters ($A, \lambda_c, \sigma, h_3, h_4$ plus two parameters for the linear equation), which can be determined by fitting the line profiles. In case of Gaussian fitting the $h_3$ and $h_4$ are fixed at zero and thus the remaining 5 parameters may be obtained from the fit of the observed profile. These parameters can be obtained by solving a Least-squares problem.

The PROFIT routine was written in IDL language and performs the fit of the observed profile using the MPFIT$^3$ routine, which is the MINPACK1 implementation of the Levenberg-Marquardt method for nonlinear least-squares problems. The IDL language was chosen because it is extensively used in astronomy and allows read the data cube from standard fits format to an array using the NASA-Goddard Space Flight Center IDL Astronomy User’s Library$^4$. The algorithm recovers the emission-line flux distribution and kinematics as follows:

1- Initial guesses for the centroid wavelength and velocity dispersion are given by the user. The initial guesses for $h_3$ and $h_4$ are fixed at zero;

2- The input data cube in standard fits format (in which the spatial dimensions are in the x and y-axis and spectral pixels are in the z-axis) is converted into an array.

Next steps are done individually for each spectrum:

3- Calculates the spectral region to be fitted using the initial guess for the centroid wavelength and the spectral information (spectral sampling and initial wavelength) contained in the header of the data cube fits file.

4- Normalizes the spectrum by its maximum value and obtain initial guesses for the parameters of the linear equation and amplitude of the Gauss-Hermite series (or Gaussian);

5- Performs the nonlinear least-squares fitting of the observed profile by the adopted the model using the Levenberg-Marquardt method;

6- Writes the solution to the output file;

7- If $\chi^2$ is less than a maximum value (defined by the user) the fitted parameters are used as initial guesses for the fit of the next spectrum. Otherwise uses the initial guesses of item 1;

8- Repeats items 3-8 for all spectra.

9- Writes the solutions to a Multiple Extensions FITS (MEF) file. The output MEF file will contain 7 extensions containing the: [0] emission-line flux distribution; [1] centroid velocity field; [2] velocity dispersion map; [3] $h_3$ map; [4] $h_4$ map; [5] reduced $\chi^2$ map defined as

$$
\chi^2 = \sum_p \frac{(O_p - M_p)^2}{\sigma_O^2} \frac{1}{(N - N_{\text{par})}},
$$

where $O_p$ is the observed spectra, $M_p$ is the best fit model, $\sigma_O^2$ is the variance of the observed spectra, $N$ is the number of spectral pixels ($p$) used in the fit and $N_{\text{par}}$ is the number of free parameters; and [6] flux distribution obtained directly by integration the emission line profile and subtracting a continuum obtained by the average of continuum regions at both sides of the line profile.

4 A First Application

In Fig. 2 I present an example of the use of PROFIT to fit the emission-line profile of $[\text{Fe}\, \text{II}]$ at $\lambda = 1.257 \mu\text{m}$ at 1$''$ north-west of the nucleus of the Seyfert galaxy Mrk 1066. This spectrum was extracted from Gemini’s Near-infrared Integral Field Spectrograph (NIFS) observations (program ID: GN-2008A-Q-30) within an aperture of $0.3 \times 0.3 \text{arcsec}^2$ (see Riffel, Storchi-Bergmann & Nagar 2010 for a description of the observations and data reduction procedures). The observed profile is shown as a continuous line, the fitting of Gauss-Hermite series as a dashed line, the fitting of a single Gaussian as a dot-dashed line and the two Gaussian curves fit as a dotted line. The best Gauss-Hermite fit is obtained...
The best fit obtained using a Gaussian curve has a lower value obtained for the Gauss-Hermite fitting. In Riffel & Storchi-Bergmann (2010) we used Gauss-Hermite moments this decision is done simple by varying the $h_3$ and $h_4$ moments.

