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KNOTS IN PLANETARY NEBULAE

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RESUMEN

Hemos estudiado las nebulosas planetarias brillantes más cercanas con el WFPC2 del *Telescopio Espacial Hubble* para caracterizar los nudos densos que existen en NGC 7293. Encontramos nudos en todos los objetos, lo cual sugiere que tales nudos son comunes y que no siempre se observan debido a la distancia. Los nudos parecen formarse temprano en el ciclo de vida de la nebulosa, probablemente formándose por un mecanismo de inestabilidad que opera en el frente de ionización de la nebulosa. A medida que el frente pasa a través de los nudos éstos son expuestos al campo de radiación fotoionizante de la estrella central, que modifica su apariencia. Esto entonces explicaría como evolución la diferencia en apariencia—por un extremo, los filamentos de encaje que se ven solamente en extinción en IC 4406 y, por otro, los nudos "cometarios" altamente simétricos vistos en NGC 7293. Las formas intermediarias de los nudos observados en NGC 2392, NGC 6720 y NGC 6853 entonces representarían fases intermediarias de esta evolución.

ABSTRACT

We have studied the closest bright planetary nebulae with the *Hubble Space Telescope's* WFPC2 in order to characterize the dense knots already known to exist in NGC 7293. We find knots in all of the objects, arguing that knots are common, simply not always observed because of distance. The knots appear to form early in the life cycle of the nebula, probably being formed by an instability mechanism operating at the nebula's ionization front. As the front passes through the knots they are exposed to the photoionizing radiation field of the central star, causing them to be modified in their appearance. This would then explain as evolution the difference of appearance like the lacy filaments seen only in extinction in IC 4406 on the one extreme and the highly symmetric "cometary" knots seen in NGC 7293. The intermediate form knots seen in NGC 2392, NGC 6720, and NGC 6853 would then represent intermediate phases of this evolution.

Key Words: **ISM: PLANETARY NEBULAE**

1. GENERAL

The planetary nebulae (PN) present a wide variety of structural detail, but the knots which are the subject of this paper are clearly a well defined subset. As we'll see, the characteristics of the knots vary widely, but this variation can be explained on the basis of their alteration with time. This paper draws heavily on material that we have recently published in more detail (O'Dell et al. 2002) and where a more extensive introduction to the literature on this subject can be found.

We define as knots those well defined condensations found within PN that have characteristic sizes of about 4×10^{10} km and a neutral core of dust and gas. This sets them apart from the other internal features of PN, which are likely to arise from very different processes. The first PN discovered to contain knots was the Helix Nebula (NGC 7293). The advent of the *Hubble Space Telescope* (*HST*) has allowed study at an unprecedented angular resolution, with the result that knots are known around many PN. In this study we report on results from *HST* observations of the five arguably closest PN, thus minimizing the problems of losing visibility due to the lack of spatial resolution.

The knots are particularly important because they probably contain a significant fraction of the total mass of material that has been ejected by the central star (O'Dell & Burkert 1997). This means that about half of all the material is trapped in a dense molecular state because of the shielding from ultraviolet radiation, thus freeing it of the photoionization processes that determine the characteristics and fate of the ionized material. This can affect how we view the PN process itself and also the nature of the material that is being fed into the interstellar medium through the PN phenomenon.

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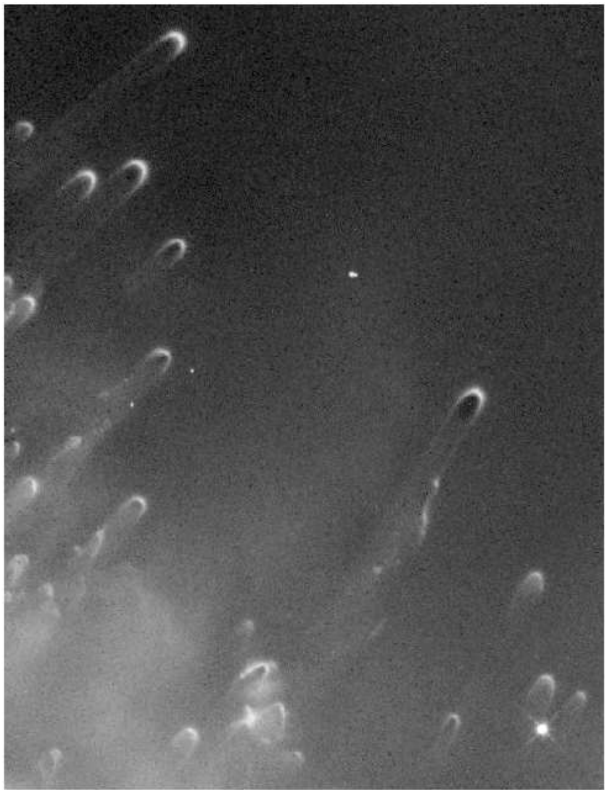

