Filamentary Structures in Planetary Nebulae

Hanna Dahlgren

M.Sc. Thesis

PLASMA PHYSICS
ALFVÉN LABORATORY
ROYAL INSTITUTE OF TECHNOLOGY
SE-100 44 STOCKHOLM SWEDEN

KTH Electrical Engineering

TRITA-ALP-2005-04

Filamentary Structures in Planetary Nebulae

Hanna Dahlgren

Master of Science Thesis in
Physical Electrotechnology

ROYAL INSTITUTE
OF TECHNOLOGY

Stockholm, May 2005

Division of Plasma Physics
Alfvén Laboratory
Royal Institute of Technology
SE-100 44 Stockholm, Sweden

Printed by
Alfvén Laboratory
Royal Institute of Technology
SE-100 44 Stockholm

Abstract

A study of small-scale, elongated structures in planetary nebulae has been conducted. The structures were mapped in two dimensions, in terms of sizes, abundances, shapes, and internal structures. Structures in the haloes were also noted. In three, out of fourteen, of the planetary nebulae studied, NGC 3132, NGC 6543 and NGC 7293, the filaments found were subject to further three-dimensional interpretation. To obtain an idea of the strength of the magnetic field in the filaments the strength of the field in planetary nebulae was calculated using two different methods. The similarity between the filamentary structures found here and structures previously studied in H II regions and supernova remnants supports the idea that all the structures are formed through the double helix mechanism. This leads to a new theory of the filaments in planetary nebulae, based on magnetized plasma filaments with frozen-in field lines. The plasma properties in the nebulae were investigated and extinction measurements undertaken, to obtain a model of a filament.

Acknowledgements

This master thesis project was made as a collaboration between the plasma division at the Alfvén Laboratory, KTH, and Stockholm Observatory. I wish to thank my supervisors Per Carlqvist at the Alfvén Laboratory and Gösta Gahm at Stockholm Observatory, for their help and inspiration, and for many interesting discussions. I also wish to thank Garrelt Mellema at ASTRON in Dwingelo, the Netherlands, for a valuable discussion at our meeting in Stockholm in December 2004.

Contents

1	Introduction	4
2	Expanding shells and the double helix mechanism	6
3	Two-dimensional analysis	7
3.1	The PNe studied	7
3.2	Elongated structures	7
3.3	Common shapes found	7
3.4	Selected PNe	8
3.5	A comparison of NGC 6751, NGC 2392 and NGC 7293	11
3.6	Occurrence of elongated structures	12
3.7	Inner structure	12
3.8	Structures in the haloes	12
4	Three-dimensional interpretations	14
4.1	Physical conditions in PNe	14
4.2	NGC 3132 — The Eight-Burst Nebula	16
4.3	NGC 6543 — The Cat's Eye Nebula	18
4.4	NGC 7293 — The Helix Nebula	19
4.5	Extinction measurements	22
4.6	Model of a filament	23
5	Conclusions	25
A	Calculations of some plasma properties	29
A.1	Equipartition times	29
A.2	The magnetic Reynolds number	30
A.3	Other parameters of the plasma	31
B	Measurements and calculations of the extinction for NGC 3132 and NGC 7293	32
B.1	NGC 3132	32
B.2	NGC 7293	33
C	Tables and images	34

1 Introduction

When the astronomer William Herschel looked through his telescope in the middle of the 1780s, he was attracted by a single star surrounded by a green-coloured, nebulous, round object. This reminded him of the planet Uranus, which he had discovered in 1781, and so he named this object, and other similar ones "Planetary Nebulae" (PNe). Herschel believed that the PNe were new solar systems in the making, but nowadays it is a well known fact that they instead represent the death of a star.

Before the end of the 1970s PNe were thought of as expanding spherical bubbles, caused by the mass-loss of Asymptotic Giant Branch (AGB) stars and driven out by stellar winds at velocities of ~ 10 km/s. This theory had many draw-backs. For instance it could not explain the higher density of the PNe shells compared to the AGB envelopes. In 1978 Kwok et al. (1978) presented the Interacting Stellar Winds (ISW) model, where a fast wind with a speed of about 2000 – 4000 km/s is ejected at a later stage, running into the slower wind from the AGB expansion, and sweeping it up like a snow plough (Figure 1). A modified model, involving an AGB wind shaped by a torus of plasma lying around the central star, was developed to account for the bipolar and elliptical PNe. But when the first images of PNe were secured by the Hubble Space Telescope (HST) in 1994 a far more complex structure than predicted by the theory was revealed. There was clearly something still missing. Nowadays it is believed that magnetic fields and gravitational influence of a companion star could be two key aspects in the shaping process, but the details are not yet fully understood.

Later on HST images have revealed several inexplicable internal structures in PNe such as jet-like streaks, knots and elongated structures. All of these structures are mainly concentrated to the rim of PNe, i.e. on the edge of the nebula's shell, or pointing radially outwards from the shell, so called jets. Micro-structures in PNe have been observed in narrowband images obtained by ground-based telescopes long before the HST era (e.g. by Zanstra 1955 in the Helix Nebula), as a result of their distinction in low-ionization lines, such as [N II], [O II], [O I] and [S II]. Because of this they are often referred to as Low Ionization Structures (LISs) (Gonçalves et al. 2001). LISs have earlier been catalogued as ansae (Balick 1987), Fast Low-Ionization Emission Regions (FLIERs) (Balick et al. 1993), bipolar rotating episodic jets (BRETs) (López et al. 1995), jets and jetlike LISs and filaments (Gonçalves et al. 2001).

In addition to the structures mentioned above HST images reveal a great number of still smaller structures in PNe. So far these structures have not

been considered in any detail. It is the aim of the present investigation to study these small scale structures in PNe, and to consider their shapes and physics. Firstly, a two-dimensional analysis will be made of a selection of PNe, where a number of small elongated structures are catalogued and named. Secondly, an attempt is made to interpret some of these formations in three dimensions. Different possibilities of the spatial appearance as well as similarities between PNe and their internal filamentary details will be discussed. In particular the structures will be compared to structures of similar appearance in H II regions, and the shells of supernova remnants. Finally the physical properties of the structures will be discussed in terms of dimension, magnetic field strength, mass, density, composition etc.

2 Expanding shells and the double helix mechanism

PNe are mainly constituted by shells that are expanding into the surrounding space. Similar expansions of shells are also found in other objects, such as H II regions and supernova remnants. In all of these cases there are different kind of stars creating a wind that together with the radiation pressure lead to an overpressure and thus a shell expansion. V-shaped filaments, and also twisted filaments, have been found in H II regions, expanding interstellar bubbles and supernova remnants. A model of these structures based on magnetized filaments was developed by Carlqvist et al. (2002, 2003). The magnetic field in the filaments, consisting of both an axial and toroidal component, is well frozen into the plasma. As the overpressure caused by the central star or stars pushes the surrounding material radially outwards, any mass concentration in the filament will not be accelerated as fast as less dense parts of the filament due to greater inertia. As a result the filament will assume a V-shape with the mass concentration placed in the apex. Any current running along the magnetic field lines will produce a toroidal component of the magnetic field, causing the magnetic field to become twisted. If the filament, and hence the magnetic field, is twisted beyond a certain critical limit the very filament closest to the mass concentration will be twisted into a double helix. Hence, the whole structure will bear a resemblance of the letter Y. This can be visualized by an analogy model, where the filament is replaced by an elastic string loaded with a weight. When twisting one end of the string the configuration will take the shape of a double helix leading to a Y-shape of the filament (Figure 19).

Since there are many similarities between the physical properties in these regions mentioned and in PNe – a fast stellar wind blowing out from a hot center into the surrounding materia – it is motivated to search for V- and Y-shapes also here. However, this study is not only concentrated to V- and Y-shapes, but other complex structures are also noted.

3 Two-dimensional analysis

3.1 The PNe studied

In this project 14 PNe, containing thin, elongated structures, have been selected. The PNe are listed in Table 1. To start with, a two-dimensional study of the structures was carried out, as the images are all shown in two dimensions which makes the investigation more objective and the mapping straightforward. In the three-dimensional interpretation (Section 4) the analysis is more subjective since the two-dimensional structures can be thought of as stretching out in several possible directions and formations. All images were modified in the Adobe Photoshop CS, to highlight the characteristics of the micro-structures by adjusting image settings such as contrast and brightness.

3.2 Elongated structures

A closer study of the HST images of PNe (image credit: NASA and the Hubble Heritage Team, figures 2-15, 17, 18, 20, 22, 23) reveals a great variety of shapes in the nebulae. Most PNe show evidence of some sort of lumpy nature where plasma, in many cases containing dust grains, is often collected in long streaks. In this investigation a two-dimensional *elongated structure* (seen in emission or absorption) will be defined as a structure having an aspect ratio (maximum length to maximum width) of at least 4. An almost infinite variety of formations of such structures may be imagined, such as straight single features, wavy streaks, structures forming a network, sinusoidal shapes etc. However, at a closer inspection the different shapes found in the PNe studied seem to be limited to certain classes with different prominent signatures. Most of the structures discovered are shown in emission rather than absorption. Possibly this may be explained by the fact that a bright filament is easier to detect than a dark one.

