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The interaction of the planetary nebula NGC 6894 with the ISM magnetic field

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ABSTRACT

We have obtained images of the planetary nebula NGC 6894 and the 'stripes' near it and have analysed their morphologies. Our analysis suggests that the material of the stripes has been ionized by the central star of NGC 6894, and could have originated from the stripping of the halo of NGC 6894 by the interstellar medium (ISM). Based on the fact that the orientation of the stripes is parallel to the Galactic plane, we speculate that the morphology of the stripes is determined by the Galactic magnetic field. The above interpretation requires the motion of NGC 6894 to be in a direction which is consistent with observations. This work further stresses the significant role of the ISM magnetic field in shaping haloes of planetary nebulae, and the potential for using planetary nebulae to probe the ISM.

Key words: ISM: kinematics and dynamics – ISM: magnetic fields – planetary nebulae: individual: NGC 6894 – ISM: structure.

1 INTRODUCTION

The idea of studying planetary nebulae (PNe) which interact with the interstellar medium (ISM) in order to learn more about the ISM itself is discussed in some detail by Jacoby (1981), Borkowski, Sarazin & Soker (1990) and Soker Borkowski & Sarazin (1991; see the reviews by Dgani 1995 and Tweedy 1995). The study of interacting PNe has received more attention since the use of CCD detectors became common (Tweedy 1995), permitting qualitative study of previously unnoticed features, and accurate quantitative study of the faint outskirts of PNe (Plait & Soker 1990; Zucker & Soker 1993; Tweedy & Kwitter 1994, 1996; Tweedy & Napiwotzki 1994). The important role which the ISM magnetic field may play in the interaction of PNe with the ISM is mentioned by Tweedy, Martos & Noriega-Crespo (1995) in their paper on the interacting PN SH 2-216, and by Soker & Dgani (1997) and Dgani & Soker (1997) in their theoretical study of instabilities in the interaction process. In this paper we study the morphology of the PN NGC 6894, and suggest another way by which the Galactic magnetic field may influence the interaction process.

We examine the optically visible gas near NGC 6894 (PN G 069.4-02.6), which is in the form of parallel stripes. The detached tail-like ISM near NGC 6894 and NGC 6857 was noticed by Chu, Jacoby & Arendt (1987), although they did not explore the full extent of the stripes near NGC 6894. Chu et al. categorize NGC 6894 as a IIb/P morphological type, namely having two attached shells with a peculiar outer shell, while Balick (1987) classifies it as middle round. High-quality images of NGC 6894 can be found in these two papers. Extending the area covered by these two studies, we present in Section 2 images of the stripes near NGC 6894. Based on morphological features and the mass in the stripes, we suggest in Section 3.1 that the gas in the stripes may have been stripped from the halo of NGC 6894. The required direction of motion – south south-east – is in the same general direction as the proper motion reported in Cudworth (1974). In Section 3.2 we argue that the central star of NGC 6894 ionized the material in the stripes, and in Section 3.3 we speculate that the Galactic magnetic field shapes the material in the stripes. We present a summary and suggestions for further studies in Section 4.

2 OBSERVATIONS

The images of NGC 6894 were taken with the Smithsonian Astrophysical Observatory's 1.2-m telescope on Mt. Hopkins, Arizona, on the nights of 1992 September 24 and 26. The seeing on both nights was typically 1.5–2 arcsec. The detector used was a 2048 × 2048 pixel Ford CCD, with each pixel projecting to ~0.33 arcsec on the sky. We obtained

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images in the lines of Ha λ6563 and [C I] λ9849 (Zucker & Soker 1993). We used an Hα filter with a bandpass (FWHM) of 22 Å; consequently the Hα images are contaminated by some [N II] emission. The degree of contamination will change according to the relative emissivity of [N II] relative to Hα, which we would expect to vary across the nebula; however, we estimate this contamination to be $\lesssim$25 per cent in our images.

The Hα images are presented in three panels in Fig. 1, while the [C I] is in the lower right panel of the same figure. North is up and east is to the left. In Fig. 2 we present the full extended Hα image, as in the upper left panel of Fig. 1, but we include several definitions, and draw lines parallel to the Galactic plane. The coordinates are J2000.0.