Fig. 1. This 55″ × 72″ view of a northern portion of the inner bright ring of NGC 7293 illustrates well the developed radial symmetry of the bright cusps and tails of the knots. Like the other figures in this article, this image is a composite of images made in Hα, [O III], and [N II]. The central star is in the direction indicated by the symmetry axes and on the side marked by a bright cusp.

2. CHARACTERISTICS OF THE HOST NEBULAE

The five PN in our study were (in order of increasing distance) NGC 7293, (210 pc, Harris et al. 1997), NGC 6853 (380 pc, Harris et al. 1997), IC 4406 (600 pc, O'Dell et al. 2002), NGC 6720 (700 pc, Harris et al. 1997), and NGC 2392 ($\geq$ 880 pc, O'Dell et al. 2002). The ages of the objects are: NGC 7293 $10{,}600^{+2300}_{-1200}$ yrs, NGC 6853 12,700 yrs, NGC 6720 1600 $\pm$240 yrs, NGC 2392 1060 yrs, and IC 4406 (?). All of the objects are bipolar, i.e., they are thick equatorial rings with extended structure along their symmetry axis. NGC 2392 is viewed almost from along the axis of symmetry, NGC 6720 and NGC 7293 are seen at angles of about 30° from this axis, and NGC 6853 and IC 4406 are viewed from almost in the plane of their equators. The objects or portions thereof are imaged in Figures 1 through 5.

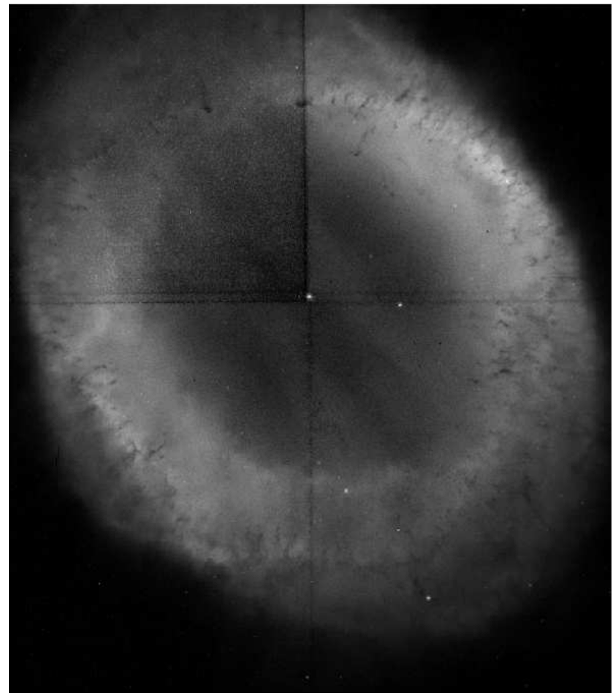

Fig. 2. This 72″ × 78″ image of NGC 6720 has the vertical axis pointed towards PA = 34°.

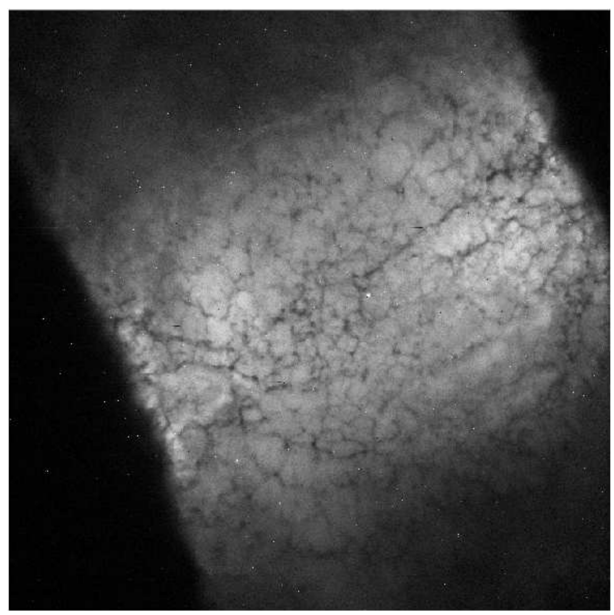

Fig. 3. This is a 33.6″ square section of IC 4406, with the vertical axis pointed towards PA = 61°.