3.3 Common shapes found

The fourth column of Table I lists the different elongated structures found in the studied PNe. *V-shapes* are elongated structures whose appearance resembles the letter V, with two branches stretching out from an apex which is most frequently directed towards the central star. These objects are often small and found near the rim of the nebula, but larger V-shapes occur too. Another common feature is a formation of three branches, connecting in an apex, and bearing the resemblance of the letter Y. This *Y-shape* is often oriented with the stem of the Y directed towards the center of the nebula. *Sinusoidals* are elongated structures showing evidence of a more or less regular, wavy nature. They are most likely to be found near the edge of the shell, often with the wavy structure being directed tangentially. In several

PNe *web structures* are found, where intertwining thin elongated structures form a network with no obvious regular internal pattern detected. Some V-shapes seem to have two smaller outgrowths from the end of the stem, turning the whole structure into a *wrench*-like formation. Other common structures are *arcs* and *azimuthal braids*, where the former can be found in some of the haloes surrounding the PNe and the latter in the shell of the nebulae, shaped as two or more filaments, directed in an azimuthal direction to the central star, crossing each other, and thus resembling a two-dimensional braid.

3.4 Selected PNe

NGC 2440

This nebula, consisting of a pair of bipolar lobes, is found at a distance of about 1.1 kpc (Strasbourg-ESO Catalogue), and contains many large-scale, elongated structures (Figure 2). Some of the most prominent structures are marked in the image. V-shapes, Y-shapes and sinusiodals are found and marked with the letters v, y and s, respectively. The structures have an average width of ~ 100 ua and a projected length of ~ 2000 ua. It is to be noted that all V- and Y-shapes seem to be directed towards the central star. Furthermore, the elongated structures are distributed over the entire nebula, but the V-shapes seem to occur at a smaller radial distance from the central star than the Y-shapes do.

NGC 6369 – The Little Ghost Nebula

In the Little Ghost Nebula prominent two-dimensional micro-structures are found in the inner part of the outer shell (see Figure 3 for some marked V- and Y-shapes). These structures bear a resemblance to the elephant trunks in the H II regions, with the difference that the elephant trunks appear in emission rather than in extinction. Other structures have also been detected in this nebula, such as azimuthal braids in the outer parts of the shell as well as in the surrounding halo. The elongated structures have a typical length of about 3000 ua and width of about 500 ua.

NGC 6302 – The Bug Nebula

In this bipolar nebula the elongated structures are less numerous but of a relatively large scale. At an adopted distance of 0.54 kpc (Strasbourg-ESO Catalogue) the structures have a projected length of more than 10 300 ua in some cases, which is comparable to half the size of the nebula itself. Most of the structures are directed towards the central star, many of them being wavy and overlapping (see region A in Figure 4). Other structures are Y-shapes with the stem directed both towards the center (marked with y), and away from it (marked y') as well as V-shapes (marked with v). The width of the elongated structures is of the same order of magnitude as found in other

PNe. From an image taken of the whole nebula with the Very Large Telescope (VLT UT1 First Light Photo No.4, European Southern Observatory) it is clear that the upper lobe contains as many elongated filaments as the lower lobe studied in detail with HST.

NGC 6751 – The Glowing Eye Nebula

This PN contains numerous elongated structures formed as V- and Y-shapes of cooler gas surrounded by a hotter region, as shown in Figure 5 a, taken with filters centered at [O III] and [N II] lines and at the photometric V-band filter. All V- and Y-shapes have their apex or stem directed towards the central star, see Figure 5 b and c for an enlarged image of one of the Y-shapes. On the inner edge of the shell several smaller V-shapes are found, whereas the larger structures seem to be stretched from this shell further in towards the center.

NGC 6543 – The Cat's Eye Nebula

This complex object is a point-symmetric nebula (Figures 6, 20) at a distance of about 1.3 kpc (Strasbourg-ESO Catalogue). The inner ring surrounding the central star contains a network of structures, a web, with many Y-shapes pointing with the stem towards the central star. The average width of these structures is here found to be ~ 180 ua. A bit further out many V- and Y-shapes are found in the rim of the outermost regions. Concentric rings are found surrounding this nebula, and a number of jets are shooting out radially from it. For a further study, see Section 4.3.

NGC 2392 – The Eskimo Nebula

In the constellation Gemini is this spectacular PN to be found (Figure 7), at a distance of 1.0 kpc (Strasbourg-ESO Catalogue). The Eskimo Nebula is divided into two main parts. Innermost there is a central bright ring of diameter $\sim 17''$ (17 000 ua) filled with curved structures. A bit further out there is another circular thick ring, reaching out to a diameter of $\sim 50''$ (O'Dell et al. 1990). Within this there are plenty of bright, radial jet-like structures and lumps, evenly distributed around the nebula. Among the V-shapes, Y-shapes, wrenches and sinusoidals it can be noted that none seem to have a particularly wavy nature, as found in previous nebulae. In the network of structures within the inner ring there are also a few possible V- and Y-shapes to be found.

NGC 6720 – The Ring Nebula

The Ring Nebula (Figure 8) has an apparent dimension of 1.4 arc minutes corresponding to $\sim 6.7 \times 10^4$ ua, at a distance of 0.8 kpc (Strasbourg-ESO Catalogue). The halo, shown in Figure 16, has a size of $\sim 1.2 \times 10^5$ ua (Corradi et al. 2003). The central part of the Ring Nebula appears to completely lack elongated structures but in the shell there are plenty of small-scaled

structures, mostly V- and Y-shapes, seen in extinction against the bright background of the PN. They all seem to start in the shell and stretch about the same distance inwards to the inner part of the nebula, with a projected width and length of ~ 200 and ~ 2000 ua, respectively. A closer study of the image reveals that they are evenly distributed around the nebula, and all are directed towards the central star.

Henize 2-104 – The Southern Crab Nebula

This nebula (Figure 9) takes the shape of one smaller hour glass placed in the center of a larger one of a projected size of about 5.2×10^5 ua (Corradi et al. 2001). The outer nebula is glowing of emission lines of mainly ionized nitrogen and built up of elongated structures. Many sinusiodals, V-shapes and Y-shapes can be found, directed radially towards the star. In the inner nebula there are more azimuthal braids.

IC 4406 – The Retina Nebula

The Retina Nebula (Figure 10) is a bipolar nebula with a thick equatorial ring that is viewed from almost in the plane of its equator (O'Dell et al. 2003). There is an irregular pattern of dark lanes running across the nebula, forming a network of dense (~ 1000 times as dense as the surrounding hot glowing gas) lanes (O'Dell et al. 2002). Several V- and Y-shapes can be found within this web of structures, many of them (but not all) pointing with the apex or stem towards the central star. At a distance of 1.6 kpc (Strasbourg-ESO Catalogue), the filaments have a width and length of ~ 250 ua and 9 700 ua, respectively.

NGC 3132 – The Eight-Burst Nebula

The image of the Eight-Burst Nebula (Figure 11) shows an elliptical nebula with a characteristic structure running across it like a waistband (marked with Y1 in Figure 17). In the upper part the structure is divided into two branches, like a Y-shape. To the right of the central stars (constituted by a binary system with the white dwarf being the fainter star shown to the upper right of the two) there is yet another long structure, also running across the whole nebula, from the top part of the shell to the bottom. In the rim of the shell there are several smaller structures, such as V- and Y-shapes and sinusiodals to be found, as well as azimuthal braids. See Section 4.2. for a further study.

NGC 7293 – The Helix Nebula

Close to the inner rim of the shell of this nebula (Figure 12) there are about 3 500 finger-like structures stretching inwards towards the center. These condensations, or cometary knots, have a width of ~ 820 ua and length of $\sim 12\,400$ ua. They are shaped like comets, with the "neutral" knot having a surface, glowing in emission, facing the central star, and a dark tail pointing

radially outwards. However, many of these tails are not straight, but possess a wavy, sinusoidal nature. Further out in the shell more V- and Y-shapes have been detected. A three-dimensional interpretation of the knots is offered in Section 4.4.

NGC 7009 – The Saturn Nebula

The Saturn Nebula (Figure 13) is an elliptical nebula placed at a distance of ~ 1.0 kpc (Strasbourg-ESO Catalogue). It contains a jetlike system of two collimated outflows and several knots and rims within the nebula have been found (Gonçalves et al. 2003). Except for these larger structures there is also a web of elongated structures near the center of the nebula. These shapes have a typical width and length of ~ 660 ua and ~ 5000 ua respectively, but no clear internal pattern can be detected.

IC 418 – The Spirograph Nebula

A clear structural pattern can be seen in the Spirograph Nebula (Figure 14). The whole visual nebula is covered with a network of sinusiodals, V- and Y-shapes, braids and web structures, that are lying so closely together that it is difficult to distinguish between them.

