NGC7009 Inner Temperature Fluctuations

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Summary. Our goal is to evaluate whether the low electronic temperature fluctuations found by Rubin et al. (2002) in the planetary nebula NGC7009 using the intrinsic line ratio [OIII] 4363/5007 can be interpreted as being real. In this analysis we use wavelet models instead of the direct HST/WFPC2 imagery in order to eliminate the intrinsic noise present in the data and search for fluctuations of high spatial frequency that cannot be explained by simple ionization effects. Our preliminary results reveal the existence of regions in the nebula where fluctuations cannot only be attributed to noise.

Key words: planetary nebula, wavelet, NGC7009, temperature fluctuations

1 Introduction

The ratio $R$ between the [OIII] 5007 (which includes the [OIII] 4959 contribution) and the [OIII] 4363 emission lines is a good electronic temperature ($T_e$) estimator. For NGC7009, density values are less than the critical for these lines ($N_e \approx 4000$ cm$^{-3}$; Luo et al. 2001), and a simple relation between dispersions in $T_e$ and in $R$ can be given by:

$$\frac{\delta R}{\langle R \rangle} = -3.2966 \times 10^4 \frac{\delta T_e}{\langle T_e \rangle^2}$$

Estimating the local dispersion $\delta R$ for regions of high spatial frequency in the $R$ map, and using the mean local values of $R$ and $T_e$, we are able to determine the temperature dispersion $\delta T_e$. Regions of interest (ROIs) can be defined as isophotal areas in the map. Our objective is to establish the significance of the temperature fluctuation in the ROIs from the dispersion measured in $\delta R$. This will be done through a comparison with an estimate of $\delta R$ due to intrinsic noise only. The last value is derived from a simulated [OIII] line ratio map.

Unlike Rubin et al. (2002), we choose not to perform bandpass, extinction, or reddening correction of the data. Rubin et al. showed that the net effect of reducing these corrections was decreasing the temperature gradients measured. Therefore, our approach allows us to investigate the lowest possible limit for the fluctuations.
2 Data and Wavelet Models

WFPC2 observations of NGC7009 in the F437N ([OIII] 4363 Å) and F502N ([OIII] 5007 Å) line filters were obtained from the HST archive. The nebula is registered over the WF3 chip, which has a pixel size of 0.0996 arcsec. Bad pixel corrections, cosmic ray subtraction and flux calibration were performed with standard packages in IRAF (Image Reduction and Analysis Facility). The F502N image was brought to the same orientation as the F437N image. The resulting images are shown in Fig. 1. Using the technique described in the other paper by Leal Ferreira et al. in this proceedings, we have produced a wavelet model for each of the original [OIII] images. The models are sky subtracted and free from noise. They are shown in Fig. 2 using the same intensity scale as in Fig. 1.

![Fig. 1. Original HST images shown in logarithmic scale](image1)

![Fig. 2. Wavelet models shown in logarithmic scale](image2)
3 Analysis

The \([\text{OIII}]\) 5007/\(4363\) Line Ratio Maps

Three line ratio maps were produced as described below:

- \(R1\): direct line ratio between original HST images (Fig. 3a)
- \(R2\): direct line ratio between the wavelet models (Fig. 3b)
- \(R3\): wavelet model of the \(R1\) map (Fig. 3c)

\(R3\) is a noiseless version of \(R1\). Note that lower intensities inside the nebula indicate larger temperatures, while lower intensities outside the nebula were artificially obtained by zeroing the \([\text{OIII}]\) 5007 fluxes below a certain threshold. It is important to stress that the signal-to-noise ratio (SNR) is different in the two filters (smaller in F437N) and that temperatures are derived from a ratio between them. Therefore, the noise in \(R1\) does not follow a Poisson distribution, and a source can be either over or underestimated by a combination of noises. This may be the reason why large dispersions can be observed in that map. \(R3\) is our attempt to reduce this dispersion, but still suffers from source definition problems, specially where the pixel flux is low. We believe \(R2\) is the best estimator of \(T_e\) because the noise present in the each filter is removed prior to obtaining the ratio. However, we choose to use both \(R2\) and \(R3\) to infer the existence or not of localized fluctuations.

![Fig. 3. Line map ratios: (a) R1, (b) R2, and (c) R3 shown in logarithm scale](image)

Simulated \([\text{OIII}]\) Line Ratio Map

The simulated line ratio map, \(R4\), is a noise only map. In this map, an emulated \([\text{OIII}]\) 4363 image was created using the following procedures: (1) The wavelet model of the F502N filter was multiplied by the ratio between the total flux of the nebula in the F437N and F502N wavelet models. This procedure redistributed the total...
emission in the [OIII] 4363 line according to the [OIII] 5007 line distribution. (2) Poisson and Gaussian noises were added to this image. The final simulated map was created by taking the ratio between the [OIII] 5007 and the emulated [OIII] 4363 wavelet models.

Selected Regions of Interest

Twenty ROIs (Fig. 4) were chosen in our search for electronic temperature fluctuations. Preliminary choices were based on a visual inspection of the $R_2$ map and the actual ROIs defined with the `roi` task in IDL (a product of ITT Vision Information Solutions, www.ittvis.com).

![Regions of interest (ROIs) shown over the $R_2$ map](image)

The analysis of the fluctuations was made by observing $\delta R$ dispersions in the ROIs. For each ROI, a histogram showing the number distribution of $R$ values was generated. The histograms for five regions are shown in Fig. 5. The table below displays the final results for all ROIs. Whenever both $R_2$ and $R_3$ dispersions were larger than the $R_4$ dispersion, the region was supposed to have a significant temperature fluctuation (labeled Y). If only $R_2$ or $R_3$ dispersion was larger than the $R_4$ dispersion, the region was classified as a possible candidate for temperature fluctuation (C). Whenever both $R_2$ and $R_3$ dispersions were smaller then the $R_4$ dispersion, the temperature fluctuation seen could simply be the result of noise intrinsic to the signal (N).

| ROI  | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T |
|      | Y | Y | N | C | Y | Y | N | N | N | N | N | N | C | N | C | C | C | N | Y | N |

Fig. 4. Regions of interest (ROIs) shown over the $R_2$ map
4 Conclusions

Rubin et al. (2002) studied WFPC2 and STIS data of NGC7009 in order to obtain high spatial resolution of the intrinsic line ratio [OIII] 4363/5007 and derive $T_e$ and the fractional mean-square temperature variation ($\Delta T_e^2$). Despite the remarkably low azimuthally averaged values of $\Delta T_e^2$ found, they claimed that temperature fluctuations could not be ruled out, since their estimates were made across the nebula (in the plane-of-the-sky), and could be interpreted as lower limits. We chose to search for pixel-to-pixel fluctuations inside regions of the nebula that cannot be addressed by simple ionization effects. Four regions presented significant $T_e$ fluctuations: A and B, associated to fliers, and E and F, to bow shock areas. Five other regions (D, M, O, P, Q) located along a semi-arch of the nebula also presented a large dispersion in either $R_2$ or $R_3$, indicating that they might have significant temperature fluctuations. Results for region S relate to the large $T_e$ gradients found around the central star. Region T (the nebula as a whole) displays the wide range of $T_e$ found in the nebula, but the two peaks observed in its $R_1$, $R_2$, and $R_3$ histograms indicate the presence of a cooler and a hotter phase in the gas.

References