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A NEW FAINT, GIANT HALO IN THE PLANETARY NEBULA NGC 7009[1]

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RESUMEN

Se presenta información sobre la morfología externa de la nebulosa planetaria NGC 7009 a un radio mayor de 40″ respecto de su estrella excitadora. Se muestra que hay un halo extendido, formado por filamentos débiles fracturados y por pequeñas condensaciones.

ABSTRACT

In this work the morphology of the planetary nebula NGC 7009 is studied beyond a radius of 40″ from the central star. Our [O III] images reveal an extended halo consisting of faint fractured filaments and small condensations.

Key words: **PLANETARY NEBULAE – GENERAL — PLANETARY NEBULAE – INDIVIDUAL (NGC 7009)**

1. INTRODUCTION

CCD-image surveys of planetary nebulae (hereafter PNe) show that surrounding the bright cores of many of them, there are envelopes containing faint but patchy or irregular structures (e.g., Jewitt, Danielson, & Kupferman 1986; Chu, Jacoby, & Arendt 1987). Such studies have shown that they are related to important phases of the PNe evolution, possibly connected to episodic events (Moreno & López 1987). NGC 7009 (PK 37–34 1, VV259, IRAS 21014–1133) is a bright planetary nebula located in the southern hemisphere. Its inner structure ($r \leq 40''$) has been recently studied in detail (Balick et al.1994; Bohigas, López, & Aguilar 1994 hereafter BO94; Hyung & Aller 1995; Lame & Pogge 1996; Balick et al.1998). The NGC 7009 images presented by these authors show that this nebula has an elliptic form measuring $26'' \times 18''$. An important characteristic of its interior structure is that it presents well defined caps and ansae distributed in symmetric form relative to the central star in the direction of its major axis; therefore, it is known as the Saturn Nebula. A recent study (Balick, Gonzalez, & Frank 1992 hereafter BA92), has revealed previously unknown outer structures in this PN. It is the purpose here, to confirm their existence and to search for any new ones as well.

2. OBSERVATIONS

NGC 7009 was observed in 1997 July 30, 31, and October 30, with a CCD camera at the Cassegrain focus of the 0.84-m telescope of the Observatorio Astronómico Nacional, located in the San Pedro Mártir Mountains, Baja California, México (OAN-SPM). A liquid nitrogen cooled Tektronics TK CCD detector with 1024×1024 pixel^2, each measuring 24 μm, was used. The interference filters were mounted in the RUCA device, a dismountable wheel for eight interchangeable filters with a codified rotating flange. The specifications for the filters are indicated in Table 1. The field of view with this instrumental set-up has a radius of 140″. Twilight sky exposures were secured for the flat fields. NGC 7009 has a very bright core, making it very difficult to observe the presence of the faint structures around the nucleus. The reflections caused on the optics of the telescope and auxiliary equipment by the central part of this nebula, contaminate the deep images (BA92). This also

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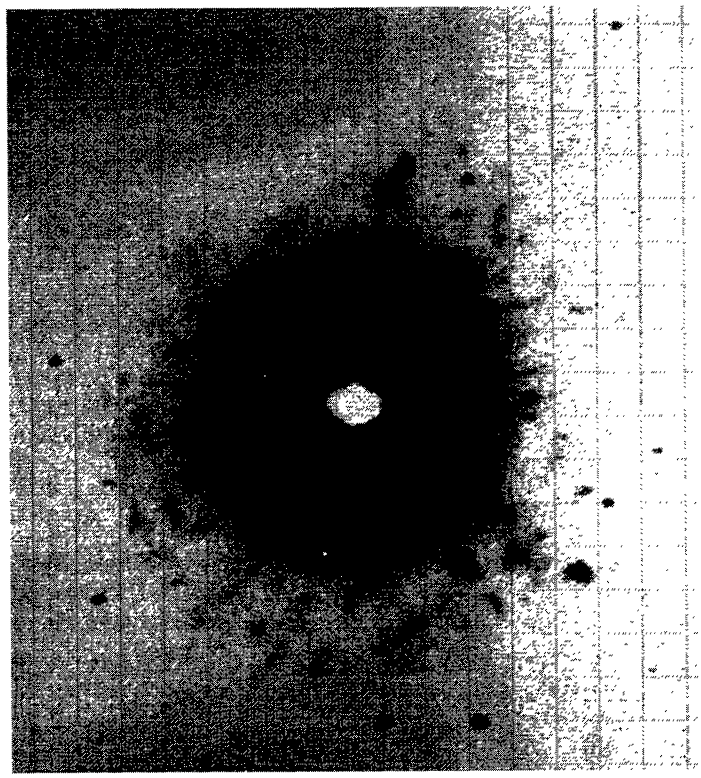