NGC 6853 – The Dumb-bell Nebula

This nebula (Figure 15) was the first PNe to be discovered, as it was found in 1764 by the French astronomer Charles Messier. Within this nebula there are several lumps and cometary knots similar to those in the Helix nebula. Many of these elongated structures are seen in extinction against the background radiation, and they are particularly present in the dumb-bell-like part of the nebula. In the shell of this part there are several extended azimuthal braids to be seen. The width of the structures is ~ 600 ua, and thus of the same order as the width of the knots of the Helix Nebula.

3.5 A comparison of NGC 6751, NGC 2392 and NGC 7293

A more detailed comparison of three of the studied PNe, the Glowing Eye Nebula, the Eskimo Nebula and the Helix Nebula, has been undertaken. They are all examples of elliptical nebulae with similar large-scale morphologies, where radially directed, elongated structures appear in emission (the Eskimo Nebula and the Glowing Eye Nebula) or extinction (the Helix Nebula). The radial structures start in the shell of the nebula, and avoid the central parts, except for the Eskimo Nebula, where a ring containing a network of lanes is surrounding the white dwarf. In all three nebulae the structures are evenly distributed in all directions of the two-dimensional field of view around the central star. The most common features found are sinusoidals, V- shapes and Y-shapes. In the Helix Nebula, which is the largest and most nearby nebula of the three, the largest amount of elongated structures have

been detected, whereas there are fewer found in the other two nebulae. The Eskimo Nebula contains mainly straight, jet-like structures rather than wavy sinusoidals. These structures are also common in the Helix Nebula, but there are also structures which seem to be wavy, as well as V- and Y-shaped. In the Glowing Eye Nebula clear, wavy V- and Y-shapes are found, and this nebula shows evidence of a more lumpy nature, with relatively larger structures.

3.6 Occurrence of elongated structures

All the PNe studied show some evidence of elongated structures, but in some PNe they are more frequent. There are also PNe where hardly any internal features can be detected. One example is Abell 39 in the constellation Hercules. The spatial properties of the elongated filaments detected in terms of length and width is of the same order of magnitude in all PNe, although a larger variation of the length is found due to projection onto the two-dimensional celestial plane.

3.7 Inner structure

Many of the filaments found have been named sinusoidals, V- and Y-shapes, and so forth, indicating the general appearance of the structure, but these terms do not reveal if there is also an internal pattern to be found. An enlargement of the images indicates that most of the elongated structures are composed of smaller parts that connect to each other. In this study a row of lumps lying closely together is considered to form an elongated structure, as long as that whole configuration complies with the requirements of the above mentioned definition of a such. The elongated structures are also observed to have twisted inner structures, as if the filaments are either twisted around each other, or just around itself, or even both of these possibilities at the same time. This is particularly common in the Y-shapes, something that has a logical explanation in the double helix mechanism.

3.8 Structures in the haloes

It is not only within the PNe that structures can be detected, but also in the haloes surrounding them, in the case a halo exists. When investigating the displayed images in Corradi's image database of Planetary Nebulae Haloes (Corradi et al. 2003) many large-scale structures are found. Common features are for example radially directed streaks as well as arcs. All images of haloes were obtained by ground-based telescopes, something that could explain the lack of similar micro-structures as the ones found within the nebulae with the HST. The Spitzer Space Telescope recently captured the halo of the Ring nebula (NGC 6720) and with the greater resolution more filaments were revealed and the shape and details of them became more prominent (see Figure 16). It is plausible that most haloes would reveal a

detailed intrinsic pattern, if observed with a better resolution.

Another example of a truly filamentary halo is found surrounding NGC 6543 (see Figure 21). Even though this image is taken with the ground-based Nordic Optical Telescope (NOT) many clear structures can be studied in detail (see section 4.3. for a further analysis).

4 Three-dimensional interpretations

In the three-dimensional analysis of the elongated structures found in the images, several conceivable interpretations exist. In this section possible configurations are discussed and physical conditions of the filaments are considered. Measurements of extinctions have been undertaken, leading to masses of the filaments. Furthermore, magnetic field strengths and electric currents in the filaments have been estimated. Three PNe have been chosen for a closer study, namely NGC 3132, NGC 6543 and NGC 7293.

4.1 Physical conditions in PNe

In the innermost region of PNe as well as in the X-ray bubble (see Figure 1) the atoms are fully ionized, due to the radiation from the central star and shock heating. In the shell it can be assumed that more than 50 % of the atoms are ionized. Mutual collisions of electrons in the gaseous nebulae lead to Maxwellian velocity distribution, characterized by the kinetic electron temperature, T_e . The electrons loose their energy mainly through excitation of forbidden lines. By comparing the line intensity ratios of certain emission lines T_e can be determined. Observations show that temperatures in PNe range over six orders of magnitude, from the cold dusty filaments of ~ 10 K (Huggins et al. 1992) to the hot X-ray bubble shown in Figure 1 of $\sim 10^7$ K (Kwok 2000). An average value of T_e of 10^4 K in the shell of a PN is chosen (Gurzadyan 1997). The same procedure is used to determine the electron density, n_e , which also varies over a large range, from the dense filaments of $\geq 10^{11} \text{ m}^{-3}$ (Huggins et al. 1992) to the low-density halo. A value of $7 \times 10^9 \text{ m}^{-3}$ in the shell of the PNe is used (see below for details). From T_e and n_e the Debye length

$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T_e}{e^2 n_e}} \quad (1)$$

can be determined, where ϵ_0 , k_B and e are the permittivity of free space, Boltzmann constant and electric charge, respectively. The value of λ_D obtained for the shell is 0.08 m, which is negligible compared to the characteristic dimension l_c of the shell of PNe. Thus the criterium for a plasma, $\lambda_D \ll l_c$, is well fulfilled in the shell.

To calculate the average density of the shell of PNe the mass of a PN of $M_{PN} = M_\odot/3$ is used (Balick & Frank 2004). If the shell is assumed to be doughnut-shaped rather than spherical, the volume of the shell is approximately $4\pi r_{PN}^2 \times \Delta r \times \frac{1}{3}$, where the volume of the spherical shell has been reduced by a factor 2/3. With a thickness of the shell of the PN of $\Delta r = \frac{1}{10} r_{PN}$, where $r_{PN} = 5 \times 10^{15} \text{ m}$, being the average distance to the swept-up shell, the volume is approximately $V_{PN} = 5 \times 10^{46} \text{ m}^3$. From this

the density of the shell, $\rho_{\text{PN}} = 1.3 \times 10^{-17} \text{ kg/m}^3$, as well as the particle density $n \approx n_e = n_i = \rho_{\text{PN}}/m_{\text{av}} = 7 \times 10^9 \text{ m}^{-3}$ is deduced, where it is assumed that the average mass of the ions, m_{av} , is $\sim 2 \times 10^{-27} \text{ kg}$.

The strength of the magnetic fields in PNe is hard to measure, as the Zeeman splitting of the emission lines of ionized gas is drowned in thermal broadening (Balick et al. 2002). To estimate the magnetic field strength in the shell of PNe two different methods will be used here. In the first method a freely expanding stellar wind with a speed $u_{\text{AGB}} \approx 10 \text{ km/s}$ (Kwok 2001) from the initial AGB star is assumed. The magnetic field lines are well frozen into the plasma, see Appendix A.2. The surface magnetic field strength of the AGB star is known to be $B_S \approx 4 \times 10^{-3} \text{ T} = 40 \text{ G}$ and has a characteristic radius, r_{AGB} , of $\sim 3 \times 10^{11} \text{ m}$ (Pascoli 1997). The radial magnetic field strength $B_{W,r}$ in the wind is inversely proportional to the distance squared

$$B_{W,r} = B_S \left(\frac{r_{\text{AGB}}}{r} \right)^2. \quad (2)$$

With $r = r_{\text{PN}} = 5 \times 10^{15} \text{ m}$, the radial component of the magnetic field in this region is $B_{\text{PN},r} = 1.4 \times 10^{-11} \text{ T}$.

As the star rotates with the angular velocity ω_{AGB} the magnetic field lines will be formed into an Archimedes spiral, just as in the solar wind. The angle between the spiral and the radial direction is

$$\psi = \arctan \frac{\omega_{\text{AGB}} r_{\text{PN}}}{u_{\text{AGB}}} \quad (3)$$

at the distance r_{PN} . PNe originate from low-mass stars ($M < 8 M_{\odot}$), which have an angular velocity in the range $20 - 200 \text{ km/s}$ in the plane of the equator. For a B5 star, with a mass of $\sim 6.5 M_{\odot}$, and a radius of $\sim 3.8 r_{\odot}$, the angular velocity is $\sim 200 \text{ km/s}$. It is here assumed that the angular momentum at the different stages of this star is conserved, yielding an angular velocity of the AGB star, ω_{AGB} , at r_{AGB} of $5.9 \times 10^{-9} \text{ s}^{-1}$. When inserting this into eq. (3) it is found that the magnetic field lines are inclined to the radial direction an angle of $\psi \approx 89.98^\circ$, giving an azimuthal magnetic field strength in the AGB wind at r_{PN} of $B_{\text{PN},\phi} = 4.1 \times 10^{-8} \text{ T}$.

