Revista Mexicana de Astronomía y Astrofísica, **45**, 85–89 (2009)

IONIZATION-BOUNDED AND DENSITY-BOUNDED PLANETARY NEBULAE

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Received 2008 December 29; accepted 2009 January 30

RESUMEN

Las nebulosas planetarias (y en general las regiones fotoionizadas) pueden clasificarse como acotadas por ionización (ionization-bounded) o bien acotadas por densidad (density-bounded). Es importante poder determinar en qué caso está la nebulosa planetaria estudiada para poder estimar a partir de observaciones nebulares, por ejemplo, la tasa total de fotones ionizantes producidos por la estrella central. En este artículo presentamos un criterio observacional sencillo que utiliza imágenes de radiocontinuo y que nos permite establecer una condición necesaria (pero no suficiente) para que la nebulosa planetaria pueda ser considerada como acotada por ionización. Aplicamos el criterio a dos nebulosas planetarias: NGC 7027 resulta muy posiblemente acotada por ionización, mientras que Hb 4 está acotada por densidad, al menos en ciertas direcciones.

ABSTRACT

Planetary nebulae (and in general any photoionized region) can be classified as ionization-bounded or density-bounded. It is important to determine in which case is the planetary nebula studied to be able to estimate from nebular observations, for example, the total rate of ionizing photons produced by the central star. In this paper we present a simple observational criterion that uses radio continuum images and allows to establish a necessary (but not sufficient) condition for the planetary nebula to be considered as ionization-bounded. We apply the criterion to two planetary nebulae: NGC 7027 is most possibly ionization-bounded, while Hb 4 is density-bounded, at least in some directions.

Key Words: planetary nebulae: individual (NGC 7027, Hb 4) — techniques: image processing

1. INTRODUCTION

Planetary nebulae, and in general any type of nebula photoionized by a central star or cluster of stars can be classified as either ionization-bounded or density-bounded. In the first case, the radius of the ionized region is determined by the absorption of the ionizing photons in the inner parts of the nebula. Even if there is more external gas available, it will remain neutral. In contrast, a density-bounded planetary nebula is one in which the ionized region terminates simply because there is no more gas available. Even if there are ionizing photons available, there will be no dense gas to ionize and the photons will escape to the diffuse halos that are known to surround planetary nebulae (Perinotto et al. 2004; Sandin et al. 2008).

When the nebula is visible in the optical, the presence of lines such as [O I] λ6300 (i. e. Bieging et al. 2008), that originate from the region of transition between ionized and neutral hydrogen, suggests that the nebula is ionization-bounded. Also the association of the planetary nebula with neutral (Rodríguez & Moran 1982) or molecular (Treffers et al. 1976) hydrogen, or with other molecular species (Thronson 1983) suggests ionization-boundedness. However, the situation is not as simple, since a nebula can be ionization-bounded in some directions (with respect to the ionizing star) and density-bounded in others and the evidence of a transition from ionized to neutral or molecular gas could be coming from some directions only.

It is relevant to know if a nebulae is ionization-bounded in all directions since in this case all the ionizing photon flux from the central star is trapped inside the nebula. Only in this case can an accurate estimate of this ionizing flux be derived indirectly by observing the nebular emission, for example in recombination lines or free-free emission. Otherwise, we will underestimate the ionizing photon flux. In an important development, Zijlstra, van Hoof, & Perley (2008) have reported Very Large Array observations of NGC 7027 taken over 25 years at frequencies above 5 GHz, where the free-free emission is optically thin. They find that the flux density is changing at a yearly rate of $-0.145\pm0.005\%$ and propose that this is caused by a decrease in the number of ionizing photons coming from the central star. However, their conclusion assumes that this planetary nebula is ionization-bounded in all directions. This assumption seems very reasonable for NGC 7027, which is known to be associated with many molecular emissions and to possess large obscuration, suggesting that the ionized region is completely engulfed in neutral gas. However, this assumption should be tested. Finally, Mellema (2004) and Schönberner, Jacob, & Steffen (2005) have noted that the apparent expansion velocity in the plane of the sky of planetary nebulae that are ionization-bounded can be larger than the true expansion velocity of the gas, since we also have the contribution of the outward motion of the ionization front as the nebula expands. This discrepancy becomes quite large during the optically-thin stage of nebular evolution (Schönberner et al. 2005). The knowledge of whether or not a nebula is ionization-bounded can be used to approximately correct for this effect.

In this paper we discuss a simple criterion that can be derived from good quality radio continuum images taken at frequencies where the ionized nebula is optically-thin. This analysis provides a necessary, although not sufficient, condition to classify a nebula as ionization-bounded. If the nebula fails the criterion, it can be considered to be density-bounded, at least in some directions (as seen from the central star).

