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ON THE ROLE OF THE ISM MAGNETIC FIELD IN SHAPING INTERACTING PLANETARY NEBULAE

Ruth Dgani

Department of Astronomy, The University of Texas, Austin, TX 78712, USA;
knill@astro.as.utexas.edu

RESUMEN

En este artículo, me concentro en un grupo de nebulosas planetarias que interactúan y que muestran evidencia de estar deformadas magnéticamente. Estas son nebulosas que tienen filamentos extendidos o "franjas" y están concentradas cerca del plano galáctico. Mi meta es comprender la dirección y dimensión de las franjas. La población de nebulosas con franjas no es homogénea; algunas tienen franjas gruesas y otras las tienen angostas. En este trabajo, derivo una fórmula sencilla que relaciona el tamaño y la orientación de las franjas con las propiedades de la interacción. Encuentro que en el caso general, la dirección de las bandas es normal a la dirección de velocidad de la nebulosa. La separación entre las franjas paralelas adyacentes (en unidades del radio de la nebulosa), está relacionada con el cociente de la componente de la velocidad Alfvén en la dirección del frente de choque a la velocidad relativa de la nebulosa. Las nebulosas con los mayores cocientes tienen franjas más gruesas. Al aplicar la fórmula al grupo de nebulosas con franjas, se predicen algunos parámetros que pueden ser confrontados con observaciones futuras.

ABSTRACT

In this article I concentrate on a group of interacting planetary nebulae that show evidence of magnetic shaping. These are nebulae that have elongated aligned filaments or "stripes". They are concentrated near the galactic plane. I aim at understanding the direction and thickness of the stripes. The striped nebulae population is not homogeneous; some have thick stripes and some have thin stripes. Here I derive a simple formula that relates the size and orientation of the stripes to the properties of the interaction. I find that in the general case the direction of the stripes is normal to the direction of the velocity of the nebula. The separation between adjacent parallel stripes (in units of the radius of the nebula) is related to the ratio of the Alfven speed component in the direction of the shock front to the relative velocity of the nebula. Nebulae with higher ratios have thicker stripes. I apply the formula to the group of striped nebulae and predict some parameters that can be confronted with future observations.

Key words: **INSTABILITIES — ISM: MAGNETIC FIELDS — PLANETARY NEBULAE: GENERAL**

1. INTRODUCTION

The process by which planetary nebulae (hereafter PNe) diffuse to become the interstellar medium (hereafter ISM), has always been difficult to observe. PNe are affected by the ISM when their emissivity is low (density$<$ 100 cm^{-1} for typical cases, see Borkowski, Sarazin, & Soker 1990). However, due to modern CCD techniques, a sample is now available of a few tens of images of planetary nebulae showing signs of interaction with the ISM.

The images look confusing. The nebulae are different from their younger sisters. There is great variety. Some nebulae show a definite bow shock at the edge, others defy our expectations and have the bow shock well inside, some show stripes, some show blobs, some look like they are being torn apart in many places. The term "diffusion" of a PN in the ISM is misleading. The typical nebula does not smoothly transform to become ISM. Dynamical instabilities must be involved in the interaction to explain this collection of distorted and disrupted objects.

Soker, Borkowski, & Sarazin (1991) show that Rayliegh-Taylor (hereafter RT) instability is effective in destroying the nebular shell of the fast moving galactic halo nebulae (i.e., $v_* > 100$ km s^{-1}, where v_* is the velocity of the central star). The deceleration of the dense nebular shell by the hot diffuse shocked ISM is RT unstable. The ISM penetrates the disrupted shell and flows inside the nebula. Neglecting magnetic effects, the PN-ISM interaction for the slower moving galactic plane PNe ($v_* \sim 60$ km s^{-1}) is RT stable. The radiative cooling in the shocked ISM gas is efficient, and it becomes as dense as the nebular material. A recent review of the theory of the PN-ISM interaction process is in Dgani (1995).