Fig. 1. The resulting image of NGC 7009. It was obtained by co-adding three 20 minute exposures taken in the [O III] λ5007 filter. N is at the top and E is to the left.

happened to our images taken with the narrow nebular filters Hα, [N II], and [S II]. On the other hand, the images obtained through the broad Hα+[N II] and [O III] filters show the existence of a halo located farther away than that reported by BO94 being more prominent in the oxygen image. On the night of July 31, we obtained several consecutive exposures of 20 minutes each. To verify that the detected structures are not the result of internal reflections, in 1997 October 30, we used a specially built coronograph interposed in the focal plane of the telescope to cover the central bright star; we took more images of NGC 7009 using the same equipment, but on this occasion only through the [O III] filter. The resulting images confirm that the flocculi found in July are indeed associated to the nebula.

TABLE 1

INTERFERENCE FILTER CHARACTERISTICS

Filter	λ (Å)	FWHM (Å)
Hα	6563	10
Hα+[N II]	6570	80
[N II]	6584	10
[S II]	6731	80
[O III]	5007	60

3. RESULTS

The images Hα+[N II] and [O III] were reduced following the usual procedures with the IRAF package[5]. The Hα+[N II] image confirms the results presented by BA92 in their Figure 10. A composite image from the three [O III] images was constructed to obtain the equivalent to one hour of effective exposure. The resulting image is shown in Figure 1. Even though the central parts of the image are saturated and the surrounding regions are overexposed, there are a number of important morphological features

[5] IRAF is the Image Reduction and Analysis Facility made available to the astronomical community by the NOAO, which are operated by AURA, Inc., under contract with U. S. National Science Foundation.

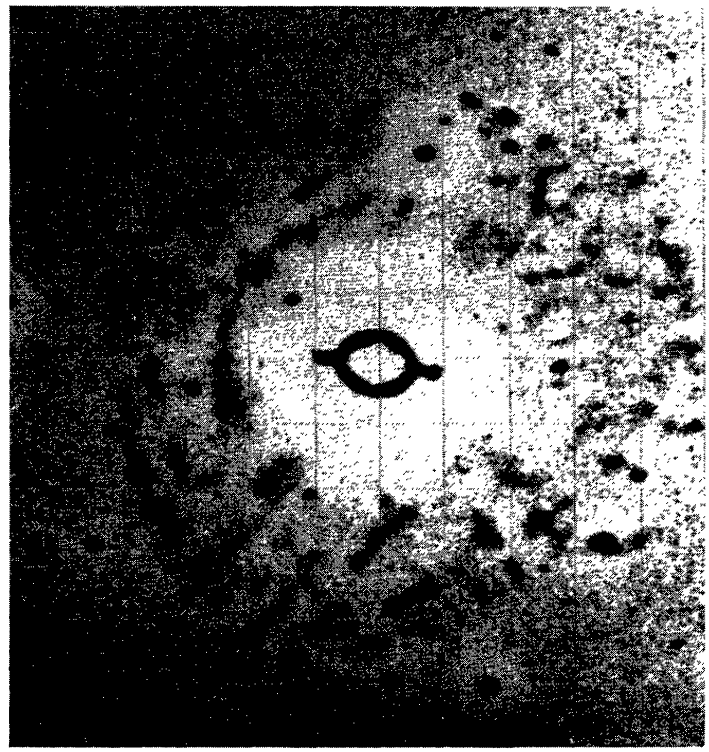

Fig. 2. The NGC 7009 image treated with an unsharp masking technique to enhance weak filaments and other structures.

in this image which reveal a faint circular outer halo containing several filaments, or flocculi, and compact condensations, or bright knots of nebulosity. In order to enhance these structures, we decided to process the image of Fig. 1 with the unsharp masking technique, creating an out-of-focus image which is used as a spatial frequency filter, to enhance rendition of any fine details, while at the same time reducing gross density variations on the resulting filtered image. The unsharp masking technique is particulary valuable when you need to study very low-surface-brightness structures on astronomical images.

