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# VLA OBSERVATIONS OF TWICE IONIZED HELIUM IN NGC6302

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RESUMEN. Presentamos observaciones hechas con el VLA de las líneas de recombinación H76α y $He^{+}$121α y los continuos adyacentes provenientes de la nebulosa planetaria NGC6302. Derivamos un valor promedio para $He^{++}/H^{+}$ $\sim$ 0.06$\pm$0.02, en acuerdo con el valor derivado en el visible. Las variaciones en el cociente H76α a continuo que se observan en NGC6302 posiblemente se deben a la combinación de tres efectos: 1) la contribución al continuo del helio dos veces ionizado, 2) la posible presencia de un gradiente en la temperatura electrónica, y 3) alejamientos pequeños (10 al 20%) del equilibrio termodinámico local. Existe evidencia marginal de que el helio podría ser anómalamente abundante (y >0.18) en algunas partes de la nebulosa.

ABSTRACT. We present VLA observations of the H76α and $He^{+}$121α radio recombination lines and their adjacent continua from the planetary nebula NGC6302. We derive an average value of $He^{++}/H^{+}$ $\sim$0.06$\pm$0.02 in agreement with the optical determination. The variations in the H76α-to-continuum ratio that are observed across the face of NGC6302 are probably due to the combination of three effects: 1) the contribution to the continuum from the twice ionized helium, 2) the possible presence of a gradient in the electron temperature and 3) small (10 to 20 percent) LTE departures. There is marginal evidence that helium is anomalously enriched (y >0.18) in some parts of the nebula.

*Key words:* NEBULAE-PLANETARY — RADIO LINES-RECOMBINATION

## I. INTRODUCTION

NGC6302 is one of the brightest planetary nebulae. In the optical, it has a bipolar appearance with two lobes extending approximately in the east-west direction. While the optical size of NGC6302 is about 1', most of the radio continuum flux comes from a compact central source (Terzian, Balick and Bignell 1974). In their multifrequency study, Rodríguez et al. (1985) concluded that the ionized core of NGC6302 is shaped like a toroid with angular extent of 8" x 10". This dense toroid has its symmetry axis approximately parallel to the symmetry axis of the optical nebula, suggesting a close relationship between both structures. Rodríguez et al. (1985) also mapped with the VLA the radio core of NGC6302 in the H76α line and the adjacent continuum at 2 cm. The H76α line map and the 2 cm continuum map turned out to be strikingly different, with the line-to-continuum ratio increasing in the outer parts of the nebula. Rodríguez et al. (1985) discussed the following explanations for this effect:

1) <u>There is pressure broadening affecting the line</u>. If some regions of the nebula are unusually dense, the line emission could be broadened and this would difficult the measurement.

2) <u>There are non-LTE enhancements of the line emission</u>. The emission measure varies across the face of the nebula and this could lead to enhancements in those lines of sight with the larger emission measures.

3) There is an electron temperature gradient in the nebula. Since line and continuum emission depend differently with electron temperature, variations in their ratio will appear.

4) There are large velocity gradients in the inner regions of the nebula. If this is the case, the line emission from the inner parts will be broadened and this effect will difficult its detection.

5) There is a significant contribution from the twice ionized helium in the inner parts of the nebula to the continuum emission. This effect would also cause a decrease in the line-to-continuum ratio in the inner parts of the nebula.

To investigate these possibilities, we made new 2-cm VLA observations of NGC6302 in the H76α and $He^+$ 121α radio recombination lines and their adjacent continua. In §II we discuss these observations, while in §III we interpret the data. A summary of our conclusions is presented in §IV.