3. CHARACTERISTICS OF THE KNOTS

We see a wide variety of forms of the knots. At the one extreme are those in NGC 7293 where the objects have a highly developed symmetry along a radius vector from the central star. The knots in

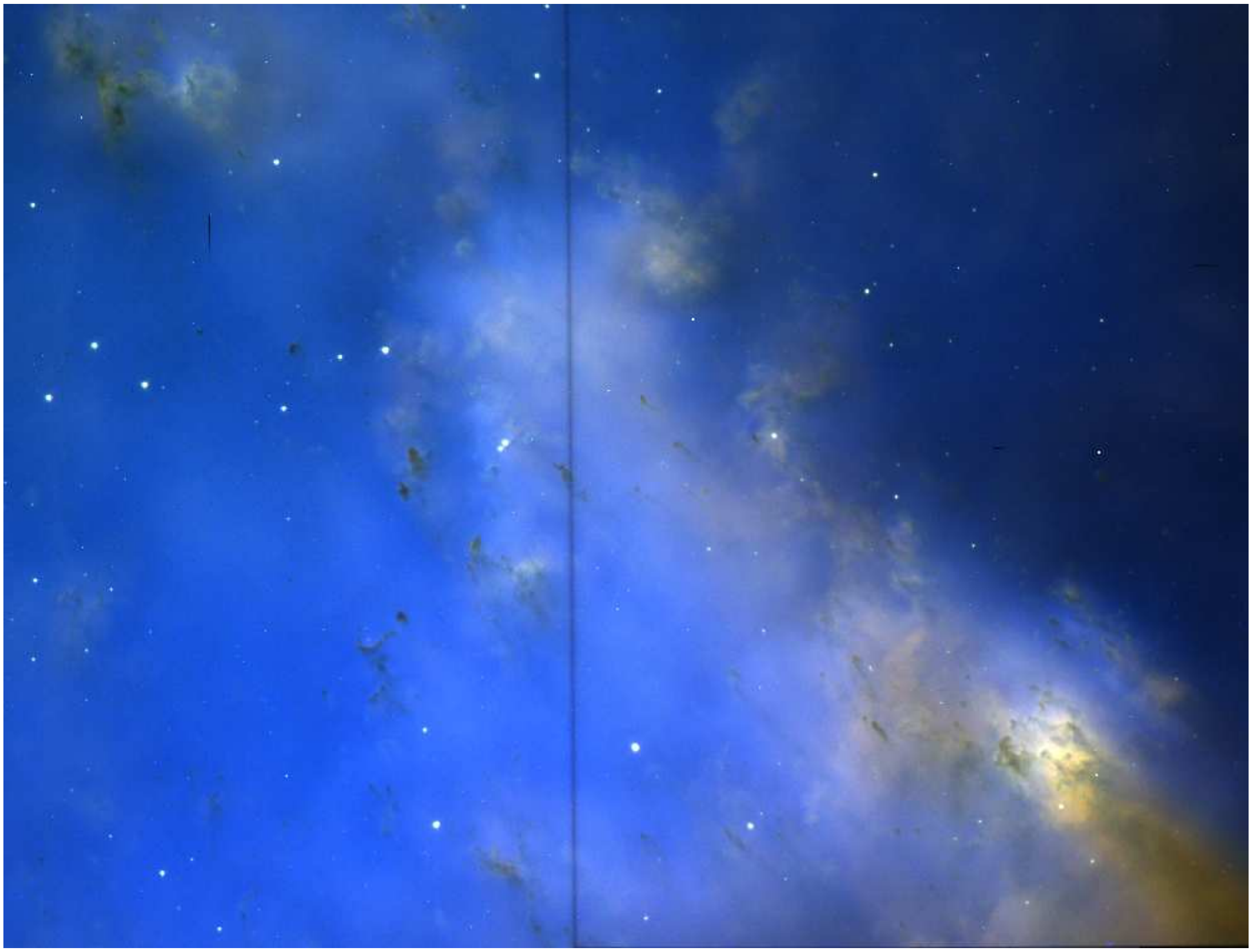

Fig. 4. This $99.5'' \times 75.5''$ section of the central region of NGC 6853 is marked by a pattern of dark and bright cusped knots and their associated dark tails.