The magnetic field pressure in the warm ISM is negligible compared to its ram pressure for an average nebula moving in the galactic plane. However, it is dominant in the interaction. This seemingly paradoxeal situation occurs because of the efficient cooling in the ISM shock. When cooled, the ISM gas is compressed, compressing with it the magnetic field. The magnetic field component parallel to the shock front grows linearly with the density until it becomes strong enough to support the ISM shocked region against the ram pressure of the ISM. In Soker & Dgani (1997; hereafter SD) we show that this happens when the density of the shocked ISM is smaller than the density in the nebula. In this way the magnetic field of the ISM destabilizes the interaction. The magnetic field of the ISM has a destabilizing effect only for modes having wave numbers perpendicular to the field lines and parallel to the shock front. Instability modes having wave numbers parallel to the magnetic field lines are supressed by magnetic tension. This effect may create elongated structures along the direction of the magnetic field lines. Thus RT is likely to be efficient for all nebulae moving in the warm medium.

Although both the observations of interacting PNe (hereafter IPNe) and theoretical calculations point to the crucial role of instabilities in the PN-ISM interaction, the interpretations of the observations ignore them. When instabilities are ignored the ISM can interact directly only with the outer edge of the nebula. The influence of the ISM on the inner parts of the nebula can only be second hand; the ISM pushes the outer edge which pushes the inner parts etc. This is the reason why in some cases asymmetric mass flux was invoked to explain features (A35, Hollis et al. 1996; IC 4593 Bohigas & Olguin 1996) that very naturally follow from the PN-ISM interaction— once we allow the ISM to penetrate into the inner parts of the nebula.

In Dgani & Soker (1997; hereafter DS) we try to narrow the gap between theory of instabilities and interpretation of observations. We interpret the bow shock inside A35 and IC 4593 as a result of PN-ISM interaction. By calculating the speed of an RT front through the outer parts of these nebulae, we show that an ISM bow shock should form around the core of IC 4593, leaving a filamentary halo around it as observed (Corradi et al. 1998).

We also find that the morphology of interacting nebulae is dependent on their distance from the galactic plane. Nebulae that have elongated aligned filaments tend to concentrate near the galactic plane. We call them "the striped nebulae". Here I will investigate some properties of the striped nebulae, in the frame of a simplified model for the shocked ISM.

2. THE MORPHOLOGY OF INTERACTING PNE AND THEIR GALACTIC LATITUDE

Several high quality observations, most notably given in the Atlas published by Tweedy & Kwitter (1996; hereafter TK96) have provided us with a sample of 34 deep images of IPNe. In Table 1 of DS, we give a list of the objects and their references. Some nebulae have several parallel stripes. We defined a nebula as striped only if it has at least two parallel long filaments. All of the 12 striped nebulae are close to the galactic plane ($|z| <250$ pc). In Figure 1 two histograms are shown, the right one shows the desribution of striped nebulae as a function of $|z|$, and on the left the same distribution for IPNe with no stripes. The difference in the distributions is obvious. The striped population is confined to the galactic plane.

In DS we discuss several selection effects. The stripes are not correlated with the angular size of the nebula, so the correlation is not related to the angular resolution. We also show that there is no correlation between the real size of the nebula and the property of having stripes. Another possible selection effect not discussed in DS is: the correlation of having stripes with our distance to the nebula. Since the striped nebulae that are close to us are also close to the galactic plane, the question arises as to whether the stripes are not seen in galactic halo nebulae simply because they are distant. In the group all nebulae with distance from us between 500 and 1000 pc, 6 are striped and 8 are not. There is a marked difference between the two populations also in this group. The striped population is concentrated near the galactic plane, the non-striped population is not.

The fact that the striped nebulae are confined to the galactic plane is compatible with the the prediction that RT will be effective for galactic plane PNe moving in the warm medium, because of magnetic effects, but only for modes perpendicular to the direction of the magnetic field. The result is elongated structures or "RT rolls". For galactic halo IPNe the cooling is inefficient and magnetic pressure is negligible. RT will be effective but it will form fingers or blobs and not stripes.