With an AGB mass-loss $\dot{M} \approx 10^{-5} M_{\odot} \text{ yr}^{-1}$ (Balick & Frank 2002), the density of the nebula at a radius r_{PN} is

$$n(r_{\text{PN}}) = \frac{\dot{M}}{m_{\text{av}} u_{\text{AGB}} A} \quad (4)$$

where m_{av} is the average mass of an ion, u_{AGB} is the velocity of the stellar wind and A is the area of the shell, $A = \frac{4}{3}\pi r_{\text{PN}}^2$, where a doughnut-shaped shell is again assumed, reducing the area by a factor $2/3$. From

this a density at r_{PN} of $3 \times 10^8 \text{ m}^{-3}$ is obtained. However, there is a compression of the medium as the faster stellar wind from the white dwarf interacts with the slower AGB wind, creating a higher density shell. The real value of this density is estimated to be $\sim 7 \times 10^9 \text{ m}^{-3}$, as shown above, and the magnetic field lines, that are considered to be well frozen into the plasma (see Appendix A.2), will be compressed to the same extent as the plasma. A better estimation of the magnetic field strength is thus $(7 \times 10^9 / 3 \times 10^8) \times B_{PN,\phi} = 9.6 \times 10^{-7} \text{ T}$.

The magnetic field strength in the shell of a PN originating from a star of $M = M_{\odot}$ and $r = r_{\odot}$ has also been calculated. The angular velocity is then assumed to be 20 km/s and the radius of the AGB star, $r_{AGB} \sim 1.5 \times 10^{11} \text{ m}$. With these values a magnetic field strength $B_{PN} = 2.6 \times 10^{-8} \text{ T}$ is obtained. Thus, the magnetic field in the shell of a PN is approximately in the range $2.6 \times 10^{-8} \text{ T} \leq B_{PN} \leq 9.6 \times 10^{-7} \text{ T}$.

The second method for estimating the magnetic field strengths in the shell is by using energy equipartition. The time characterizing the exchange of energy between electrons and ions is found to be of the order of 10^3 hours (see appendix A.1), which is small compared to the age of the nebula. Thus T_e and T_i are expected to be the same. The thermal plasma pressure and energy density is obtained through

$$p_{PL} \approx 2nk_B T \quad (5)$$

where $T = T_e = T_i \approx 10^4 \text{ K}$. This gives a total thermal energy density of the plasma of $1.9 \times 10^{-8} \text{ J/m}^3$. The magnetic energy density of the plasma is

$$p_m = \frac{B^2}{2\mu_0}. \quad (6)$$

Energy equipartition then gives $B = 4.9 \times 10^{-8} \text{ T}$.

If there is convection in the plasma with ten times larger energy density than p_{PL} (cf. molecular clouds), energy equipartition then yields $B = 1.6 \times 10^{-7} \text{ T}$.

Both of these methods give a resulting magnetic field that is approximately in accordance to the values found in the literature of $10^{-8} - 10^{-7} \text{ T}$ (Lang 1999). A value of $B = 10^{-7} \text{ T}$ will be used in the further calculations.

4.2 NGC 3132 — The Eight-Burst Nebula

One particularly interesting PN to study in three-dimensions is the Eight-Burst Nebula, which possesses striking filamentary features. When studying the main filament in this nebula (marked with Y1 in Figure 17 and shown

in Figure 18) in more detail, it is clear that it is constituted by lumps of gas and dust. The filament runs across the whole nebula, but the upper part of this elongated structure is darker than the lower, with a clear transition in intensity about halfway through the nebula. This indicates that the upper part is a Y-shape that ends where the transition occurs. The two branches, stretching down from the shell and joining in the stem of the Y, have a characteristic width of 0.3" and a total length of approximately 18". At a distance of 1.1 kpc (Strasbourg-ESO Catalogue) this corresponds to 360 ua and 2×10^4 ua, respectively. The uniformity of the width of the filaments studied indicates cylindrical shapes.

In order to find the masses and densities of the filaments considered extinctions have been measured from images taken with different filters (see Section 4.5 and Appendix B for details of the measurements and calculations). For the main Y-shaped filamentary structure in NGC 3132 a density of 8.1×10^{10} atoms/m³ and a mass of 3×10^{27} kg was found.

From the dimensions of the filaments it is possible to estimate the magnitude of the electric current in the filament. If the twisting of the filament (caused by convection) is assumed to be such that the inclination angle of the magnetic field lines is approximately 45° at $r = R_0$ near the surface of the cylinder (cf. Carlqvist et al. 2003), the toroidal component of the magnetic field, B_φ , is of the same magnitude as the axial component. The B_φ component corresponds to a current in the filament, of

$$I = \frac{2\pi R_0 B_\varphi}{\mu_0}. \quad (7)$$

A filament is approximately ten times denser than the surrounding shell. Because of frozen-in magnetic field lines the magnetic field will thus be compressed as much, yielding a toroidal magnetic field in the filament, $B_{\varphi,fil}$, of $10 \times B = 10^{-6}$ T. With a radius of the filament of $R_0 = 1.5 \times 10^{13}$ m the current is 7.5×10^{13} A. This may be compared to the electric currents found, $I_p \approx 10^{11} - 10^{12}$ A, in the much smaller prominences on the sun.

The two filaments constituting the branches of Y1 could be situated at different distances along the line of sight. It is however more likely that they are meeting in the same point, the apex, and from there twisting around each other downwards. This is based on the observation that the two filaments seem to repeatedly overlap each other, just as if they were twisted. The fact that many Y-shapes are found in the two-dimensional analysis and most of them seem to contain an internal pattern is supporting this. If instead Y-shapes are created by two filaments being observed in the same line of sight but placed at a far distance from each other, that would not explain the change of direction of the filaments in the apex of the Y. Instead an X-shape

would be detected. X-shapes occur but are not that frequent.

If this structure, resembling a Y, is caused by the double helix mechanism, one might think that it should be directed towards the central star. However, this is not what is being observed. To find an explanation to this it is necessary to study the morphology of the PN. Several models have been developed to account for the shape of NGC 3132. In one of them (Reimers et al. 2000) it is believed that (in the ISW-model) there is an angle-dependent mass loss from the central star, causing the matter to concentrate in the equatorial plane of the PN and create a weakly bipolar shape of the nebula. As these two bubbles are expanding outwards by pressure from the plasma outflows, any structure connected to the surface of the bubbles would not be directed towards the central star, but rather along the pressure gradient, perpendicular to the surface. This is exactly what is being observed, supporting the hypothesis of a bipolar shape. The two fainter rims running across the nebula on opposite sides of the binary system could then possibly be interpreted as being the intersection of the bubbles, and the central part of the nebula.

Another possible three-dimensional interpretation of the Y-shaped elongated filament could be that the structure is not directed inwards from the boundary surface but is rather lying on it. A support for this view comes from the azimuthal braids found on the inner rim of the shell of the nebula, shaped like long filaments running more or less all the way around the PN. However, in contradiction to this view is the fact that the Y-shaped structure does not resemble the braids. Still another possibility is that the structure is part of the fainter filament crossing the nebula and shown behind and beneath it. Nevertheless, the clear transition of brightness between the Y-shape and the fainter filament is suggesting that they are two individual, separate objects.

It is interesting to note that the smaller V- and Y-shapes found in the shell of the nebula are all pointing in a direction perpendicular to the shell rather than towards the central star. This, together with the remarkable resemblance between the main filament and the analogy model shown in Figures 18 and 19 is supporting the theory of the filaments being created through the double helix mechanism.

4.3 NGC 6543 — The Cat's Eye Nebula

The Cat's Eye Nebula is an extraordinary and complicated PN with many filamentary structures. The central ring (Figures 6 and 20) is most probably constituted by a bubble, on which a network of structures is seen. Several of the filaments seem to be twisted and pointing in a radial direction towards the central star, but many of them also appear to follow a net on the surface

of the bubble. Possibly, structures are stretching from the surface net into the bubble. Other bubbles are overlapping this central bubble in the two-dimensional image, mainly one at the top and one at the bottom. Elongated structures within these are also seen through the central bubble. Similar regions have been detected in the Eskimo Nebula, where the central ring surrounding the white dwarf bears a great resemblance to this bubble, with many filaments within it (Figure 7). Also the Retina Nebula is containing a similar pattern.

Several large-scaled filaments can be seen in NGC 6543. These are outlining the surface of the bubbles. From these, there are smaller V- and Y-shapes originating, all directed perpendicular to the surface itself. These structures are of low ionization ($O^+/O \sim 1$) and of a high density ($n_e \geq 10^{10} \text{ m}^{-3}$), whereas their temperatures are comparable to the rest of the nebula (Balick 2004). A few larger structures, shown in emission, are pointing inwards from these surfaces (marked with Y1 and Y2 in Figure 20). The righthand one (Y2) is lumpy and with a clear twist, whereas Y1 is fainter. Just like the filament in NGC 3132 Y2 is not pointing towards the central star, but rather perpendicular to the surface of the bubble.