In the case of the NGC 7009 image we used a gaussian filter with different values of σ (30, 20, 10, and 5 pixels), finding best results with $\sigma = 20$ pixels. The resulting image is shown in Figure 2. Indeed, we found in this image that the nebula has three clearly separate structures. The very interior is the main elliptical body of the nebula, that was discovered by Herschel in 1782. Surrounding this first component, including the ansae, is the spherical halo reported by BO94. According to our data, this spherical halo is bigger than previously reported, since it has a radius of 58″. Finally, further outside this second component, a very extended but weaker halo appears, formed by irregular filaments and compact condensations already present in Fig. 1, but being much noticeable in Fig. 2. To our knowledge, this extended structured halo of the PN has not been reported before, except for a few isolated diffuse structures in the SW direction (cf. Balick et al. 1992, see their Figure 10). The halo we report here, contains these same structures and many other filaments and bright knots. The NE sector of NGC 7009 shows a well defined semi-circular shell of radius of 63″ relative to its central star. This filament surrounds more than one fourth of the spherical halo previously reported by BO94, extending to parts of the SE quadrant. In Fig. 2, it is possible to observe few filaments and condensations farther outside this shell. The sparseness of these structures is probably because this same shell has inhibited subsequent flow of material to the more external parts of the nebula, serving as a containment barrier, or because it obstructs the ionizing radiation that could excite the material already accumulated in the outer regions of the extensive halo, or both. In the lower part of the SW quadrant, we observe a dagger shaped structure 97″ from the central star (cf. Figure 3, knots B, G, H, and I), where the hilt is formed by two small radial filaments and a

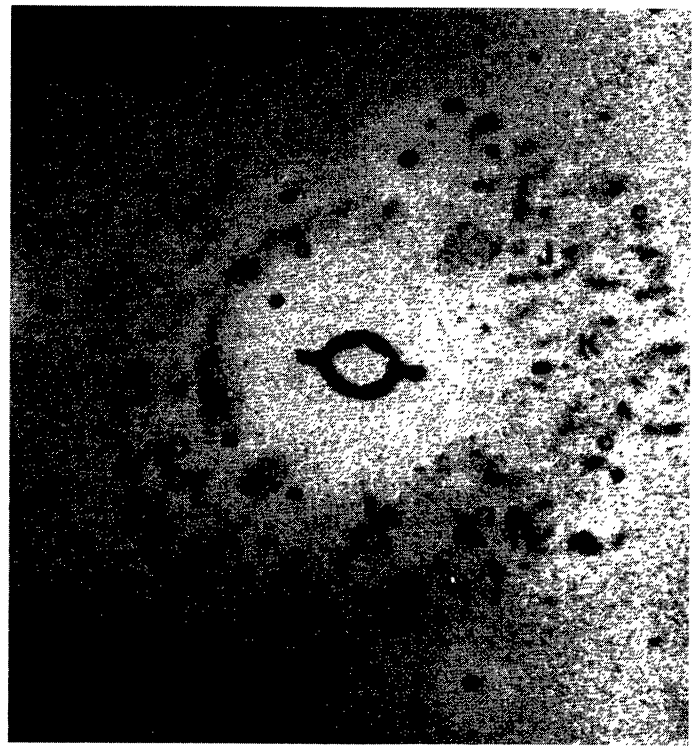

Fig. 3. Prominent filaments and semi-circular structures in the NGC 7009 giant halo.

bright knot. These features are precisely the ones appearing in Figure 10 of BA92. In addition. a greater number of filaments and knots appear on the NW and SW regions of the outer halo. There are also several knots present in the SE region. Finally, we need to point out that in our images we did not find any cometary nebulae like those existing in the external halo of NGC 6543.