3 THE STRIPES

3.1 The source of the material of the stripes

There are three morphological features which suggest that the gas making the stripes was stripped from the nebula as the nebula moved to the south south-east. First, it would be

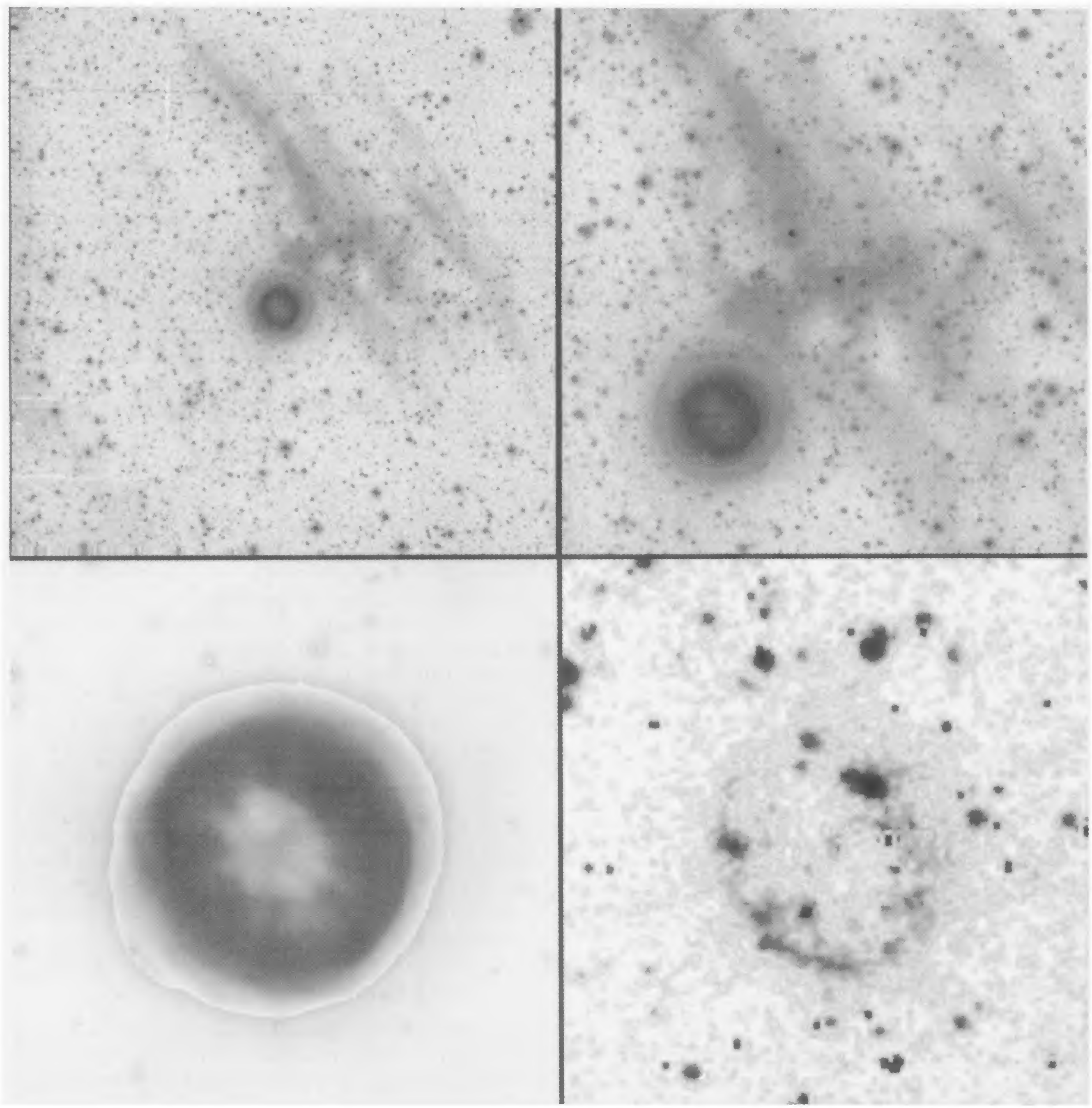

Figure 1. Images of NGC 6894: 10 × 10 arcmin^2 Hα (upper left); 5 × 5 arcmin^2 Hα (upper right); 90 × 90 arcsec^2 Hα (lower left); 90 × 90 arcsec^2 [C I] (lower right).