One of the most interesting parts of NGC 6543 is its halo (Figure 21), which is completely built up by filaments. This matter is constituted by earlier, slower AGB mass ejections. Most structures are seen either directed radially or in the azimuthal direction. The interpretation of the azimuthal filaments is most likely that they represent filaments lying on the surface of expanding shells. The matter furthest out in the PN is not yet affected by the fast stellar wind from the central star. When these regions run into the interstellar medium the mass condensations within it have a greater momentum and are not slowed down as much as the less dense parts. V-shapes are created, but now with the apex pointing outwards. Twisted Y-shapes, with the stem pointing outwards instead of towards the central star, are also found (see structure denoted Y1 in Figure 21).

4.4 NGC 7293 — The Helix Nebula

The dense cometary knots in this nebula are seen in extinction against the background radiation, with a photoionized surface facing the central star, and a tail pointing radially outwards. Hence, the name cometary knots.

Several models have been developed to account for the shapes of these structures. One scenario is that the knots are formed in the atmosphere of the red giant progenitor, and then carried out by the expanding envelope (Dyson et al. 1989). The tail of the knot is then considered to be created by a radially directed stellar wind sweeping matter from the globule into

the tail. However, CO-velocity measurements carried out by Huggins et al. (2002) show that the velocity of the CO emission in the tail is nearly the same as in the dense knots. The relative velocity of the matter in these outflows is therefore not sufficient to produce the long tails observed. An alternative view is provided by the photoevaporation model, where the surface gas on the knot is ionized by the radiation from the central star, and an ionized outflow is produced (López-Martin et al. 2001). According to Huggins et al. (2002) the ambient gas, with a density of $\sim 5 \times 10^7 \text{ m}^{-3}$, is much too thin compared to the dense knots to affect the shaping of the tails. A different possibility for creating a tail behind a preexisting knot is by shadowing (Cantó et al. 1998). Underpressure of gas in the region shadowed from radiation by the globule would then create the tail. However, this shadowing can only account for modest density increases in the tail, and can not explain the substantial molecular tails found by Huggins et al (2002). An alternative scenario for the shaping of the elongated structures is that they are products of the Rayleigh-Taylor instability at the ionization front (e.g. Capriotti 1973). As this front moves outwards in the nebula the knots are left behind.

Here, another mechanism for the creation of the cometary knots will be discussed in some more detail. When looking closer at several of the structures it is clear that not all of them appear as a globule with a straight radially directed tail behind it. Instead many of the tails possess a wavy pattern or a sinusoidal shape. In some cases more than one filament are involved in the tail. Some of the wavy filaments can be seen in Figure 22. These shapes can not be accounted for by any of the existing models. Further out in the nitrogen shell of the nebula the filament shown in Figure 23 is found. This structure is clearly not straight but wavy, and one way of interpreting the three-dimensional appearance of it is indicated in Figure 24. The filament is here interpreted to be twisted into a double helix, pointing towards the center of the nebula. Even straight structures in the Helix Nebula may be interpreted in terms of the double helix mechanism as being narrow V-shapes, or twisted internal structures seen with insufficient resolution. In this new model of the formation of cometary knots shadowing and ionized outflows may still play a role.

In the ISW-model the PN consists of several regions: Fast stellar winds closest to the white dwarf, followed by an inner shock, and a hot X-ray emitting bubble reaching out to the shell of the nebula. Furthest out is the halo (Figure 1). It is of interest to investigate at what radial distance the position of the inner shock front is situated, to see whether the cometary knots are placed within the X-ray bubble or not. It is assumed that the X-ray region is dominated by thermal pressure, which is balanced by the dynamic pressure, p_d , of the fast stellar wind at the inner shock front. The dynamic pressure

is given by

$$p_d = \rho(r)u^2, \quad (8)$$

where u is the radial velocity of the stellar wind, and the density is

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 u} \quad (9)$$

Combining eq. (8) and eq. (9) gives the expression for the dynamical pressure,

$$p_d = \frac{\dot{M}u}{4\pi r^2}. \quad (10)$$

With the mass loss of the star $\dot{M} \approx 10^{-8} M_{\odot} \text{yr}^{-1}$ (Balick & Frank 2002) and $u \approx 3000 \text{ km/s}$ (Kwok 2001), $p_d \approx 1.5 \times 10^{20} \times r^{-2}$ is obtained.

The particle density of a cometary knot is $n_C \approx 2 \times 10^{12} \text{ m}^{-3}$ (O'Dell et al. 1996) and the temperature $T_C \approx 30 \text{ K}$ (Huggins et al. 1992). The thermal plasma pressure is then $p_{th} = n_C k T_C \approx 8 \times 10^{-10} \text{ Pa}$. By assuming a pressure equilibrium between the knots, if placed in the hot X-ray bubble, and the surrounding plasma the thermal pressure in this bubble can be determined. Putting the thermal pressure equal to the dynamic pressure of the stellar wind, gives the radius of the inner shock, $R_S = 4 \times 10^{14} \text{ m}$. Since the cometary knots are placed at a radius of $200'' \approx 6 \times 10^{15} \text{ m}$ (O'Dell et al. 2004) they are found far inside the hot X-ray bubble, as assumed.

In these rough calculations no consideration to the magnetic fields has been taken. The magnetic pressure has been accounted for in calculations on stellar wind bubbles by Chevalier & Luo (1994). It is then found that the thermal and magnetic pressure vary with the radius r . The thermal pressure decreases with the radial distance, whereas the magnetic field strength grows until the point where the magnetic pressure starts dominating the total pressure in the plasma. At a larger radial distance the magnetic pressure is still dominating, but is decreasing due to magnetic tension. Close to the surrounding swept up shell the magnetic and thermal pressure contribute to the total pressure with approximately equal amounts. At the innermost shock front the magnetic pressure is insignificant compared to the thermal pressure, thus a neglect of the magnetic pressure is here legitimate. In this investigation it has further been assumed that the cometary knots are placed in the region still dominated by thermal pressure.

In the hot ($T \approx 3 \times 10^7 \text{ K}$ (Kwok 2000)) X-ray bubble the ions, with an average mass of $2 \times 10^{-27} \text{ kg}$, have a thermal velocity of $v = \sqrt{kT/m} \approx 4.6 \times 10^5 \text{ m/s}$. With a distance from the inner shock to the knots of approximately $6 \times 10^{15} \text{ m}$ it would take the ions ~ 400 years to travel this distance. This is relatively little compared to the age of the nebula, thus it can be assumed that the pressure in the plasma is isotropic.

4.5 Extinction measurements

The mass and density of a cometary knot in NGC 7293 and the filament in NGC 3132 are determined through extinction measurements. From images taken of PNe with the Wide Field Planetary Camera 2 (WFPC2) on HST it is possible to measure the extinction caused by a filament, and thus obtain its column density and the mass of the dust component. These measurements are carried out in SAOImage DS9, an astronomical imaging and data visualization application. It is assumed that the extinction law is the same in PNe as for normal interstellar clouds (Savage et al. 1979):

$$A_\lambda/E(B-V) = E(\lambda-V)/E(B-V) + R \quad (11)$$

A_λ is the total extinction at a wavelength λ , $E(\lambda-V)$ refers to the extinction in magnitudes between the wavelength λ of the filter used, and the V band of the photoelectric UBV system. $E(B-V)$ is the $(B-V)$ colour excess in magnitudes. $E(\lambda-V)/E(B-V)$ is plotted as a function of $1/\lambda$ in Figure 25, and $R = A_V/E(B-V) \approx 3.1$. By measuring the intensity of the filament (I) and the background (I_0) the extinction is obtained through

$$A_\lambda = -2.5 \log (I/I_0) \quad (12)$$

and can be transferred to A_V by using eq. (11) (see Appendix B for details). It is here assumed that the gas to dust ratio is the same as in interstellar clouds, namely 100, and that the column density of molecular hydrogen is obtained through

$$N(H_2) = 9.4 \times 10^{24} A_V \quad (13)$$

(Harjunpää et al. 2004). The total mass of the molecular hydrogen is

$$M(H_2) = 2 \times 1.67 \times 10^{-27} N(H_2) \text{ kg/m}^2. \quad (14)$$

Finally, a cosmical chemical composition is assumed, and an additional 36% in mass, accounting mainly for He, is added. The total mass is $M = 1.36 M(H_2)$. By dividing $N(H_2)$ by the average depth of the filament the density in molecules/m³ is obtained. $N(H)$ is then $2 \times N(H_2)$. This constitutes 70 % of the matter and the rest can be considered to consist of mainly He atoms. From this the total density, N_{tot} , is derived.