## II. OBSERVATIONS

The observations of the H76α (14689.99 MHz) and $He^+$121α (14672.07 MHz) radio recombination lines and their adjacent continua were made with the Very Large Array of the National Radio Astronomy Observatory[1] during 1985 October 18-19. The VLA was then in the mixed C/D configuration, providing an angular resolution of ∿3" at 2 cm for a southern source like NGC6302. We observed in the spectral-line mode using 15 channels with a resolution of 16 km $s^{-1}$ after Hanning weighting. The spectral data were bandpass-normalized by the autocorrelation spectrum of each antenna and bandpass-calibrated with a strong unresolved source (3C273). The continuum contribution was subtracted from the line channels using the average of eight channels without evident line emission (four at each side of the line). A continuum channel contained 75% of the total bandwidth of 12.5 MHz. Figure 1 shows the spectra obtained after integrating

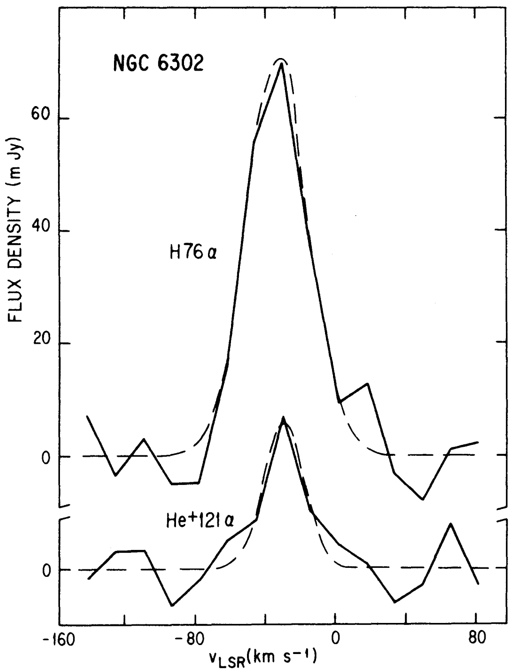


Fig. 1. Spectra of H76α (top) and $He^+$ 121α (bottom) for NGC 6302. The velocity resolution is ∿16 km $s^{-1}$. The dashed lines show the least-squares Gaussian fits to the spectra.

[1] The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

the flux per channel in a 20" x 30" region containing most of the detectable emission. The continuum flux density from this region was 2.2$\pm$ 0.1 Jy and the line parameters from a Gaussian fit are given in Table 1. There is good agreement with the parameters for the same line given by Rodríguez et al. (1985).

TABLE 1. Parameters of the H76α and $He^+$121α Radio Recombination Lines

| Parameters | H76α | $He^+$121α |
|---|---|---|
| Peak Flux, $S_L$ (mJy) | 72$\pm$5 | 26$\pm$5 |
| Full Width at Half Power, Δv (km $s^{-1}$) | 40$\pm$3 | 27$\pm$6 |
| Radial Velocity with Respect to the LSR, $V_{LSR}$ (km $s^{-1}$) | -33$\pm$1 | -29$\pm$3 |

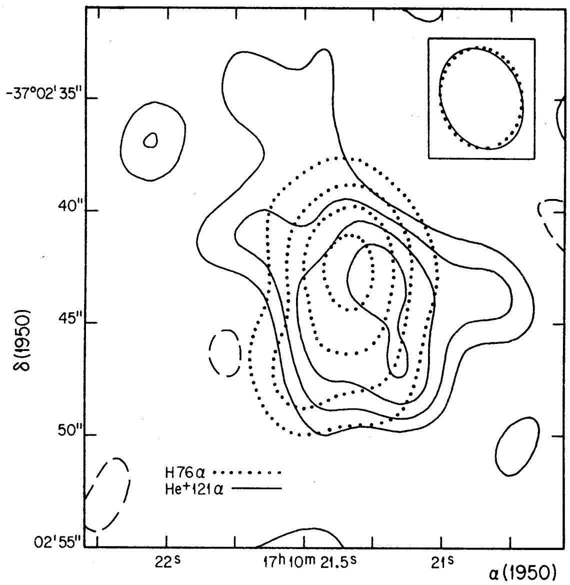


Fig. 2. Contour maps of the H76α (dotted line) and $He^+$ 121α (solid line) radio recombination line emission from NGC 6302. The half power contour of the beams is also shown. Contours are -0.3, 0.3, 0.5, 0.7 and 0.9 of the peak flux density per beam area, which is 12.6 mJy/beam for the H76α emission, and 5.2 mJy/beam for the $He^+$ 121α emission.