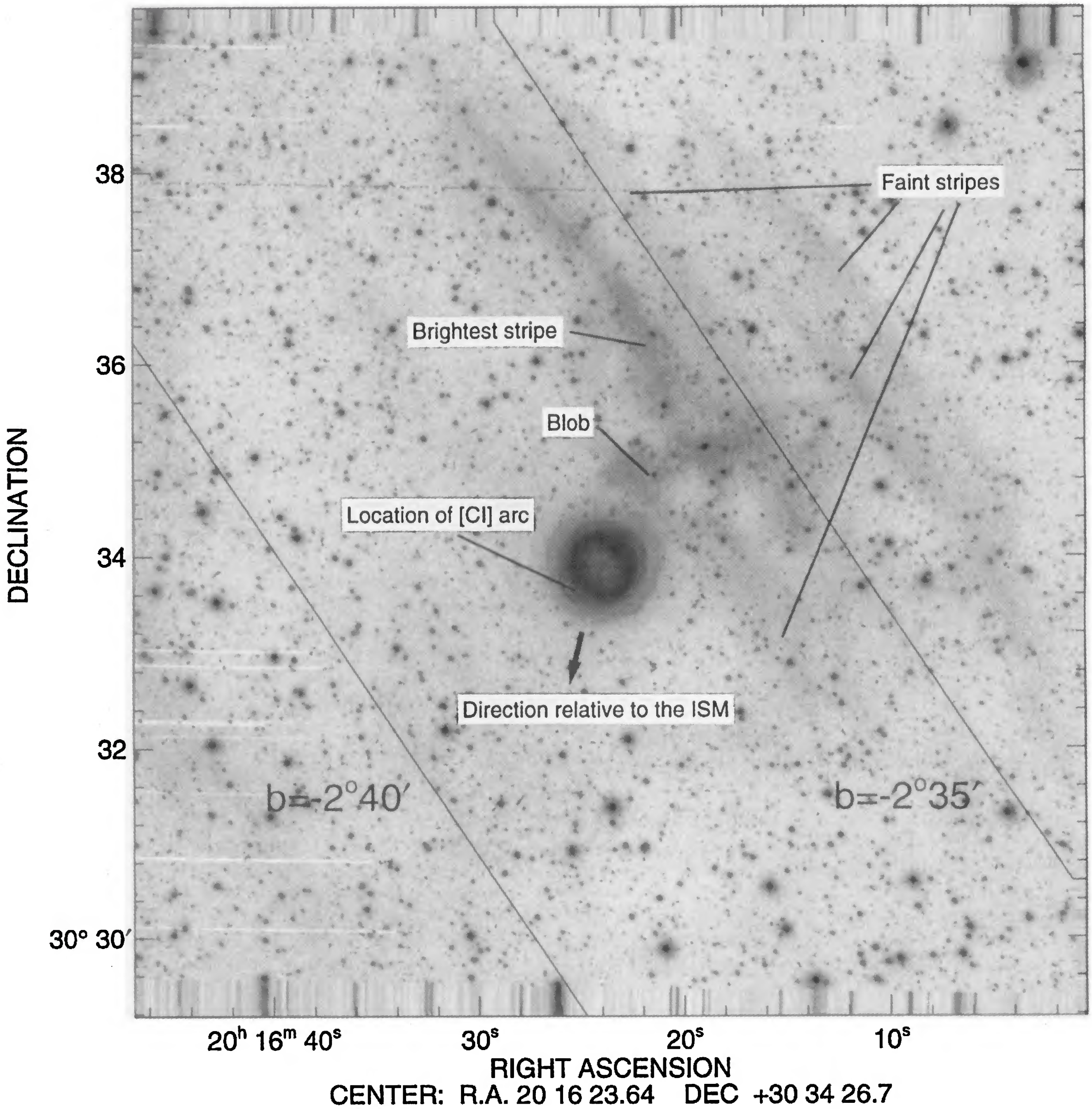

Figure 2. Hα image of NGC 6894, with definitions, and two Galactic latitude lines, where b is the Galactic latitude.

a fortuitous coincidence that originally unrelated ISM gas would be located only on the north-west of the nebula, close enough to be ionized by the central star (see Section 3.2). Secondly, the location of the 'blob' 1 arcmin north north-west of the centre of the nebula (Fig. 2), which seems to link the nebula with the stripes, would require a similar coincidence if the blob did not originate in the halo of the nebula. The third feature is the enhanced emission from the arc in the [C I] image (lower right panel of Fig. 1), which is on the opposite side of the nebula from the blob. Further support for the stripping hypothesis is our estimate that the total mass of the stripes is $\sim 1\ M_{\odot}$ (see Section 3.2), which is what one would expect for extended haloes of PNe.