These measurements and calculations were carried out for structures in the PNe NGC 3132 and NGC 7293 (see appendix B), yielding a density and mass for the main Y-shaped filament in NGC 3132 of $8.1 \times 10^{10} \text{ atoms m}^{-3}$ and $3.1 \times 10^{27} \text{ kg} = 1.6 \times 10^{-3} M_\odot$, and for the head of a cometary knot in NGC 7293 of $5.8 \times 10^{11} \text{ atoms m}^{-3}$ and $6.6 \times 10^{25} \text{ kg} = 3.3 \times 10^{-5} M_\odot$, respectively.

4.6 Model of a filament

A filament in a PN can be modeled as a straight cylindrical pillar of length l and radius R_0 , containing magnetized plasma. The filament is subject to convection, causing one end of the pillar to be twisted N turns. An initially homogenous magnetic field will be wound up into a helical geometry, since the magnetic field lines are well frozen into the plasma. If it for the sake of simplicity is assumed that the plasma is incompressible, the relationship between the axial magnetic field component, B_z , and the azimuthal component, B_φ , at the radius r is

$$\frac{B_z}{l} = \frac{B_\varphi}{2\pi r N}. \quad (15)$$

The presence of an azimuthal magnetic field component is equivalent to an electric current, I , running along the pillar. The total current in the filament is

$$I(r) = \int_0^{R_0} 2\pi i_z(r) r dr. \quad (16)$$

This can be simplified to $dI(r) = 2\pi i_z(r) r dr$ and thus

$$\frac{dI(r)}{dr} = 2\pi i_z(r) r. \quad (17)$$

Solving for B_φ from eq. (15) and inserting this into eq. (7) gives

$$I(r) = \frac{4\pi^2 N B_z r^2}{\mu_0 l}. \quad (18)$$

If it also here is assumed that the magnetic field in the filament is ten times larger than in the shell of a PN (see Section 4.2) and that a filament has a characteristic length and width of 10^{14} m and 10^{13} m, respectively, the total current in the pillar is $I \approx N \times 10^{13}$ A.

By inserting eq. (18) into eq. (17) it is found:

$$i_z = \frac{4\pi N B_z}{\mu_0 l}. \quad (19)$$

Consequently i_z is not dependent on r . For the magnetic field surrounding the filament to stay homogenous the net current of the filament must be zero. This is the case, since the current inside the filament is flowing on the surface of the pillar on its way back.

In this filament an internal thermal plasma pressure is being balanced by the outer thermal pressure in the hot X-ray bubble. The force keeping this pinch intact is mainly a radially directed force, produced by the axial current and the azimuthal magnetic field. The dust particles in the plasma can also

be considered frozen into the magnetic field lines, since they easily pick up free electrons and become a part of the plasma.

5 Conclusions

It has previously been established that magnetic fields play an important role in the shaping of PNe, although it is yet not clear exactly how they influence the variety of morphologies. In the ISW-model, with a fast stellar wind creating a shocked X-ray bubble, a magnetic field from the central star will be compressed in the shock front, causing a significantly stronger field in the bubble and the shell surrounding it. These are the regions in which filamentary structures, as defined in this work, have primarily been detected in the 14 PNe studied. It is thus most likely that the magnetic fields have influenced the shaping of the filaments to a great extent.

In the PNe many V- and Y-shapes are found, directed perpendicular to the surface of the bubble where they originate. Their shapes are often in agreement with the double helices found in H II regions and supernova remnants. Other shapes occur, for example sinusoidals and web structures. It is, however, possible to interpret the web structures as being filaments lying on the surface of the bubble/bubbles constituting the nebula. The V- and Y-shapes are believed to originate in these filaments, stretching inwards from the surface. Tangentially directed wavy structures may in some cases be thought of as many small-scaled V-shapes next to each other, viewed with a poor resolution. From the model of a filament made in this work it is clear that magnetic fields in a dusty plasma can create pinches. All elongated structures found in this investigation can be explained as such pinches, frequently twisted into double helices. The main filament in NGC 3132 is one likely example of a double helix consisting of twisted magnetic flux ropes, and containing a strong current.

The detection of the wavy nature of the cometary knots in the Helix Nebula is of considerable interest, as it has previously not been accounted for by any existing theory. The resemblance between the knots and the fingers previously found in the Crab Nebula by Carlqvist (2004) is striking. This observation, together with calculations of typical currents and magnetic field strengths, support the view that the cometary knots are caused by the double helix mechanism. It can be argued that the lack of similar wavy patterns of filaments in other PNe, such as the Eskimo Nebula, could be the result of a poorer resolution, as the Helix Nebula is one of the largest and closest PNe studied.

The extinction measurements conducted in NGC 7293 give reasonable values for the mass and density of a cometary knot, when compared with values obtained by Huggins et al. (1992) and Meaburn et al. (1992). One source of error could be the dust to gas ratio, which is unknown and here assumed

to be the same as in interstellar clouds. By using the same method for NGC 3132, values of the mass and density of the main filament in this nebula is obtained. The density is of the same order of magnitude as the density of the cometary knots, suggesting similarities between the structures.

To be able to apply the double helix mechanism to the filaments in PNe it is of great importance to estimate the magnetic field strength in these regions. In the first method used here it has been assumed that the AGB star has an angular velocity corresponding to the same angular momentum as its progenitor star. The surface magnetic field of the AGB star of 40 G was issued from calculations (Pascoli 1997), assuming a continuity of the magnetic field and its first derivative at the stellar surface. The magnetic field strength in the shell of a PN is by this method found to be $2.6 \times 10^{-8} \text{ T} \leq B_{PN} \leq 9.6 \times 10^{-7} \text{ T}$. In the second method energy equipartition between the magnetic pressure and the thermal pressure in the shell is assumed. With consideration of convection in the plasma the energy density is approximately ten times larger, leading in turn to an increase of the magnetic field. This method thus yields a magnetic field strength in the range $2.6 \times 10^{-8} \text{ T} \leq B_{PN} \leq 9.6 \times 10^{-7} \text{ T}$. The obtained values are in accordance to earlier estimated values of magnetic field strengths in PNe.

The approach presented here, coupling the filaments in PNe closely to magnetic fields provides a new model for the small-scale, elongated structures detected. The presence of double helices in PNe might also offer information on the strength and distribution of the magnetic fields, leading to a deeper understanding of the shaping of PNe.

References

- [1] Acker A., Ochsenbein F., Stenholm B., Tylenda R., Marcout J., Schohn C., 1992, *Strasbourg-ESO catalog of Galactic Planetary Nebulae*, ESO publications.
- [2] Alfvén H. & Fälthammar C-G., 1963, *Cosmical Electrodynamics, Fundamental Principles*, 2nd ed. Oxford U. Press.
- [3] Balick B., 1987, AJ, 94, 671-678.
- [4] Balick B., 2004, ApJ, 127, 2262-2268.
- [5] Balick B., Rugers M., Terzian Y. & Chengalur J.N., 1993, ApJ, 411, 778-793.
- [6] Balick B. & Frank A., 2002, ARA&A, 40, 439-486.
- [7] Balick B. & Frank A., 2004, ScA, 291, 27-35.
- [8] Cantó J., Raga A., Steffen W. & Shapiro P.R., 1998, ApJ, 502, 695-707.
- [9] Capriotti E.R., 1973, ApJ, 179, 495-516.
- [10] Carlqvist P., 2003, Ap&SS, 289, 47-53.
- [11] Carlqvist P., Gahm G. & Kristen H., 2002, Ap&SS, 280, 405-412.
- [12] Carlqvist P., Gahm G.F. & Kristen H., 2003, A&A, 403, 399-412.
- [13] Chevalier R.A. & Luo D., 1994, ApJ, 421, 225-235.
- [14] Corradi R.L.M., Schönberner D., Steffen M. & Perinotto M., 2003, MNRAS, 340, 417-446.
- [15] Corradi R. L. M., Livio M., Balick B., Munari U. & Schwarz H.E., 2001, ApJ, 553, 211-218.
- [16] Dyson J.E., Hartquist T.W., Pettini M. & Smith L.J., 1989, MNRAS, 241, 625-630.
- [17] Fälthammar C-G., 2001 *Plasmafysik*, 2nd ed. Stockholm.
- [18] Gonçalves D.R., Corradi R.L.M. & Mampaso A., 2001, ApJ, 547, 302-310.
- [19] Gonçalves D.R., Corradi R.L.M., Mampaso A. & Perinotto M., 2003, ApJ, 597, 975-985.
- [20] Gurzadyan G.A., 1997, *The physics and dynamics of planetary nebulae*, Springer.

