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PHYSICAL CONDITIONS IN NGC 6543 FROM ISO AND HST DATA AND THE PITFALLS OF TEMPERATURE MAPS

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RESUMEN

Determinamos las condiciones físicas en NGC 6543, obteniendo dos distintas estimaciones de la temperatura electrónica (T_e) y una de la densidad electrónica (N_e). La temperatura electrónica es calculada por medio del cociente de [O III] $\lambda\,5007/\lambda\,4363$, y del diagrama de diagnóstico que combina $\lambda\,5007$ con las líneas infrarrojas de [O III] $52\,\mu$ y $88\,\mu$. La intensidad en el continuo medida en espectros ópticos es mucho mayor que la predicha bajo las hipótetis más sencillas. Sugerimos que la fuente más probable del continuo adicional es la conversión de fotones Lyα a continuo de dos fotones. Aunque los valores de T_e y N_e derivados con el diagrama de diagnóstico están en acuerdo con las determinaciones más recientes, T_e derivada del cociente $\lambda\,5007/\lambda\,4363$ es inferior a los valores publicados en la literatura, probablemente debido al sesgo en $\lambda\,4363$ introducido por la incertidumbre en el continuo. Nuestra conclusión principal es que no es posible, con los datos actualmente disponibles, obtener mapas precisos de temperatura de nebulosas fotoionizadas.

ABSTRACT

We determine the physical conditions in NGC 6543, obtaining two different estimates of the electron temperature (T_e) and one estimate of the electron density (N_e). The electron temperature is computed by means of the [O III] ratio $\lambda\,5007/\lambda\,4363$, and of the diagnostic diagram combining $\lambda\,5007$ to the [O III] infrared lines $52\,\mu$ and $88\,\mu$. The continuum intensity measured on slit spectra is much higher than theoretically predicted under the simplest assumptions. After considering several possibilities, we suggest enhanced 2-photon emission as the most probable source of the additional continuum. While T_e and N_e derived from the diagnostic diagram agree with the most recent determination, T_e derived from $\lambda\,5007/\lambda\,4363$ is smaller than previously published values, probably due to the bias in $\lambda\,4363$ introduced by the uncertainty in the continuum. Our main conclusion is that it is not possible, with present-day data, to derive accurate temperature maps of photoionized nebulae.

Key Words: **INSTRUMENTATION: MISCELLANEOUS — PLANETARY NEBULAE: GENERAL — PLANETARY NEBULAE: INDIVIDUAL: NGC 6543**

1. INTRODUCTION

In this work, we investigate the physical conditions in the planetary nebula NGC 6543 using two different diagnostics: the temperature-sensitive [O III] ratio $I(\lambda\,5007)/I(\lambda\,4363)$, and the ($T_e$, N_e) diagnostic diagram based on the [O III] optical and infrared lines proposed by Dinerstein et al.(1985) (henceforth DLW). The intensity of the infrared lines is obtained from ISO archive spectra, and the intensity of [O III] $\lambda\lambda\,5007, 4363$ from HST archive images. Additionally, Hα and Hβ HST images were used to determine the reddening correction to be applied to the other images, and HST images around $\lambda\,6584$ were used to correct the Hα images for the [N II] contribution. Finally, long-slit data obtained with the 2.5m Isaac Newton Telescope (INT) at the Observatorio del Roque de los Muchachos, on La Palma, were used to correct the HST images for the contribution of other lines and the continuum. A full description of this research can be found in Luridiana et al.(2003).

2. THE ISO DATA

NGC 6543 (the ‘Cat’s eye’) was routinely observed by ISO for calibration purposes, thereby a large set of spectra is available. We selected 20 out of the 92 Long-Wavelength Spectrometer spectra available in the ISO archive, and based our analysis on the data measured with the SW2 and LW1 detectors only, obtaining the following line intensities: $I(52\mu) = (5.10 \pm 0.61) \times 10^{-10}$ erg sec^{-1}cm^{-2}, and $I(88\mu) = (1.39 \pm 0.17) \times 10^{-10}$ erg sec^{-1}cm^{-2}.