The arc is very prominent in [C I] but is not detectable in our Hα image. Two effects could contribute to this apparent discrepancy. First, if the gas is predominantly ionized, the C I fraction is proportional to the electron density n_e, and the [C I]-line emissivity goes as n_e^3 (John Raymond, private communication). The surface brightness of the arc is ~ 50 per cent higher than the opposite side of the shell. If the volume is similar, then the density in the arc is ~ 15 per cent higher than in the rest of the shell. (We note that there is considerable uncertainty in this measurement since in the [C I] line the intensity of the arc is only 20 per cent above background). If the arc is filamentary (or clumpy) then the density contrast is even higher. On the other hand, in the regions where we observe [C I], the H α and [N II]-line emissivities are proportional to n_e^2 (John Raymond, private communication). Therefore, the [C I]-line intensity is more sensitive to an increase in density. In addition, it is generally expected that some features which result from interaction with the ISM are prominent in some emission lines (low ionization lines, e.g. [C I]), while they are almost absent in other emission lines ([O III] for example) (Jacoby 1981; Zucker & Soker 1993; Tweedy & Kwitter 1994; Corradi et al. 1997).

Secondly, the arc is narrow, it covers a small area, and it is projected on to the bright shell (the so-called 'rim') in the Hα image. The Hα rim is not smooth, but rather has strong fluctuations in intensities on short length-scales. We examined several points on the rim, and the intensity differences between adjacent locations can exceed $\sim$15 per cent. Therefore, we would expect that even if the arc were brighter than its surroundings in Hα, it would be drowned out by these fluctuations in the Hα image.

If the [C I] arc is the result of compression by the ISM and the blob points in the opposite direction, then NGC 6894 is moving at position angle 160 (20° east of south) relative to the ISM. This is close to the direction of proper motion as reported by Cudworth (1974), who found the proper motion to be at a position angle of 166 (14° east of south). Given this interpretation for the arc, one or a combination of the following three scenarios can explain the observed location of the [C I] arc on the rim *inside* the nebula, rather than on its outskirts.

(1) The arc is indeed on the outskirts of the main shell, but is projected on the rim inside the shell. If this is the case, then we can estimate that the nebula-ISM relative velocity is at $\sim$45° from the plane of the sky. In several cases, arcs or stripes have been observed in the interfaces of PNe interacting with the ISM, close to the Galactic plane (e.g., S 176 and HW 4; Tweedy & Kwitter 1996). Dgani & Soker (1997) attribute these arcs (or stripes) to the ISM magnetic field. This may by the case here, where we expect the ISM magnetic field to play a significant role in the interaction process.

(2) The shell outside the arc expands at subsonic velocity, and the compression by the ISM sends weak sound waves which compress the nebular material further in. For example, if the outer shell expands at 10 km s^{-1}, then the sound waves, with a speed of 15 km s^{-1} at a temperature of 10^4 K (appropriate for the ionized nebula), move at 5 km s^{-1} with respect to the central star. If, as we estimate, the ionization of the nebula started $\sim$3500 yr ago (Section 3.3), during that time the sound waves moved a distance of $\sim$0.018 pc relative to the central star, and $\sim$0.054 pc relative to the expanding shell, for the physical values given above. The projected distance between the outer boundary of the main nebular shell and the [C I] arc is 10 arcsec = 0.074 pc (at a distance of 1.53 kpc). Considering the uncertainties, mainly in the distance to NGC 6894 and the time the shell was ionized, there is a reasonable agreement between the two distances, of 0.054 and 0.074 pc.

(3) As shown by Dgani & Soker (1997) the low-density outer regions of PNe moving through the ISM can be fragmented by the Rayleigh–Taylor instability. This allows the ISM to flow into inner regions, and to form a bow shock inside of the outer boundary. This could have happened with the halo of NGC 6894. However, as we argue in the present paper, a substantial fraction of this fragmented halo was shaped into stripes by the ISM magnetic field. This mechanism is less likely to fragment the shell, which is much denser than the halo. We would therefore expect that the arc location is best explained by one of the first two effects.