- [21] Harjunpää P., Lethinen K. & Haikala L.K., 2004, A&A 421, 1087-1099.
- [22] Huggins P.J., Forveille T., Bachiller R., Cox P., Ageorges N. & Walsh J.R., 2002, ApJ, 573, L55-L58.
- [23] Huggins P.J., Bachiller R., Cox P. & Forveille T., 1992, ApJ, 401, L43-L46.
- [24] Kwok S., Purton C.R. & Fitzgerald P.M., 1978, ApJ, 219, L125-L127.
- [25] Kwok S., 2001, *Cosmic Butterflies, The colorful mysteries of planetary nebulae*, Cambridge U. Press.
- [26] Kwok S., 2000, *The Origin and Evolution of Planetary Nebulae*, Cambridge U. Press.
- [27] Lang K.R., 1999, *Astrophysical Formulae, Vol.1*, 3rd ed. Springer. Table 1.2.
- [28] López J.A., Vázquez R. & Rodríguez L.F., 1995, ApJ, 455, L63-L66.
- [29] López-Martin L., Raga A.C., Mellema G., Henney W.J. & Cantó J., 2001, ApJ, 548, 288-295.
- [30] Meaburn J., Walsh J.R., Clegg R.E.S., Walton N.A., Taylor D. & Berry D.S., 1992, MNRAS, 255, 177-182.
- [31] O'Dell C.R., Weiner L.D. & Chu Y., 1990, ApJ, 362, 226-234.
- [32] O'Dell C.R. & Handron K.D., 1996, AJ, 111, 1630-1640.
- [33] O'Dell C.R., Balick B., Hajian A.R., Henney W.J. & Burkert A., 2002, ApJ, 123, 3329-3347.
- [34] O'Dell C.R., Balick B., Hajian A.R., Henney W.J. & Burkert A., 2003, RMxAC,15, 29-33.
- [35] O'Dell C.R., McCullough P.R. & Meixner M., 2004, AJ, 128, 2339-2356.
- [36] Pascoli, G., 1997, ApJ, 489, 946-950.
- [37] Reimers C., Dorfi E.A. & Höfner S., 2000, A&A, 354, 573-578.
- [38] Savage B.D. & Mathis J.S., 1979, ARA&A, 17, 73-111.
- [39] Zanstra H., 1955, Vistas Astron, 1, 256-268.

APPENDIX

A Calculations of some plasma properties

A.1 Equipartition times

In the collisional interaction between an electron and an ion gas with Maxwellian velocity distributions and temperatures T_e and T_i respectively, the temperatures will approach each other according to

$$-\frac{dT_e}{dt} = \frac{T_e - T_i}{\tau_{eq}} \quad (20)$$

(Alfvén & Fälthammar 1963). The thermic energy exchange between electrons and ions is characterized by the equipartition time τ_{eq} . If T_e and T_i are of the same order of magnitude, then

$$\tau_{eq} = 0.517K \frac{m_i T_i^{3/2}}{Z^2 n_i m_e^{1/2}}, \quad (21)$$

where

$$K = \frac{(4\pi\epsilon_0)^2 (3k)^{3/2}}{0.714e^4 8\pi \ln \Lambda}. \quad (22)$$

The equipartition time can thus be calculated for the electron and proton gas in PNe, which have the characteristics:

the temperature $T_p \approx T_e = 10^4$ K,
the density $n_p = n_e \approx 7 \times 10^9 \text{ m}^{-3}$,
the nuclear charge $Z = 1$,
the mass $m_p = 1.67 \times 10^{-27}$ kg and
the Coulomb logarithm $\ln \Lambda \approx 20$ for $T_e = 10^4$ K.

This gives an equipartition time of $\tau_{eq} = 1.8 \times 10^3 \text{ s} = 30 \text{ min}$.

The equipartition time in the shell of a PN is much smaller than the average age of PNe ($\sim 10^4$ years) and therefore it can be assumed that the protons and electrons are in thermic equilibrium.

Equipartition times have been calculated for other ion gases in the PNe, such as [N II], [O III] and [S II], and are found to be of the same order of magnitude as for the protons. However, since the densities of the ion gases are much lower than that of the electron gas, and hence a temperature of the same order of magnitude can no longer be assumed, it is not possible to obtain completely reliable values.

A.2 The magnetic Reynolds number

The average distance an electron can travel freely in the plasma parallel to B before colliding with an ion is the mean free path given by

$$\lambda_e = 10^8 \frac{T_e^2}{n_e} \quad (23)$$

and is $\lambda_e = 1.4 \times 10^6$ m in the shell plasma, with $n_e = 7 \times 10^9 \text{ m}^{-3}$ and $T_e = 10^4$ K. Perpendicular to the field lines the electrons are limited to stay within the Larmor radius of ~ 20 m (see Appendix A.3). The characteristic dimension of the planetary shell is $l_c \sim 10^{14}$ m, and since $\varrho \ll \lambda \ll l_c$ this is a plasma of medium density. This implies that the magnetic field introduces a significant anisotropy in the plasma, leading to a highly anisotropic diffusion and electric conductivity (Alfvén & Fälthammar 1963).

The conductivity of a plasma of medium density is given by (e.g. Alfvén & Fälthammar 1963):

$$\sigma \approx \frac{e^2 n_e \tau_e}{m_e} \quad (24)$$

The collision time is given by

$$\tau_e = \lambda_e / v_{Te} \quad (25)$$

and is with $\lambda_e = 1.4 \times 10^6$ m and the thermal velocity $v_{Te} = 3.9 \times 10^5$ m/s $\tau_e = 3.6$ s. The conductivity is then found to be $\sigma = 710$ S/m.

By means of the conductivity the *magnetic Reynolds number* may be expressed as

$$R_m = \mu_0 \sigma l_c v_c \quad (26)$$

where μ_0 is the permeability of free space. With $l_c = 10^{14}$ m, $n_e = 7 \times 10^9 \text{ m}^{-3}$ and v_c equal to the expansion of the shell of 2×10^4 m/s, $R_m = 1.8 \times 10^{15}$ for the shell plasma, which indicates that the magnetic field lines are well frozen into the plasma. From the magnetic diffusion equation

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \Delta \mathbf{B} \quad (27)$$

it is found

$$\tau \approx \mu_0 \sigma l_c^2 \quad (28)$$

yielding the frozen-in time $\tau \approx 3 \times 10^{17}$ years, which is much greater than the age of the PN. The diffusion of the magnetic field lines is thus negligible.

A.3 Other parameters of the plasma

The plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad (29)$$

only depends on the electron density and for the plasma in the shell of a PN $\omega_{pe} \approx 4.7$ MHz.

Knowing the magnetic field strengths in the shell of PNe it is possible to obtain other parameters for the plasma, such as the Larmor radius

$$\varrho = \frac{mv_{\perp}}{|q|B} \quad (30)$$

where $v_{\perp}$ is the speed of the particle perpendicular to the magnetic field and q is the charge. As regards the magnetic field, $B = 10^{-7}$ T is adopted. With $T_e = T_i = 10^4$ K the electrons and ions (protons) have a thermal velocity $v_{Te} = 3.9 \times 10^5$ m/s and $v_{Ti} = 9.1 \times 10^3$ m/s, respectively. 2/3 of the kinetic energy is perpendicular to the magnetic field, thus $v_{Te,\perp} \sim \sqrt{2/3} \times v_{Te} = 3.2 \times 10^5$ m/s and $v_{Ti,\perp} \sim \sqrt{2/3} \times v_{Ti} = 7.4 \times 10^3$ m/s. This gives a Larmor radius of $\varrho_e = 18$ m and $\varrho_i = 770$ m for the electrons and ions respectively. From this the gyro frequency ($\omega_{ge} = \frac{v_{\perp}}{\varrho_e}$) as well as gyro period ($T_{gc} = 2\pi/\omega_{ge}$) is found, see Table (2).

The Alfvén velocity,

$$V_A = \frac{B}{\sqrt{\mu_0 \rho}} \quad (31)$$

with $B = 10^{-7}$ T and $\rho = 1 \times 10^{-17}$ kg/m³ (determined in Section 4.1) is $V_A = 2 \times 10^4$ m/s. With a shell of thickness 10^{14} m it will take an Alfvén wave ~ 130 years to propagate across it.

B Measurements and calculations of the extinction for NGC 3132 and NGC 7293

B.1 NGC 3132

The filament Y1 in the Eight-Burst Nebula (Figure 17) was captured in a narrow-band H α -image (filter F656N), with an exposure time of 400 000 s. From this image the intensity of the filament, I , was measured and compared to the average background intensity I_0 , $I \sim 400$ and $I_0 \sim 500$. First, A_λ has to be transferred to A_V , that is centered around 555 nm. The value of $E(\lambda - V)/E(B - V)$ for $\lambda = 656.3$ nm is found in the graph of wavelength dependence of extinction (Figure 25) to be ~ -0.5 . With $R = 3.1$ in eq. (11) an expression for A_λ is obtained:

$$A_\lambda = 2.6E(B - V). \quad (32)$$

If instead in eq. (11) $R = A_V/E(B - V)$ is inserted the expression is

$$A_\lambda = -0.5E(B - V) + A_V \quad (33)$$

From eq. (32) an expression for $E(B - V)$ is obtained and by substituting this into eq. (33) we find that

$$A_V = 1.2A_\lambda \quad (34)$$

By putting the values of the intensities into eq. (12) an extinction at the wavelength 656.3 nm A_λ of 0.24 mag is obtained. This gives an A_V of 0.29 mag.