3. THE INT DATA

NGC 6543 was observed spectroscopically as part of a wider study of PNe on 1995 July 8 and 9, using

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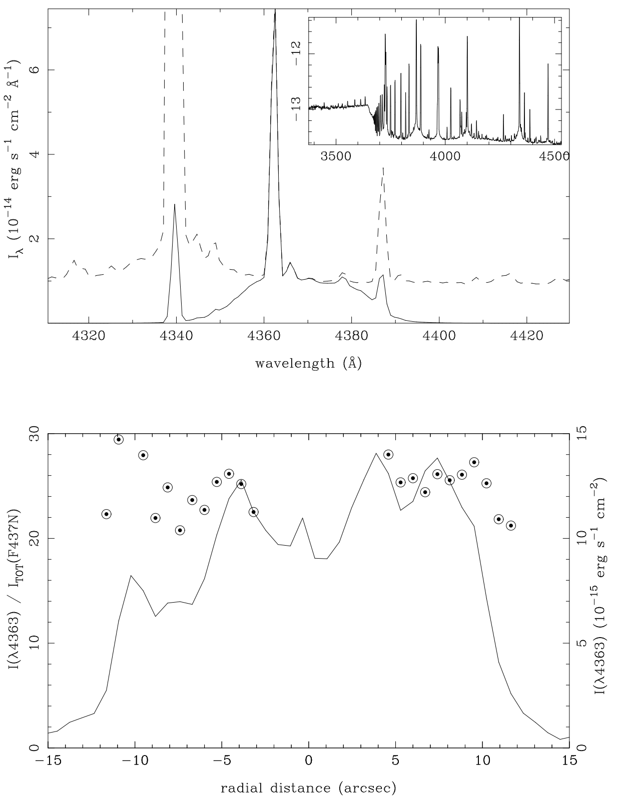

Fig. 1. Top: nebular spectrum of NGC 6543 around $\lambda\,4363$, along position angle 5°. Bottom, left handside scale: the dotted circles show the percent of the total intensity in F437N contributed by the $\lambda\,4363$ line; right hand side scale: variation of $I(\lambda\,4363)$ along the slit.

the Intermediate Dispersion Spectrograph attached to the INT (Luridiana et al. 2003, for further details). The top panel of Figure 1 illustrates the very high quality of these data.

4. THE HST IMAGES

From the HST data archive, we retrieved images of NGC 6543 through the narrow band filters F437N, F487N, F502N, F656N, and F658N, centered on the emission lines [O III] $\lambda\,4363$, Hβ, [O III] $\lambda\,5007$, Hα, and [N II] $\lambda\,6584$ respectively. The calibration of the images is conceptually straightforward, but the procedure contains several potential pitfalls. One of the most delicate point is the estimation of the contribution to the flux of the continuum and of neighbouring lines: see, e.g., O'Dell & Doi (1999). In the following, we will describe some problems related to the continuum subtraction.

4.1. *Continuum subtraction*

The processes contributing to the nebular continuum flux are H I, He I, and He II recombination, bremsstrahlung, and 2-photon decay. The 2-photon continuum intensity is quite difficult to compute accurately, as it depends not only on the local physical conditions N_e and T_e, but also on the fate of the Lyα photons produced by recombination (Brown & Mathews 1970). The continuum contribution is very important in filters centered on weak lines, such as [O III] $\lambda\,4363$, but it barely affects the intensity in filters centered on strong lines, such as Hα or [O III] $\lambda\,5007$. Our computations show that, neglecting Lyα conversion, the continuum yields 40 percent of the total intensity in F437N. Subtracting out the contribution of the other lines, we found that $\lambda\,4363$ yields 44 percent of the total flux.

We compared this computation with a measurement of the continuum flux on the INT spectra, finding that the continuum contributes 58 percent and that $\lambda\,4363$ contributes only 26 percent of the total intensity in F437N (Figure 1, bottom). To investigate the discrepancy with respect to our previous calculations, we considered three likely mechanisms that would enhance the continuum: X-ray emission, dust scattering, and 2-photon emission.

The third possibility is the most plausible to explain the difference between the spectroscopic data and our computations. The occurrence of Lyα conversion can enhance the total continuum in the region around $\lambda\,4363$ (where 2-photon emission is a dominant process) by as much as a factor 2.5. The detailed calculation of the actual efficiency of this process is virtually impossible, since it would require knowledge of the local escape probabilities and the dust structure of the nebula, and the implementation of this information in a 3D computation. The only feasible alternative is to bracket this process by computing the 2-photon emission in the extreme cases of minimum and maximum efficiencies. Figure 2 compares the observational data to the continuum range predicted by recombination theory, as a function of the Hγ intensity. The data are compatible with a Lyα-conversion enhancement of the 2-photon continuum. The figure also shows that the relation between Hγ and the measured continuum is not linear, and that there are large fluctuations around the best-fit straight line: this agrees with our hypothesis, since the Lyα conversion process acts with different efficiencies across the nebula. This fact implies that it is not possible to rely on theoretical calculations alone to correct the total flux in each image for the continuum contribution, and that precision photometry of weak lines cannot be done with HST/WFPC2 images in the absence of data specifically designed to measure the continuum.