Let us next estimate the age of the nebulae and its velocity relative to the ISM. The maximum expansion velocity of the main nebulae is 43 km s^{-1} (Weinberger 1989), and its radius at a distance of 1.53 kpc is 0.15 pc (Kaler 1983). It is likely, however, that the outer parts of the main nebula expand at $\sim$15 km s^{-1}. If we assume a constant expansion velocity, the main nebula formed from a mass-loss episode which started $\sim$few $\times 10^4$ yr ago. We assume that the closest stripe, which is at a distance of 0.5 pc from the central star, was stripped from the halo which once enveloped the main nebula. Thus, if it was stripped, say, 3×10^4 yr ago, then NGC 6894 is moving at $\sim$20 km s^{-1} relative to the ISM. Careful spectroscopic analysis is required here in order to find the relative line-of-sight velocity of the stripes and main nebula, which will give us a better indication as to the absolute relative velocity.

3.2 Ionization source of the stripes

The luminosity of the central star of NGC 6894 is 300 L$_\odot$ and its surface temperature is 9×10^4 K, and it is therefore already declining toward the WD region (Kaler 1983). Tylenda (1986) further suggests that the nebulae of NGC 6894 is already recombining. The maximum distance of the stripes from the centre of NGC 6894 is $\sim$300 arcsec = 2.2 pc at a systemic distance of 1.53 kpc. In the list of 34 interacting PNe given in Table 1 of Dgani & Soker (1997) there are 3 PNe larger than NGC 6894, and 6 of comparable size. Kaler (1983)'s Fig. 6 gives several PNe with radii of $\sim$0.5 pc and with central stars having properties similar to those of NGC 6894. Thus a comparison with other PNe suggests that the central star of NGC 6894 is capable of ionizing the stripes.

The size of the blob and the widths of the stripes are of the order of the nebula shell thickness, while the average Hα surface brightness of the blob, the brightest stripe, and the fainter stripes, relative to that of the main nebula, are $I_{\mathrm{H}\alpha} = 0.02$, 0.015, and 0.008, respectively. The average electron density in these components is therefore $n \simeq n_{\mathrm{neb}}\sqrt{I_{\mathrm{H}\alpha}}$. Taking for the average electron density of the main nebula $n_{\mathrm{neb}} = 450$ cm^{-3} (Stanghellini & Kaler 1989), we obtain for the electron densities $n_{\mathrm{blob}} \simeq n_{\mathrm{brightest\ stripe}} \simeq 60$ cm^{-3}, and $n_{\mathrm{faint\ stripes}} \simeq 40$ cm^{-3}. The recombination time of hydrogen is given by (Tylenda 1986) $\tau_{\mathrm{rec}} = 1.2 \times 10^5\ \mathrm{yr}/n_e$, where n_e is the electron density in cm^{-3}. The recombination time is therefore $\gtrsim$2000 yr. We find that even if the ionization ceased a thousand years ago (in the next subsection we estimate that it started $\sim$3500 yr ago), the stripes would still not be fully recombined. Here again, a spectroscopic study is required to better understand the relation between the stripes and NGC 6894.

Let us now estimate the total mass in the stripes and the blob. If we make the simplistic assumption that there are four full cylindrical stripes, touching one another, then the radius of each stripe is 23 arcsec = 0.17 pc, and the length is l = 500 arcsec = 3.7 pc, at an assumed distance of 1.53 kpc. With an average electron density of 50 cm^{-3}, we find the total mass to be $\sim 2\ \mathrm{M}_{\odot}$. Looking carefully at the optical images, we see that the stripes do not touch one another and that they are shorter than 500 arcsec. The typical radius is half the previous value, and the typical length is only ~ 250 arcsec. These values give a total mass of $\sim 0.3\ \mathrm{M}_{\odot}$. We conclude that the mass of the stripes is in the range $M_{\mathrm{max}} = 0.3$–$2\ \mathrm{M}_{\odot}$. This is the expected mass range for extended haloes of PNe.

3.3 Shaping the material in the stripes

As indicated in Fig. 2, the stripes are parallel to the Galactic plane. At a distance of 1.53 kpc, NGC 6894 is 0.07 kpc below the Galactic plane (Kaler 1983), where the Galactic magnetic field is parallel to the Galactic plane, the strength of the ordered magnetic field being $B_u \sim 5\ \mu$G, and that of the total field, ordered plus turbulent, being $B \sim 7\ \mu$G (Wielebinski & Krause 1993). In order to confine the gas, the magnetic field should be such that the magnetic pressure is larger than the thermal pressure of the gas $B_u^2/8\pi \gtrsim P_{\mathrm{th}}$, and larger than the ram pressure $B_u^2/8\pi \gtrsim \rho v_{\mathrm{rel}}^2$ (e.g. Palumbo & Platzeck 1993). Here v_{rel} is the relative velocity of the presumed stripped material to the ISM. The ISM pressure near the Galactic plane can stop the expansion of typical PN haloes at radii of ~ 1 pc (Soker & Dgani 1997). Therefore, we expect that the ram pressure of the stripped halo will be very small, with $v_{\mathrm{rel}} \lesssim 1\ \mathrm{km\ s^{-1}}$.