The column density, $N(H_2)$, in the filament can then be calculated by using eq. (13) yielding 2.7×10^{24} molecules m^{-2} . The mass of such a column is obtained through eq. (14) and is 9.1×10^{-3} kg m^{-2} . With a cosmical chemical composition the mass is $M = 1.2 \times 10^{-2}$ kg m^{-2} .

The size of a pixel in an image taken with the WFPC2 is 0.1" and with a distance to NGC 3132 of 1050 pc this corresponds to 210 ua (3.1×10^{13} m). The filament studied has an average width of 2 pixels and a total length of approximately 130 pixels, giving an area A of 2.6×10^{29} m 2 . A spherical symmetry is assumed, giving the filament a depth of ~ 2 pixels, or 6.2×10^{13} m. $N(H_2)$ is then 4.4×10^{10} molecules m^{-3} and $N(H) = 8.8 \times 10^{10}$ atoms m^{-3} . This constitutes 70 % of the gas. The rest can be assumed to consist of a monoatomic gas, mainly He. $N(He)$ is then $\frac{3}{7} \times N(H) = 3.8 \times 10^{10}$ atoms m^{-3} . The total atomic density is $N_{tot} = N(H) + N(He) = 8.1 \times 10^{10}$ atoms m^{-3} . The total mass of the filament is 3.1×10^{27} kg = 1.6×10^{-3} $M_\odot$.

B.2 NGC 7293

One of the cometary knots in the Helix Nebula (position 22:29:37,77 -20:48:00,2) was studied in an image taken with a F502N filter (centered on [O III] emission) with an exposure time of 4 800 000 s. In the measurement of the extinction the cometary knot studied is divided into two parts, the head, denoted A, and the tail, denoted B. The intensities are here found to be $I_A \sim 5$ and $I_B \sim 9$ and a background intensity of $I_0 \sim 12$. From eq. (12), $A_{\lambda,A} = 0.95$ mag and $A_{\lambda,B} = 0.31$ mag are calculated. In Figure 25 $E(\lambda - V)/E(B - V)$ is found to be approximately 0.5 for $\lambda = 502$ nm. From this the relation between A_V and A_λ is extracted:

$$A_V = 0.86A_\lambda \quad (35)$$

and thus $A_{V,A} = 0.82$ mag and $A_{V,B} = 0.27$ mag. Eq. (13) gives a column density of the head of $N(H_2)_A = 7.7 \times 10^{24}$ molecules m^{-2} and of the tail of $N(H_2)_B = 2.5 \times 10^{24}$ molecules m^{-2} .

The area of the head of this filament is that of an ellipse, with a major axis of 26 pixels and minor axis of 16 pixels. The Helix Nebula is found at a distance of 0.16 kpc corresponding to 4.9×10^{18} m, giving the length of a pixel of 16 ua or 2.4×10^{12} m. The area of the head is thus 1.9×10^{27} m^2 . The thickness is for simplicity assumed to be equal over this area and of the same size as the minor axis, 3.8×10^{13} m, and it is further assumed that the cometary knot is viewed completely from the side. The total volume of the head is then 7.3×10^{40} m^3 . With $N(H) = 2 \times N(H_2)$, $N(He) = \frac{3}{7} \times N(H)$ and a thickness of the head of 3.8×10^{13} m, the total atomic density is $N_{tot} = 5.8 \times 10^{11}$ atoms m^{-3} . From eq. (14) and with a cosmical chemical composition, the total mass of the head is 6.6×10^{25} kg = $3.3 \times 10^{-5} M_\odot$.

The tail of this filament is assumed to have a column depth of the same size as the width, namely 3.4×10^{13} m. This gives a total density, with cosmical chemical composition, of 2.1×10^{11} atoms m^{-3} . From eq. (14) a total mass of the tail of 8.8×10^{25} kg is obtained. The total mass of the head and the tail is approximately 1.5×10^{26} kg = $7.7 \times 10^{-5} M_\odot$.

The mass of the head obtained here of $3.3 \times 10^{-5} M_\odot$ is in accordance with the result obtained by Meaburn et al. (1992), where the mass of similar clumps is $M_g \geq 1.0 \times 10^{-5} M_\odot$. In the calculations by Meaburn et al., an abundance of atomic hydrogen has been taken into consideration, yielding a two times higher value of the mass.

C Tables and images

Figure 1: The creation of a planetary nebula according to the ISW model. The slow-moving hydrogen envelope from the AGB phase is hit by the faster stellar wind, which results in a shock front (from Kwok 2001).

Figure 2: Filamentary structures in NGC 2440, v, y and s indicates V-shapes, Y-shapes and sinusoidals, respectively.

(a)

(b)

Figure 3: (a) Enlarged part of the Little Ghost Nebula. (b) Marked V- and Y-shapes.

Figure 4: V- and Y-shapes marked in the Bug Nebula. Y-shapes directed outwards are marked with y' , and a region with many wavy structures is marked with A.

Figure 5: The Glowing Eye Nebula (a) in which a Y-shape is enlarged (b) and marked (c).

Figure 6: NGC 6543

Figure 7: NGC 2392

Figure 8: NGC 6720

Figure 9: He 2-104

Figure 10: IC 4406

Figure 11: NGC 3132

Figure 12: NGC 7293

Figure 13: NGC 7009

Figure 14: IC 418

Figure 15: NGC 6853

Figure 16: The halo around the Ring Nebula taken with the Spitzer Space Telescope. Image credit: NASA/JPL-Caltech/J. Hora (Harvard-Smithsonian Center for Astrophysics).

Figure 17: The PN NGC 3132 with its Y-shaped filament marked.

Figure 18: Enlargement of Y-shaped filament in NGC 3132

Figure 19: Analogy model of a Y-shaped filament with double helix.

Figure 20: Two Y-shapes shown in the upper left corner of the nebula NGC 6543, marked with Y1 and Y2.

Figure 21: The halo of NGC 6543, captured with NOT (image credit: Romano Corradi).

Figure 22: Wavy sinusoidals found in the Helix Nebula.

Figure 23: Y-shape in the Helix Nebula

Figure 24: Marked Y-shape

Figure 25: Average normalized interstellar extinction versus $1/\lambda$. The references of the curves are extended with an indication on how many stars were used to derive each average curve. By adding $R = 3.1$ to the curves the total normalized extinction, $A_\lambda/E(B-V)$ is obtained (from Savage & Mathis 1979).

Planetary Nebulae	Equatorial Coordinates (2000)	Distance (kpc)	Detected 2D structures
IC 418	05 27 28.3, -12 41 48	1.5 ± 0.46	V, Y, S, web, braids
NGC 2392	07 29 10.7, +20 54 37	1.0 ± 0.30	V, Y, web, wrench
NGC 2440	07 41 55.4, -18 12 33	1.1 ± 0.34	V, Y, S
NGC 3132	10 07 01.8, -40 26 10	1.1 ± 0.26	V, Y, S, braids
He2-104	14 11 52.2, -51 26 24	7.1 ± 0.80	V, Y, S, braids
IC 4406	14 22 26.5, -44 09 06	1.6 ± 0.49	V, Y, S, web
NGC 6302	17 13 44.3, -37 06 06	0.54 ± 0.17	V, Y
NGC 6369	17 29 20.8, -23 45 32	0.86 ± 0.26	V, Y, S, arcs, braids
NGC 6543	17 58 33.4, +66 37 59	1.3 ± 0.41	V, Y, S, web, wrench, braids
NGC 6720	18 53 35.7, +33 01 40	0.79 ± 0.090	V, Y, arcs
NGC 6751	19 05 55.6, -05 59 28	2.4 ± 0.70	V, Y
NGC 6853	19 59 36.2, +22 43 01	0.33 ± 0.070	V, Y, S, braids
NGC 7009	21 04 10.8, -11 21 57	0.98 ± 0.30	web
NGC 7293	22 29 38.7, -20 50 15	0.16 ± 0.043	V, Y

Table 1: The PNe studied and their coordinates, distances and detected two-dimensional structures.

Characteristic quantity	Value
Debye length λ_D (m)	0.08
Self-collision time τ_{ee} (s)	2
Self-collision time τ_{ii} (s)	82
Magnetic Reynolds number R_m	1.2×10^{15}
Frozen-in time τ (yrs)	2×10^{17}
Larmor radius for electrons ϱ_e (m)	18
Larmor radius for ions ϱ_i (m)	770
Gyro frequency for electrons ω_{ge} (Hz)	1.8×10^4
Gyro frequency for ions ω_{gi} (Hz)	9.6
Gyro period for electrons T_{ge} (s)	3.6×10^{-4}
Gyro period for ions T_{gi} (s)	0.66
Alfvén velocity (m/s)	2.4×10^4

Table 2: Characteristic properties of the plasma in the shell of a PN, with $n_e = 7 \times 10^9 \text{ m}^{-3}$, $T_e = T_i = 10^4 \text{ K}$ and $B = 10^{-7} \text{ T}$.

ISSN 1103-6613
TRITA-ALP-2005-04
ISRN KTH/ALP-05/04-SE