2. THE CRITERION

We make the following assumptions: (i) the central star produces a photoionizing flux that is isotropic as seen from the position of the star, and (ii) the nebula is optically-thin in the free-free continuum. The first assumption implies that, if the nebula is ionization-bounded, the rate of photoionizations (and recombinations) produced in the nebula is independent of direction and is a constant for a given solid angle (as seen from the star). Then, the number of free-free photons (which in steady state is proportional to the number of recombinations, e. g. Schraml & Mezger 1969), produced per differential of solid angle as seen from the star is a constant. This conclusion is valid even if the radius of the ionized gas is different in different directions. A larger density in a given direction will cause a smaller ionized radius, but the number of free-free photons produced per unit of volume will be larger, so the number of free-free photons produced per differential of solid angle will remain constant. The second assumption implies that all free-free photons produced escape from the nebula.

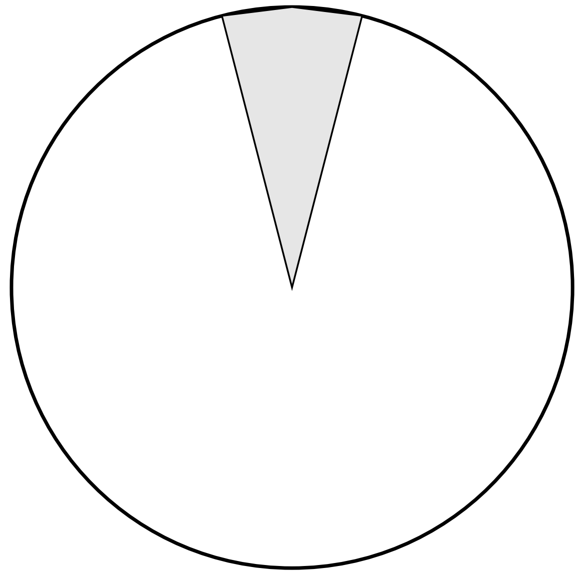

Fig. 1. If we divide the emission from a nebula in the plane of the sky in n pie slices, each slice will have an opening angle of $2\pi/n$ radians (see figure) and its apex will coincide with the ionizing star. From the point of view of an observer in the central star, each of these slices will appear as a spherical wedge with a solid angle of $4\pi/n$ steradians.

We now ask: what implications have these conclusions on the appearance of the nebula in the sky? As seen by the observer, we can split the nebula in n identical "pie" slices centered in the central star (see Figure 1), each with an opening angle given by $2\pi/n$ radians. As seen from the central star each of these slices is a spherical wedge with solid angle given by $4\pi/n$ steradians. Since this solid angle is constant for all wedges, we conclude that for a nebula to be

TABLE 1

OBSERVATIONAL PARAMETERS

PN	$\alpha(2000)^a$	$\delta(2000)^a$	ν(GHz)
NGC 7027	21 07 01.74	42 14 09.4	43.34
Hb 4	17 41 52.81	−24 42 07.8	8.46

[a]Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

ionization-bounded the flux density in each of the slices should be constant, within the noise.

This simple test can be implemented by following the next steps: (1) obtain a good quality radio continuum image of a nebula at a frequency where it is known to be optically thin in the free-free emission; (2) define a center for the nebula, either using the stellar position or symmetry considerations applied to the nebula; (3) use the task IRING of the NRAO software package AIPS (Astronomical Image Processing System) to determine the flux density in each of n identical slices centered on the position determined in the previous step. The radius of these slices has to be large enough to contain all the nebular emission. Finally, (4) plot these flux densities as a function of the position angle of the slices to analyze their behavior.

3. OBSERVATIONS

The two sets of observations used in this study were obtained in the standard continuum mode and taken from the archive of the VLA of the NRAO[1]. One set was obtained for NGC 7027 (= PN G084.9-03.4), and was taken at 43.34 GHz on 2001 November 9 in the D configuration, as part of the VLA Calibrator Flux Density project (R. A. Perley & B. Butler 2008, in preparation). The amplitude calibrator used was 1331+305, with an adopted flux density of 1.46 Jy. NGC 7027 was used as its own phase calibrator, with a bootstrapped flux density of 4.90±0.13 Jy. This set was analyzed with the specific goal of testing the hypothesis of ionization-boundness of Zijlstra et al. (2008). The second set was obtained for Hb 4 (= PN G003.1+02.9), and was taken at 8.46 GHz on 2001 February 18 in the BnA as part of project AK528. The amplitude calibrator used was 1331+305, with an adopted flux density of 5.21 Jy. The phase calibrator used was 1745−290, with a bootstrapped flux density of 0.67±0.02 Jy.