In Figure 2 we show the H76α and $He^+$121α maps obtained in each case from the average of the central three channels of the spectrum, which include the -54 to -6 km $s^{-1}$ velocity range. To improve the signal-to-noise ratio, the maps were convolved with a 3" x 3" Gaussian. It is evident, despite the modest signal-to-noise ratio of the $He^+$ 121α map, that there are differences in the spatial distribution of the line emissions.

Finally, in Figure 3 we show an H76α line-to-continuum ratio contour map superposed on a 2-cm continuum map. The variation in the ratio is clearly present. The larger values are reached in the north and south extremes of the nebula, and the smaller values in the central part.

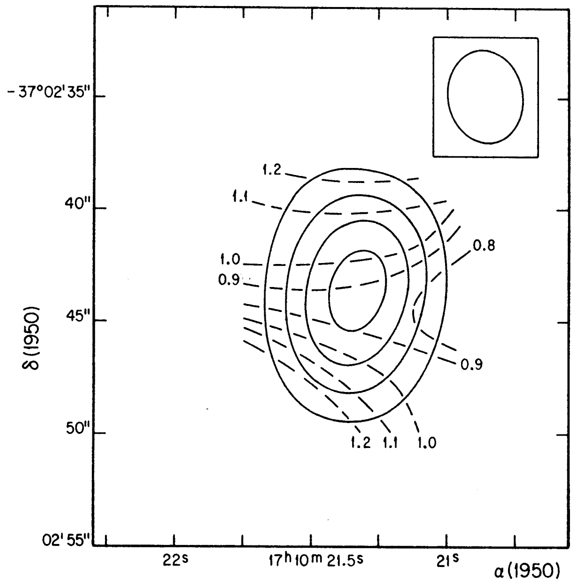


Fig. 3. Contour map of the 2-cm continuum emission adjacent to the H76α line (solid line) and H76α to-continuum ratio contours (dashed line) for NGC 6302. The values of the line-to-continuum ratio are in units of 1.15 km $s^{-1}$. The half power contour of the beam is also shown.

III. INTERPRETATION OF THE DATA

We will first derive the average $He^{++}/H^{+}$ ratio from the radio data. For a $He^{+}\alpha$ and Hα radio recombination lines that are close in frequency, and assuming LTE, the ratio is given approximately by:

$$\frac{He^{++}}{H^{+}} \simeq \frac{1}{4} \frac{\int S_L\,(He^{+}121\alpha)\,dv}{\int S_L\,(H76\alpha)\,dv} \simeq \frac{1}{4} \frac{S_L(He^{+}121\alpha)\,\Delta v(He^{+}121\alpha)}{S_L\,(H76\alpha)\,\Delta v(H76\alpha)}$$

From the values given in Table 1, we derive $He^{++}/H^{+} \simeq 0.06 \pm 0.02$, in agreement with the value of 0.065 determined optically (Aller et al. 1981).

The H76α spectrum shown in Figure 1 has twice the velocity coverage of that shown by Rodríguez et al. (1985). We do not find evidence in our H76α profile of wing emission, suggesting that the bulk of the ionized hydrogen is detected within the 40 km $s^{-1}$ wide line emission. Of course, we could have missed a very weak and wide component, but we consider this unlikely. Consequently, we propose that the line-to-continuum ratio is not being affected significantly by the presence of high velocity gas and thus rule out the fourth possibility presented in the Introduction.

It is also possible to rule out the first possibility (pressure broadening) since electron densities above $10^{6}$ $cm^{-3}$ are required to broaden the H76α line, while the electron density of NGC6302 is $\sim 2\times10^{4}$ $cm^{-3}$ (Meaburn and Walsh 1980).