NGC 2392 are almost as symmetric, although the tails are a bit more irregular and the knots are of lower ionization. In NGC 6720 the knots have a developed sense of symmetry but they are only seen in silhouette against the background emission from the equatorial ring of the nebula. In NGC 6853 the knots vary in appearance from symmetric objects with tails to rather irregular tail-less objects. Like NGC 7293 and NGC 2392 the heads of the knots have bright cusps which are local photoionization fronts. At these cusps the knots have become optically thick to Lyc photons from the central stars. The knots in IC 4406 are entirely different in appearance, having no ordered symmetry in the direction of the central star and appear as a "lacy" pattern. None of the IC 4406 features have bright edges. In spite of the variety of appearances, the knots share the common feature of the small dimensions being within a factor of 1.5 of 4×10^{10} km. A detailed description of the knots in each PN is found in O'Dell et al. (2002).

4. LOCATION OF THE KNOTS

The characteristics of the knots allow us to determine information about where they lie within the structure of the host PN. This is because they have a sufficiently high column density of material that they will become optically thick to the ionizing radiation coming from the central star. If there is not a bright border in Hα on the side facing the central star, then one knows that the knot falls outside of the main ionization boundary of the nebula. If they fall slightly inside this boundary, radiation capable of photoionizing N^+ and O^+ will not be present and there will not be emission from the strong [O III] lines, but [N II] will be strong in those knots. If the knots fall within the zone where helium has been singly ionized, then [O III] will be strong, with a layer of [N II] emission inside of it.

In the case of IC 4406 we see no evidence for emission around the dark features. This indicates that the knots lie within the neutral portion of the neb-

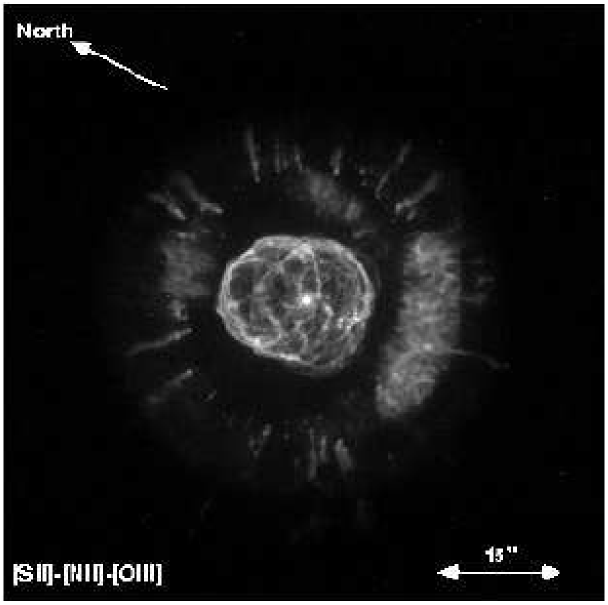

Fig. 5. This $73'' \times 72''$ view covers all of NGC 2392, with the vertical axis pointed towards PA = 296°.

ula. In the case of NGC 6720 there may be [N II] emission at the tips of the knots that face the central star, but most of the knots are neutral, appearing only in extinction. This means that they too lie in the neutral zone, but the appearance of a few with possible [N II] emission indicates that they are closer to the ionization front than in IC 4406. In NGC 6853 one sees a variety of illuminations. Some of the knots are only in silhouette (indicating a location outside of the nebula's ionization front) while others have photoionized cusps on the side facing the central star. This indicates that a certain fraction of the knots in this object fall within the ionized part of the nebula. However, none of them have cusps that are bright in [O III]. In NGC 2392 the knots are bright rimmed and quite low ionization, indicating a location within the ionized zone but close to the boundary. In NGC 7293 one finds the knots closest to the central star, but even there they are not found within about 25% of the outer boundary of the nebula. They have some [O III] emission, which indicates that they are located farther within the nebula's main ionization front, where helium is singly ionized.