[1]The National Radio Astronomy Observatory is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

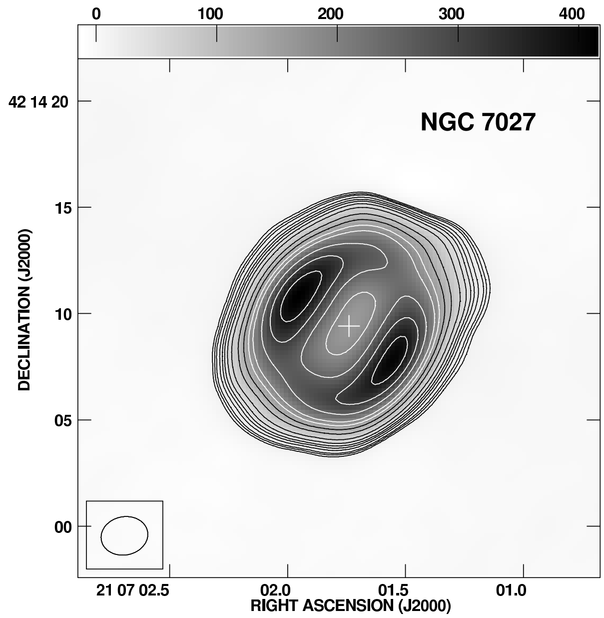

Fig. 2. 43.34 GHz contour and greyscale image of the planetary nebula NGC 7027. The contours are −5, −4, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 50, 60, 80, 100, and 120 times 3.1 mJy beam^{-1}, the rms noise of the image. The greyscale is shown in the top band, in mJy beam^{-1}. The synthesized beam ($2''.21 \times 1''.80$ with a position angle of −79°) is shown in the bottom left corner of the image. The cross marks the position adopted as the center of the nebular emission (see Table 1).

In Table 1 we present, for each planetary nebula, the position adopted as the center of the nebula (in both cases taken to be equal to the position of the minimum emission in the "bowl" that characterizes the morphology of these objects), and the frequency of the observations.

The data were reduced using the standard VLA procedures in the software package AIPS of NRAO and then self-calibrated in phase and amplitude. The images were made with the ROBUST weighting parameter (Briggs 1995) of AIPS set to 0.

4. INTERPRETATION AND RESULTS

4.1. *NGC 7027*

In Figure 2 we show the 43.34 GHz image of NGC 7027. This planetary nebula is known to be optically-thin above ∼5 GHz (Zijlstra et al. 2008), so we expect this 43.34 GHz image to be tracing optically-thin free-free emission. In Figure 3 we plot the flux densities of each slice as a function of their position angle. The slices were made with an angular radius of 10″ and an opening of 10°, with the position angle increasing by 10°. This flux density per slice is

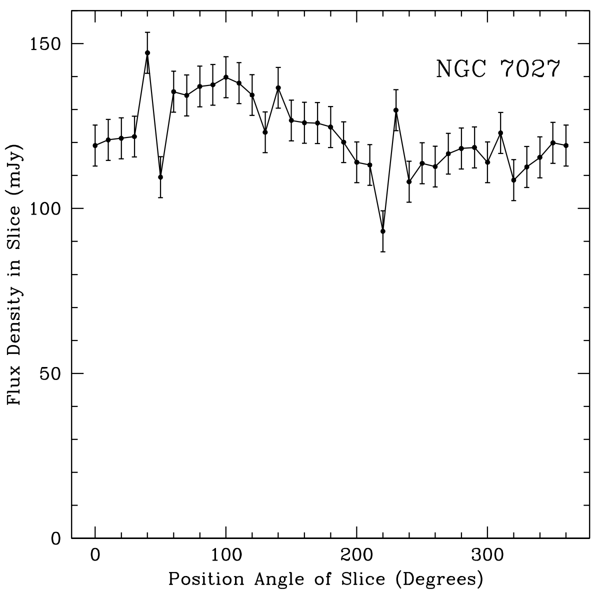

Fig. 3. Flux density of the image slices of NGC 7027 as a function of their position angle.