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To carry on our analysis in spite of these difficulties, we adopted the continuum flux measured on the INT spectra. Combining the infrared intensities measured on ISO spectra with the [O III] $\lambda\,5007$ intensity derived from the HST data, we obtained the point shown in the diagnostic diagram of Figure 3, where the data points by DLW and Dinerstein, Haas, Erickson, & Werner(1995) (DHEW) are also plotted. This figure shows that our results disagree with the point by DLW, and are in excellent agreement with those by DHEW. The values we obtain are $N_e = 1650^{+550}_{-400}$ cm^{-3}, $T_e = 8600 \pm 500$ K, while the corresponding values quoted by DLW and DHEW are N_e= $10000^{+\infty}_{-6000}$ cm^{-3}, $T_e = 5800 \pm 300$ K and N_e= 2000^{+500}_{-400} cm^{-3}, $T_e = 8500 \pm 500$ K respectively.

5. SUMMARY AND CONCLUSIONS

In this work we attempted to derive self-consistently the physical conditions in the bright core of NGC 6543, using the standard nebular-to-auroral temperature diagnostic, and the diagnostic diagram based on infrared lines developed by DLW. The N_e and T_e values derived by means of the diagnostic diagram are not compatible with those by DLW, but they are in very good agreement to the more recent result by DHEW. On the other hand, the nebular-to-auroral temperature we derive is somewhat lower than the values published in the literature. This disagreement may depend on a bias in the adopted continuum level, since we found that the continuum level measured on slit spectra differs from the one expected at $T_e \sim T_e(\mathrm{O}^{++})_{opt}$ when Lyα conversion is neglected. We investigated several possibilities to explain the extra continuum: the most plausible turned out to be enhanced 2-photon emission originated by conversion of scattered Lyα photons, but we were not able to work out a theoretical prescription to compute accurately the continuum intensity that would eliminate the necessity of relying on spectroscopic information.

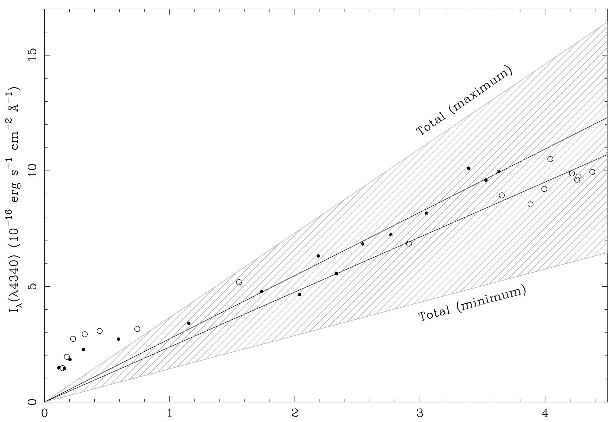

Fig. 2. Observed Hγ and nearby continuum fluxes measured along the INT slit, at different distances from the central star. The shaded region corresponds to the region predicted by recombination theory. Dots and open circles represent the two directions along the slit, and the two solid lines the corresponding best-fit linear relations.

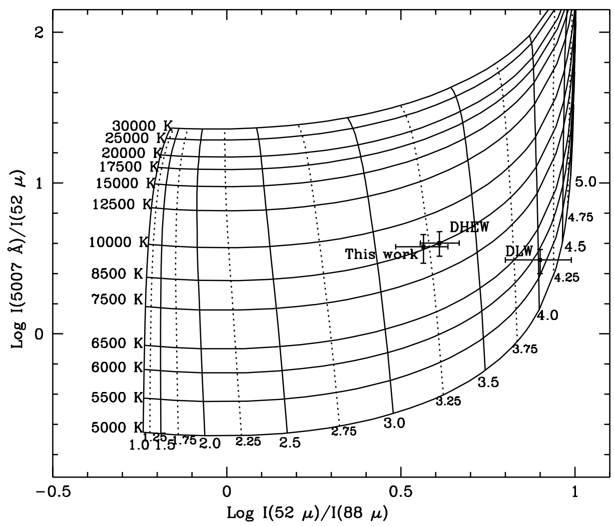

Fig. 3. [O III] infrared-line diagnostic diagram.

As the work progressed, it became evident to us that the archival data we used were not optimized for this particular task. As a result, the most important source of uncertainty in the determination of the optical temperature is the continuum subtraction in the $\lambda\,4363$ image; a specific conclusion we draw is that it is not possible with these data to obtain an accurate bidimensional temperature map of the nebula.

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