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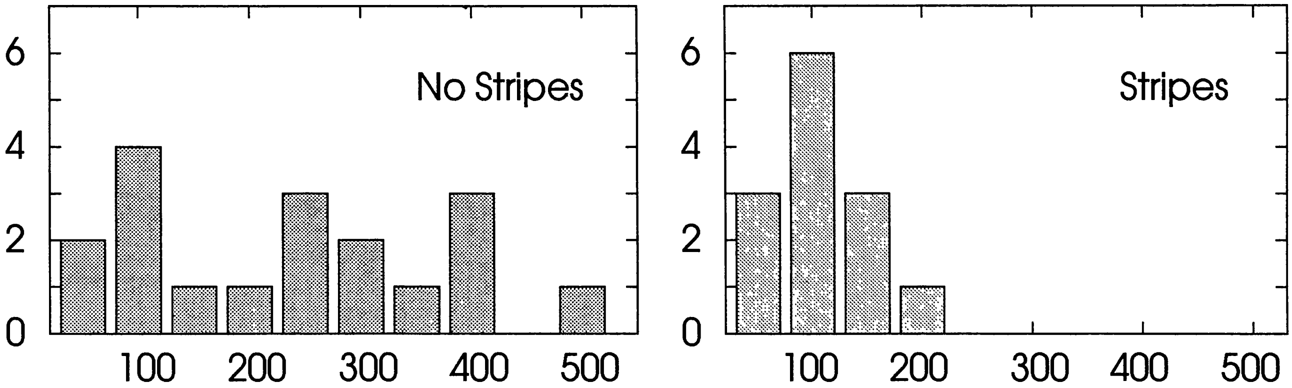

Fig. 1. The distribution of IPNe versus galactic height $|z|$ in pc. On the right striped IPNe, on the left non striped IPNe. The vertical axis is the number of nebulae in each 50 pc bin.

3. THE DOMINANT WAVELENGTH OF THE RT ROLLS

All the 12 striped nebulae have at least two parallel filaments. The distance between adjacent filaments varies from one nebula to another. Some nebulae have thin stripes i.e., distance between stripes $\sim 1/20$ of the size of then nebula, some have thicker stripes $\sim 1/5$ of the size of the nebula. What is the meaning of the distance between stripes? What can we learn about the magnetic field of the ISM from this separation? Assuming the stripes are RT modes, their separation is related to the wavelength of the dominant RT mode.

The growth rate of the magnetic RT instability modes with wave number $k = 2\pi/\lambda$ is given by (Priest 1982; see also SD):

$$\sigma = \sqrt{gk\left(1-\frac{\rho_s}{\rho_n}\right)\left(1+\frac{\rho_s}{\rho_n}\right)^{-1} - \frac{\rho_s}{\rho_n}\left(1+\frac{\rho_s}{\rho_n}\right)^{-1} v_A^2 k^2 \cos^2\theta}, \qquad (1)$$

where g is the deceleration of the leading shell, $v_A = B_s/\sqrt{4\pi\rho_s}$, ρ_s is the density of the shocked ISM, ρ_n the density in the nebula and θ is the angle between the magnetic field and the wave vector $\vec{k}$. RT rolls are modes for which $\theta = \pi/2$. For them, the magnetic tension term i.e., the second term on the rhs of eq. (1) is zero and the growth rate is maximal. The growth rate is highest for short wavelength modes; however, they are confined to the interface. "The bouyancy rise time" (i.e., the time it takes a mode to reach a wavelength distance from the interface) is $\lambda\sigma$ and is shorter for long wavelengths. The dispersion relation assumes that the two plasmas separated by the interface are uniform and of infinite extent i.e., the relation is valid when λ is smaller than the smallest length scale in this problem. There are three length scales in this problem: (1) the width of the shocked cooled ISM Δz, (2) the size of the decelerated nebular shell ΔR, and (3) the size of the nebula $2R$. Since the shocked ISM cools, let us assume that the width of the shocked cooled ISM Δz is smaller than the other two scale lengths of the problem. An RT roll with $\lambda > \Delta z$ will contain a mixture of light ISM and heavy nebular material. This will make it less bouyant.