In Riffel & Storchi-Bergmann (2010) we used PROFIT to study the gaseous kinematics of the inner $700 \times 700 \text{ pc}^2$ of Mrk 1066 using Gemini NIFS observations. The profiles of $[\text{Pa} \beta] \lambda 1.2570 \mu \text{m}$, $[\text{Fe} \text{II}] \lambda 1.2570 \mu \text{m}$, $\text{Pa} \beta$ and $H_2 \lambda 2.1218 \mu \text{m}$ emission lines were fitted by Gauss-Hermite series in order to obtain the centroid velocity field, velocity dispersion map and $h_3$ and $h_4$ maps for each emission line. The same observations presented in Riffel & Storchi-Bergmann (2011) were used to fit the $[\text{Fe} \text{II}] \lambda 1.2570 \mu \text{m}$ by Gaussian curves in order to compare the resulting fit with the ones obtained using Gauss-Hermite series. Figure 3 presents the comparison of the $\chi^2$ values from the Gauss-Hermite fitting ($\chi^2_{GH}$ - y-axis) with the ones obtained for the fitting of Gaussian curves ($\chi^2_G$ - x-axis) for $\sim 1800$ spectra of the inner $700 \times 700 \text{ pc}^2$ of Mrk 1066 extracted within apertures of $0.05 \times 0.05 \text{ arcsec}^2$. As observed in this figure, $\chi^2_{GH}$ is smaller than $\chi^2_G$ for most spectra, indicating that the $[\text{Fe} \text{II}]$ line profile in the central region of Mrk 1066 is better reproduced by Gauss-Hermite series than by Gaussian curves. A similar behavior is observed for $[\text{P} \text{II}]$, $H_2$ and $H$ emission lines at the same spatial region.

In order to illustrate the importance of properly map the emission line profile wings Fig. 4 presents a map for the $h_3$ Gauss-Hermite moment obtained for the Pa$\beta$ emission in the central region of Mrk 1066. This map is similar to the ones obtained for the $[\text{Fe} \text{II}]$ and $[\text{P} \text{II}]$ emission lines Riffel & Storchi-Bergmann (2011), showing several regions with values different than zero, indicating that the Pa$\beta$ emission-line profile presents asymmetric deviation from a Gaussian curve, such as blue (negative values) and red (positive values) wings. In case of Gaussian fitting this information could be lost! The smallest values of up to $-0.3$ are observed at $\approx 1''$ north-west of the nucleus in a regions close to the edge of the radio structure (thick black contours). Some high values are also observed near to the edge of the radio jet to south-east of the nucleus. The presence of
wings have also been observed by Knop et al. (2001) for the near-IR emission lines using long slit spectroscopy along the PA=135°. These wings may be originated in an outflowing gas component driven by the radio jet, with the north-west side slightly oriented towards us and the south-east side away from us, being partially hidden by the disc of the galaxy. This interpretation is supported by the near-IR emission line kinematic maps, which show that the near-IR emitting gas presents at least three kinematics components: a rotating disk, an inflowing gas component and an outflowing component (Riffel & Storchi-Bergmann, 2010). The above interpretation is also in good agreement with optical observations of the [O III] emission, which seems to being originated in a bi-cone oriented along the same position angle PA=135° – approximately the same orientation of the radio jet (Bower et al. 1995).

The $h_4$ map, shown in the bottom panel of Fig. 4 presents values near to zero in most locations of the central region of Mrk 1066. However, some positive $h_4$ values are observed co-spatially with regions of lower velocity dispersion, indicating that part of the Paβ emission originates from a colder gas than those which produces most of the line emission. For more details on the gaseous kinematics of the inner 350 pc radius of Mrk 1066 see Riffel & Storchi-Bergmann (2010).

5 Final Remarks

I presented a new routine to fit emission-line profiles from fits data cubes using Gauss-Hermite series or Gaussian curves, which provides a new alternative to the study of the emission-line flux distribution and kinematics for several astronomical objects. The PROFIT routine is written in IDL and is available at [http://www.ufsm.br/rogemar/software.html](http://www.ufsm.br/rogemar/software.html). The main advantages of PROFIT compared with previous methods are:

- It allows the fitting of the line profiles by Gauss-Hermite series as an alternative to the ‘traditional’ Gaussian curves used in most studies and thus better describe the kinematics of the emitting gas.
- It is automated and can be applied directly on the final data cubes fits files from observations using most integral field units and Fabry-Perot interferometers.

A first application has been discussed for the case of near-IR emission-line profiles from the inner 350 pc of the Seyfert galaxy Mrk 1066. The main scientific conclusions are:

- The near-IR emission line profiles for this galaxy are better reproduced by Gauss-Hermite series than by

![Paβλ1.2822μm](image.png)

**Fig. 4** Top: $h_3$ Gauss-Hermite moment map for Paβ emission line on the inner 700×700 pc$^2$ of Mrk 1066. The thick black contours are from the radio continuum emission of Nagar et al. (1999). Bottom: $h_4$ Gauss-Hermite moment map.
Gaussian curves, as indicated by the smaller $\chi^2$ obtained for the former.

- The two-dimensional map for the $h_3$ Gauss-Hermite shows that the near-IR emission lines present asymmetric profiles, which can be explained as being originated in an outflowing gas driven by the radio jet.

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