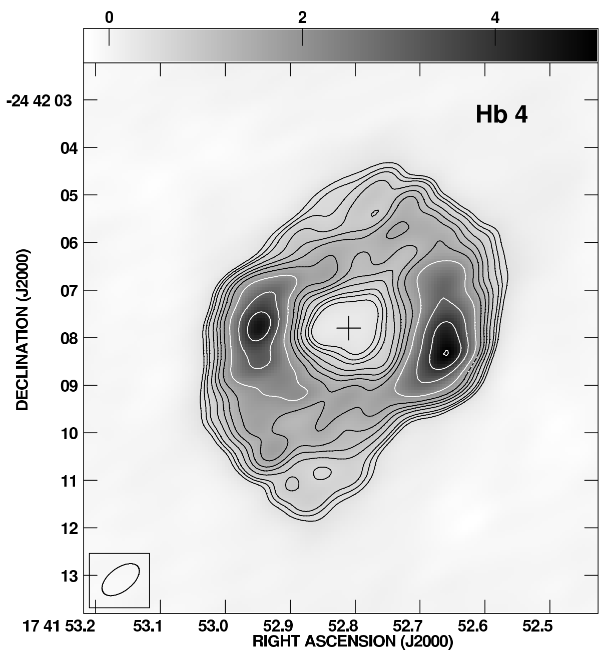

Fig. 4. 8.46 GHz contour and greyscale image of the planetary nebula Hb 4. The contours are −5, −4, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, and 50 times 0.10 mJy beam^{-1}, the rms noise of the image. The greyscale is shown in the top band, in mJy beam^{-1}. The synthesized beam ($0''.91 \times 0''.49$ with a position angle of $-53°$) is shown in the bottom left corner of the image. The cross marks the position adopted as the center of the nebular emission (see Table 1).

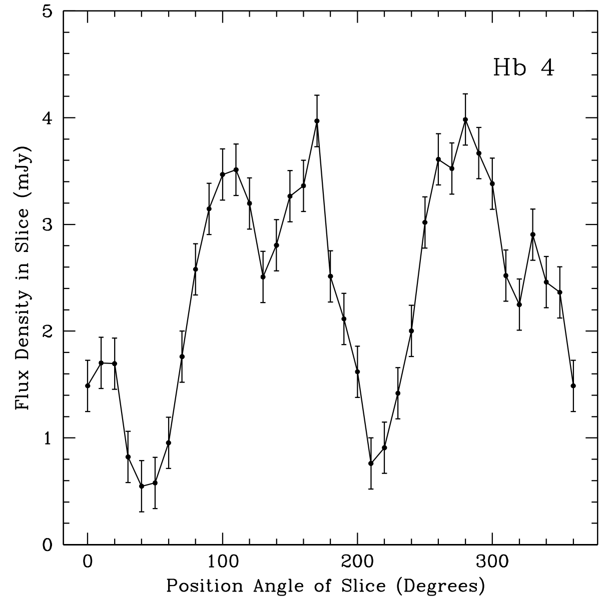

Fig. 5. Flux density of the image slices of Hb 4 as a function of their position angle.

approximately constant (only small modulations at the ∼10% level are present). We conclude that this result is consistent with NGC 7027 being ionization-bounded in all directions, in agreement with the assumption of Zijlstra et al. (2008). This test is relevant because if NGC 7027 were density-bounded in some directions, the observed decrease in flux density could be due to the expansion of the nebula, allowing more ionizing photons to escape in the directions where the nebula is density-bounded and not to a decrease in the number of ionizing photons from the central star. The assumption of NGC 7027 being ionization-bounded is fundamental for the Zijlstra et al. (2008) analysis and our results are consistent with this assumption.

Unfortunately, the constancy in the flux density of the slices is not a sufficient condition to assure ionization-boundness: an ionized ring seen face-on would show this same constancy but it will be density-bounded along the line of sight.

4.2. *Hb 4*

In Figure 4 we show the 8.46 GHz image of Hb 4. The 1.4 and 5.0 GHz flux densities of this planetary nebula are 158 mJy (Condon & Kaplan 1998) and 170 mJy (Aaquist & Kwok 1990), respectively. This indicates that the nebula is optically-thin above ∼1.4 GHz, so we expect the 8.46 GHz image to be tracing optically-thin free-free emission. In Figure 5 we plot the flux densities of each slice as a function of their position angle. The slices were made, as for NGC 7027, with an angular radius of 10″, every 10°. In contrast to NGC 7027, the flux density per slice of Hb 4 shows a strong modulation. This modulation implies that the nebula is density-bounded at least in the NW and SE position angles, where ionizing photons will be escaping to the interstellar medium. We conclude that this result indicates that Hb 4 is not ionization-bounded in all directions. An estimate of the stellar ionizing flux from indicators like Hα or free-free emission will then result in an underestimate of the true value.

5. CONCLUSIONS

We present a simple observational test that allows to establish if an ionized nebula is ionization-bounded or not. The condition is necessary but not sufficient. We applied this test to NGC 7027 and Hb 4, finding that the first object is probably ionization-bounded while the second is density-bounded, at least in some directions.

LFR and YG acknowledge the support of DGAPA, Universidad Nacional Autónoma de México, and of Conacyt (México). This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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