The conclusion is that the dominant RT mode in the this case is of the order of Δz. In order to estimate the width of the shocked ISM region, note that, as a result of magnetic tension effects, the flow near the stagnation point will not be symmetric and will favor the direction along the field lines (see SD section 3.2, Fig. 2). I therefore, take the ISM shocked region to be a box with width Δz, where z is the direction of motion of the central star, and sides of length $2R$ in the xy plane, where R is the radius of the nebula and y is the direction of the magnetic field. The mass loss rate from the sides of the box is:

$$\dot{M} = 2(\rho_s v_y)2R\Delta z + 2(\rho_s v_x)2R\Delta z\,, \qquad (2)$$

where $v_x \ll v_y \sim v_*$ The mass flux into the box is $\rho_0 v_*(2R)^2$.

ρ_s is given SD as a function of the nebular density by a solution of a quadratic equation. Since here this is not needed, let us simplify the the treatment and neglect the thermal pressure of the shocked cooled ISM. Let α_0 be the angle between the magnetic field in the pre shocked ISM, and the shock front. In a strong shock with α_0

not too close to $\pi/2$ the postshock magnetic pressure is dominated by the component parallel to the shock wave front. The postshock magnetic field component parallel to the shock front is given by $B_{pa} \simeq (\rho_s/\rho_0)B_0 \cos\alpha_0$, where ρ_s is the density of the cooled shocked ISM and B_0 is the preshock ISM magnetic field. The postshock magnetic pressure is given by $P_s \simeq B_{pa}^2/8\pi = \rho_s^2 v_{A0}^2 \cos^2\alpha_0/(2\rho_0)$. v_{A0} is the Alfvén speed in the pre-shocked ISM. Equating the ISM ram pressure, which according to our assumption is much larger than the magnetic and thermal ISM pressures, with the magnetic pressure in the shocked cooled ISM gives

$$\frac{\rho_s}{\rho_0} = \frac{\sqrt{2}v_*}{v_{A0}\cos\alpha_0}. \tag{3}$$

Substituting ρ_s from the expression in the mass conservation equation (2) gives

$$\frac{\Delta z}{R} = \frac{v_{A0}\cos\alpha_0}{v_*\sqrt{2}}. \tag{4}$$

Let α be the angle between the magnetic field line and in the post shock ISM. Since the normal component of the magnetic field does not change after the shock

$$\alpha = \arctan\left(\sin\alpha_0 v_{A0}/(v_*\sqrt{2})\right). \tag{5}$$

The angle α is very small for the typical case. The information about the original direction of the magnetic field is lost during the passage through the ISM shock. The stripes should be perpendicular to the relative velocity between the ISM and the nebula.

In general, the formula predicts that the distance between stripes should depend on the ratio on the right hand side of eq. (4). This means that the faster ones for which v_* bigger, and the ones moving in the warm neutral medium for which v_{A0} is smaller, will have shorter distances (relative to their sizes) between stripes. It is in principle easy to to measure the direction of the stripes, and the distance between them.

In S176, S188, DHW5, Ton 320, IW2 (images in TK96 and Tweedy & Kwitter 1994) the stripes form parallel bended bows. These cases are the easiest to analyze if we assume that the relative velocity between the ISM and the nebula is along the axis of symmetry of the bows. The magnetic field is then expected to be aligned with shock and so are the stripes. In S176 and in S188 the distance between the stripes $\Delta z \sim R/10$. In DHW5, IW2 and in Ton 320 it is about $\Delta z \sim R/5$. This implies that they move slower than S176 and S188, or that in S176 and S188 move in a medium in which the Alfvén speed component normal to the shock is smaller. In A35 the stripes are parallel to the direction of motion. The model is not expected to work if $\cos\alpha_0$ is close to zero.

More accurate predictions await numerical MHD simulations. The group of striped nebulae holds a lot of information about their surrounding ISM. On the observational side, knowing the velocities of the central stars in this group will allow us to estimate the the Alfvén speed in their surrounding ISM.

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