4. DISCUSSION

The structures in the external halo of NGC 7009 are reminiscent of the features observed throughout the haloes of NGC 6543, NGC 6826, and NGC 7662 (cf. Figures 4, 8, and 11 of BA92); therefore, it is possible that the flocculi present in the Saturn Nebula are being excited collisionally as suggested by Middlemass et al. (1991). In general, this new halo has a circular form, slightly elongated in the NW-SE direction. The radius for this complex structure determined from our [O III] image is $R_{\rm H} = 108''$. Many of the filaments that conform the halo show radial elongation with respect to the main body of the nebula but, they are predominantly located in the NW and SE directions. We have estimated the surface brightness of the most conspicuous flocculi reported here to be $\approx 10^{-4}$ that of the central body of the planetary nebula, thus making their detection by any observer very difficult. The angular sizes of these structures are variable, typically of a few arcseconds and are given in Table 2. From the images presented here, one readily sees that the new halo is formed by, at least, a set of three semi-circular shells. The most prominent shell is marked with letter *a* in Figure 3,

TABLE 2

ANGULAR DIMENSIONS OF CONSPICUOUS FLOCCULI IN THE GIANT HALO OF NGC 7009

Filament	d ($''$)	Filament	d ($''$)
A	29.7	*G*	14.5
B	17.1	*H*	17.9
C	29.5	*I*	11.0
D	11.0	*J*	21.7
E	9.3	*K*	33.2
F	11.1	...	...

TABLE 3

ANGULAR RADII AND DIMENSIONS OF CIRCULAR SHELLS IN THE EXTERNAL ENVELOPE OF NGC 7009

Shells	r (″)	Dimensions (″)
a	63	113
b	97	83
c	131	238

TABLE 4

DIMENSIONS OF GIANT HALOES IN SOME PLANETARY NEBULAE

NGC	R_H (″)	d (kpc)	R_H (pc)	Ref.[a]
6543	165	1.1	0.88	(1)
6826	72	2.3	0.80	(1)
7009	108	1.6	0.83	(2)
7662	72	1.5	0.52	(3)

[a] References: (1) Middlemass et al. 1989; (2) this work; (3) Middlemass et al. 1991.

and is surrounding the halo reported by BO94, as was mentioned before. Further outside and concentric to this structure, there is a second fragmented and dimmer semi-circular envelope, which we have marked with letter *b* in Figure 3. Finally, in the NW quadrant of our [O III] image, an outermost third semi-circular shell *c* can be found, which is the exterior boundary of the new halo in this direction, to our detection limit. The dimensions of these semi-circular shells are given in Table 3. The presence of radial filaments, but mainly structures *a*, *b*, and *c* suggest that the halo of NGC 7009 reported here, was formed by episodic mass ejection of the central star.

The distance to this planetary nebula is very uncertain, anywhere between 0.45 and 2.5 kpc (Acker et al. 1992). Based on recent work, it is considered that this nebula is probably at 1.6 kpc (Maciel 1995). With this distance, we find that the extended halo of NGC 7009 has a size of 0.83 pc, similar to the values reported for the same type of structures of other PNe (Bryce, Meaburn, & Walsh 1992). If we consider that r_{neb} is the major semi-axis of the main body of this nebula, we obtain $R_H/r_{neb} = 7.2$, leading us to consider it as a member of those planetary nebulae with giant haloes, since the criterion established by Capriotti (1978) is that PNe with $R_H/r_{neb} \geq 5$ form the subgroup with giant haloes. Objects of this type are NGC 6543 and NGC 6826 (Middlemass, Clegg, & Walsh 1989; Bryce et al. 1992), and NGC 7662 (Middlemass et al. 1991). Table 4 shows the dimensions of the haloes in these PNe. Besides its giant halo, NGC 7009 shows features shared with other PNe proven to have multiple shells. For example, the spectrum of its central star is the same as NGC 3242, both classified as O(H) by Mendez (1991); or similar to that of NGC 6543 (Of/WR(H)) and of NGC 6826 (O3f(H)), meaning that the spectra of the central stars of these PNe clearly show the presence of stellar hydrogen. For this reason, Mendez (1991) has classified them within the group of exciting stars of planetary nebulae rich in this element (H-rich CSPN). Moreover, the inner part of NGC 7009 shows microstructures similar to those found by BA94; while NGC 3242, NGC 6543, NGC 7009, and NGC 7662 have all ansae. Finally we stress the importance of giant haloes, like the one reported here for NGC 7009; Middlemass et al. (1989) found that there is significant mass contained in the giant haloes of NGC 6543 and NGC 6826, thus the haloes are relevant for the theory of stellar evolution.

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