As shown in Figure 2, the $He^{+}121\alpha$ emission zone is somewhat more compact than the H76α emission zone in the north-south direction, but more extended in the east-west direction. Rodríguez et al. (1985) have modeled the ionized core of NGC6302 as a toroid with projected symmetry axis approximately in the east-west direction. The plane of the toroid has an inclination of about 45° with respect to the line of sight (Rodríguez et al. 1985). Based on this geometry we could speculate on the differences between the $He^{+}121\alpha$ and H76α maps. In the north-south direction the nebula is probably ionization bounded. It is well known from models of the ionization structure of planetary nebulae, that the $He^{++}$ zone is smaller than the $H^{+}$

zone in ionization-bounded nebulae. This could explain the smaller size of the $He^+ 121\alpha$ zone in the north-south direction.

It is less clear why the $He^+ 121\alpha$ emission region is more extended in the east-west direction than the $H76\alpha$ emission region. Assuming LTE conditions, the ratio of $He^+ 121\alpha$ flux to $H76\alpha$ flux (for the same beam solid angle) is given approximately by

$$\frac{S_L\ (He^+ 121\alpha)}{S_L\ (H76\alpha)} \simeq 4\ y^{++} \ ,$$

where $y^{++}$ is the ratio of twice ionized helium to ionized hydrogen in the observed volume. For NGC6302, $y \simeq 0.18$ (Aller et al. 1981), and thus $y^{++} \leq 0.18$ for any given region in the nebula. We then obtain the following upper limit:

$$\frac{S_L\ (He^+ 121\alpha)}{S_L\ (H76\ \alpha)} \leq 0.72 \ .$$

In other words, the ratio should not exceed the value of 0.72. From Figure 2 we can see that in the east and west edges of the nebula the observational ratio reaches and even exceeds the maximum value of 0.72. This result has to be taken cautiously because the $He^+ 121\alpha$ map has only modest signal-to-noise ratio. Nevertheless, we suggest that in the east-west direction NGC6302 is density-bounded and that helium is twice ionized all the way in this direction. It would be important to verify if the maximum value of 0.72 is exceeded because this could imply an anomalous enrichment of helium ($y >> 0.18$) in some regions of NGC6302. Embedded zones or knots of nearly pure helium have been discovered in Abell 30 and Abell 78 (Hazard et al. 1980; Jacoby and Ford 1983). It appears worthwhile to undertake an optical study of NGC6302 to test if it has zones with anomalously enriched helium. Unfortunately, the core of NGC6302 has significant obscuration and this could difficult such an optical study.

We have tried to take into account the contribution to the continuum from the twice ionized helium as follows. The LTE radio of $H76\alpha$ flux to continuum flux (for the same beam solid angle) is given by:

$$\frac{S(H76\alpha)}{S(2\ cm)} = C \frac{1}{(1+y^+ + 4\ y^{++})}$$

Where C is a constant for an LTE, optically-thin, isothermal nebula. On the other hand;

$$\frac{S(He^+\ 121\alpha)}{S\ (2\ cm)} = C \frac{4y^{++}}{(1+y^+ + 4y^{++})}$$

Adding the last two equations:

$$\frac{S(H76\alpha) + S(He^+\ 121\alpha)}{S\ (2\ cm)} = C \frac{1+ 4\ y^{++}}{(1 + y^+ + 4\ y^{++})}$$

We do not have a radio map of once ionized helium, but the contribution of this ion to the continuum is not as important as that of $He^{++}$. Neglecting the term $y^+$ in the last equation, we come to the conclusion that, if the assumed conditions were valid,

$$\frac{S(H76\alpha) + S(He^+ 121\alpha)}{S\ (2\ cm)} \simeq C \ ,$$

that is, the ratio of the addition of the $H76\alpha$ and $He^+ 121\alpha$ maps over the 2-cm continuum map should be constant across the face of the nebula. This is not the case and the variations seen in Figure 3 are still present, although in a less marked way (Figure 4). This result suggests that the contribution of twice ionized helium to the continuum affects the $H76\alpha$ line-to-continuum ratio, but that it is not the only effect.