The characteristics just described also correlate with the "structural" appearance of the objects. The knots in IC 4406 are completely tail-less. In NGC 2392, NGC 6720, and NGC 6853 there can be well developed tails and these tails are often of a noticeable optical thickness in the visual continuum. In the case of the knots located furthest within the ionized zone of the nebula, the tails are of only a marginal optical depth, with their appearance largely determined by their being shielded from ionizing photons coming directly from the central star (O'Dell 2000).

Since PN are finite shells of gas slowly expanding as their central stars heat up, one expects the ionization boundary to increase in size, so that knots that formerly had been shielded from ionizing radiation will then be illuminated. This appears to be what we see, i.e., the knots form close to or outside of the main ionization front when the nebula is quite young, then they are overtaken by the growing ionization front. The new conditions of illumination immediately start to photo-ablate material out of the knots and to alter the appearance and nature of their tails.

5. ORIGIN OF THE KNOTS

Almost certainly these knots originate in an instability on the neutral side of the main ionization front. Capriotti (1973) has posited this as being a result of Rayleigh-Taylor instabilities. The particular attraction of this theory of their origin is that it predicts that a significant fraction of the nebula's mass would be trapped into knots. Initially the process was attractive because the shapes of the instabilities were radially symmetric and these look like what is seen in the prototypical host, NGC 7293. However, we now see that there are a number of mechanisms, including gas flow (Dyson, Hartquist, & Biro 1993) and radiation shadowing (Cantó et al. 1998; O'Dell 2000) that will "sculpt" the shape after a knot is formed. The thin-layer instability (Vishniac 1994) appears to be an equally attractive alternative. Theoretical models have considered only symmetric instabilities, but there seems to be nothing that precludes the formation of elongated concentrations like one sees in IC 4406.

It has been proposed that the knots we see in PN originated as the result of instabilities operating in the atmosphere of the precursor central star while in the extended-cool atmosphere phase (Dyson et al. 1989). This now appears to be unlikely. If this were the source of the knots, then one would expect to have a distribution of the knots throughout the nebular shell even in the earliest phases and we do not. Moreover, there have been recent searches looking for scattered light from such knots in the youngest PN and the upper limit to the masses that could have been seen (but were not) is much smaller than would have been able to survive to that phase (Huggins & Mauron 2002).

6. THE FATE OF THE KNOTS

What the future holds in store for the knots in PN is quite important because whichever mechanism is producing them is locking a substantial fraction of the mass into molecular knots and these knots are escaping from the gravitational field of the central star (Meaburn et al. 1998). The process of photoionization means that there will be photoevaporation of material from the knots. The situation will be very much like the proplyds in the Orion Nebula, where the inner molecular core is heated by photons of less than 13.6 eV, causing a slow flow of gas away from the core. When this gas reaches the knots' ionization front it is photoionized and heated, then it is rapidly accelerated to a velocity of about 10 km s^{-1}. The estimated evaporation timescale for the outward moving knots is several thousand years. Many or most of them will therefore survive the hot-luminous phase close to the star and will be ejected into the surrounding interstellar medium.

Over the lifetime of the Galaxy PN could populate the general interstellar medium with tiny, cold and dense molecular knots. When moving into the low-pressure environment of the ISM the free-floating knots will expand until a pressure equilibrium is achieved with their surroundings. When in a high-temperature/low-density portion of the interstellar medium, there would probably be enough confining pressure to allow equilibrium and survival. The average knot densities in the interstellar medium will be a few times $100\,\mathrm{cm}^{-3}$ with temperatures of the order 10 K to 100 K. Their evaporation timescales can be estimated to be of the order of a few 10^9 yrs as long as they are surrounded by diffuse H I gas phase with temperatures of the order of 10^4 K. The inner regions of these dark knots would then still be optically thick to the diffuse interstellar radiation field. However, as soon as the knots are hit by supernova remnants, they will evaporate quickly. Before then, the dust grains within the knots could grow efficiently inside their cold gas environments. Dust grains with masses larger than 10^{-21} g would then segregate and sink to the center of the knot where they could build up large solid cores very much like comet nuclei. A full analysis of these stages and all reasonable and possible scenarios has not been done.

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