For a temperature of 10^4 K, and a total number density of $n = 150\ \mathrm{cm}^{-3}$ (Section 3.2), the thermal pressure in the blob is $P_{\mathrm{blob}} = 2 \times 10^{-10}\ \mathrm{erg\ cm^{-3}}$, with similar pressure in the stripes. On the other hand, the ISM magnetic pressure is $B_u^2/8\pi \simeq 10^{-12}\ \mathrm{erg\ cm^{-3}}$, which is much lower than the thermal pressure. Thus, we do not expect the magnetic field to confine the gas making the stripes after the gas has been reheated by the radiation of the central star. However, before the central star started to ionize the nebula, the nebula temperature was probably only $\sim 10^2$ K (e.g. Huggins 1993). The density was higher, but the material was recombined, so the number density was lower than that of the ionized material. Thus, at early stages the Galactic magnetic field could have confined the gas, assuming that the relative velocity had already been reduced to $\lesssim 1\ \mathrm{km\ s^{-1}}$. Since the gas is mostly neutral at such low temperatures, the magnetic force acts on charged dust particles and the small numbers of ionized particles. After the material in the stripes is heated to 10^4 K and its pressure increases to become higher than the magnetic pressure, it will start to expand at some fraction of its local sound speed, i.e. $\lesssim 10\ \mathrm{km\ s^{-1}}$. This expansion starts when the object becomes a PN. At the same point in evolution, the fast wind starts to accelerate the inner boundary of the slow wind, and forms the rim – the bright thin shell around the central star. Since the maximum expansion velocity in the main nebula is 43 $\mathrm{km\ s^{-1}}$ (Weinberger 1989), the material in the stripes will expand a distance of $\sim 10/43 = 0.23$ times the distance of the rim from the central star. In Fig. 1 we see that the typical half width of the stripes is on the order of 11 arcsec = 0.08 pc compared with the typical distance of the rim from the nebula, 18 arcsec = 0.13 pc. Considering that the stripes had a finite radius before expansion started, this is compatible with the above confinement scenario. The expansion age of the rim under these assumptions is ~ 3500 yr. This would be approximately the time the ionization of the nebula started.

4 SUMMARY

Our goal in this paper was to explore a possible effect of the ISM, in particular the magnetic ISM, on the structure of PNe. For this purpose we obtained images of the PN NGC 6894 and the stripes near it (Fig. 1) and analysed its morphology. Our analysis suggests that the material of the stripes has been ionized by the central star of NGC 6894, and seems to have originated from the stripping of the halo of NGC 6894 by the ISM. The stripping conjecture is based on three morphological features: the location of the stripes on one side, the blob to the north-west (just outside the nebula), and the arc seen in the line of [C I]. It is also consistent with the total mass in the stripes, which we estimate to be in the range of 0.3–2 $\mathrm{M}_{\odot}$, as expected for haloes of PNe.

Based on the fact that the stripes are parallel to the Galactic plane, we argue that the morphology of the stripes is determined by the Galactic magnetic field. In reaching this conclusion we had to assume that the halo of NGC 6894 was at a temperature of ~ 100 K before it was stripped and then reionized by the central star, which seems to be a reasonable assumption. The orientations of the stripes and the blob, and the arc location, require the motion of NGC 6894 to be in a direction which is compatible with observations (Cudworth 1974).

To be able to conduct a deeper analysis, observations in radio and IR are necessary in order to look for atomic and molecular gas, and to search for dust. Spectroscopy will help in finding the composition and line-of-sight velocity of the nebula and stripes near it. This may give a definite answer to the question of whether the material in the stripes was originally part of NGC 6894. In addition to further observations of NGC 6894, our results strongly encourage further theoretical study, following the analytical preliminary study of Soker & Dgani (1997), of the stripping of PN haloes by a magnetized ISM. Such a study, preferably using 3D MHD numerical calculations, should take into account the temperature and dust content of the mass leaving the AGB star progenitor of the nebula while it is being stripped by the ISM.

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