We are now left with two effects to explain the line-to-continuum ratio variations seen in Figure 4; electron temperature variations in the nebula and/or non-LTE effects. The

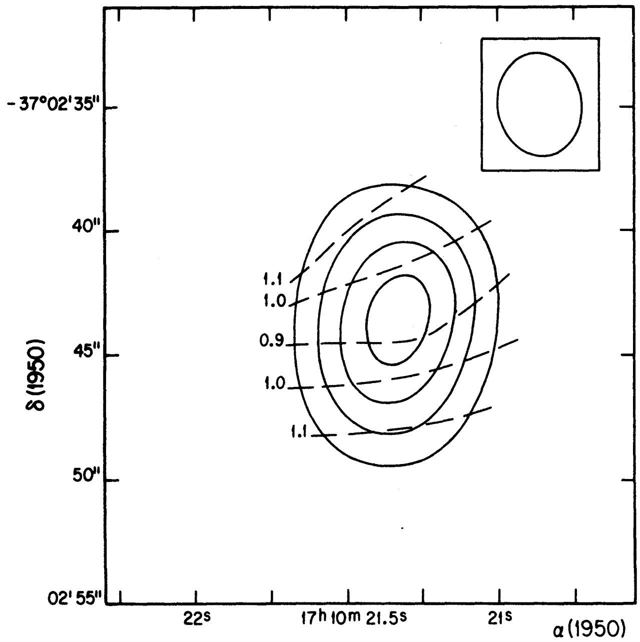


Fig. 4. Contour map of the 2-cm continuum wmission adjacent to the H76α line (solid line) and (H76α + $He^+$ 121α)-to-continuum ratio contours (dashed line) for NGC 6302. The values of the line-to-continuum ratio are in units of 1.64 km $s^{-1}$. The half power contour of the beam is also shown.

line-to-continuum contours shown in Figure 4 are in units of 1.64 km $s^{-1}$. Neglecting the contribution of once ionized helium, the LTE electron temperature is given by (Rodríguez et al. 1985):

$$T_e^* \underset{\sim}{\sim} 3\times10^4 \left[\frac{S(2\ \mathrm{cm})}{S(\mathrm{H76}\alpha)\Delta v(\mathrm{H76}\alpha)+S(\mathrm{He}^+121\alpha)\Delta v(\mathrm{He}^+121\alpha)}\right]^{0.87} .$$

Correspondingly, from Figure 4 we derive that $T_e^*$ varies from ∿21,000 K in the central parts to ∿18,000 K at the north and south edges of the nebula. The consideration of once ionized helium will lower these electron temperatures by about 10 percent. These large electron temperature values are in agreement with those found in the optical (Oliver and Aller 1969; Danzinger, Frogel and Persson 1973; Aller and Czyzak 1978; Aller et al. 1981). The models of Harrington (1968) for planetary nebulae indicate that the $He^{++}$ zone could have an electron temperature a few $10^3$ K higher than the outer parts of the planetary nebula. This gradient in the electron temperature could explain our results. However, from Figure 5 of Rodríguez et al. (1985) it is clear that we can expect line enhancements of 10 to 20 percent from LTE departures. This is also comparable to the observed variations. We conclude that the line-to-continuum variations observed in NGC6302 are due (once the effect of twice ionized helium is corrected) to modest electron temperature variations and small non-LTE enhancements. These effects can alter the line-to-continuum ratio, by about 20 percent. Garay, Gathier and Rodríguez (1986) have shown that these effects are similar in other planetary nebulae and that assuming LTE conditions allows a reasonable determination of the bulk parameters of the nebula.

## IV. CONCLUSIONS

Our main conclusions are:

1) Using our radio observations we derived a mean value for the twice ionized helium to ionized hydrogen in NGC6302. Our result, $He^{++}/H^+ \sim 0.06 \pm 0.02$, is in agreement with the optical results.

2) The H76α-to-continuum ratio varies significantly across the face of NGC6302. This variation can be attributed to the combination of three effects: i) the contribution to the continuum from the twice ionized helium, ii) a modest gradient in the electron temperature, which could be decreasing with nebular radius and, iii) small (10 to 20 percent) LTE departures.

3) There is marginal evidence of anomalously high helium abundance (y>0.18) in some parts of NGC6302. An optical study could address this possibility.

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