NONTHERMAL RADIO EMISSION FROM PLANETARY NEBULAE

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ABSTRACT

In a recent analysis of the radio emission from the planetary nebula A30, Dgani, Evans, & White claim that the emission, located in the inner region, is probably dominated by nonthermal emission. We propose a model to explain this. We assume that the fast wind, blown by the central star of A30, carries a very weak magnetic field. The interaction of this wind with a cluster of dense condensations traps the magnetic field lines for a long time and stretches them, leading to a strong magnetic field. If relativistic particles are formed as the fast wind is shocked, then the enhanced magnetic field will result in nonthermal radio emission. The typical nonthermal radio flux at 1 GHz can be up to several millijanskys. In order to detect the nonthermal emission, the emitting region should be spatially resolved from the main optical nebula. We list other planetary nebulae that may possess nonthermal radio emission.

1. INTRODUCTION

The possibility of magnetic fields carried by the fast winds in planetary nebulae (PNe; Chevalier & Luo 1994, hereafter CL; Chevalier 1995; Garcia-Segura 1997) raises the question of whether the interaction between this wind and the previously ejected slow wind gives rise to particle acceleration and hence nonthermal emission from relativistic electrons (Chevalier 1995). Chevalier notes that the major problem with detecting the nonthermal emission is the strong thermal free-free emission emanating from the dense shell. In many PNe, however, knots and tails are present relatively close to the central star, where both the ram pressure of the fast wind and the magnetic field are higher, increasing the nonthermal emission. In the hydrogen-deficient PNe A30 and A78, for example, knots with tails appear in a disk structure close to the central star (Borkowski, Harrington, & Tsvetanov 1995). These nebulae are believed to have had a helium flash late in their evolution and are known to possess fast winds, \( v_w \sim 4000 \text{ km s}^{-1} \) (Leuenhagen, Koesterke, & Hamann 1993). The knots are believed to be photoevaporating globules (Dyson 1968; Kahn 1969; Borkowski et al. 1995). The Hubble Space Telescope (HST) images of the knots in the central region of A30 (Borkowski et al. 1995) show that they are being disintegrated and accelerated by the dilute shocked fast wind from the central star, giving rise to Rayleigh-Taylor instability. In addition, hydrogen-deficient nebulae have lower thermal emission (see discussion in Dgani, Evans, & White 1998), allowing the nonthermal component to be detected.

Jones, Kang, & Tregillis (1994) have simulated the evolution of dense gas clouds moving supersonically through a magnetized low-density medium. They took a passive magnetic field and found that the synchrotron emission from relativistic electrons increases rapidly when the cloud begins to fragment under Rayleigh-Taylor instability. The synchrotron emission is dominated by field enhancement through stretching in the shear turbulent layers formed between and behind the fragments. Jones, Ryu, & Tregillis (1996) performed full, two-dimensional MHD calculations and found that when the ambient field is transverse to the flow, fast amplification of the field also occurs at the nose of the cloud and not only in the turbulent regions.

Dgani et al. (1998) present a radio map of the central region of A30. The map shows an extended source of about 0.15 mJy stretching from the central star to a point 3° to the west. Based on a comparison with the optical line emission from that region, they claim that the source is probably nonthermal. Motivated by this recent finding, we apply the theoretical results of Jones et al. (1994, 1996) to the interaction of a magnetic fast wind with knots in PNe. The amplification of the magnetic field is calculated in §2, while in §3 we estimate the nonthermal radio emission from the interaction region. In §4 we summarize and list PNe, other than A30 (Dgani et al. 1998), that we expect to have nonthermal radio emission.

2. INTERACTION OF DENSE KNOTS WITH A MAGNETIZED WIND

Like CL, we examine a slowly rotating central star, for which the tangential component of the magnetic field dominates far from the star. For a field line that starts radially from the stellar equator, the downstream tangential component of the field at \( r \gg r_s \), where \( r \) is the distance from the central star and \( r_s \) its radius, is given by

\[
B = B_s \frac{v_{rot}}{v_w} \frac{r}{r^2},
\]

where \( v_{rot} \) is the equatorial velocity of the rotating star, \( v_w \) is the fast wind terminal velocity, and \( B_s \) is the (radial) magnetic field on the stellar surface. Since both the magnetic pressure \( B^2/8\pi \) and the ram pressure \( \rho v_w^2 \) drop as \( r^{-2} \) before hitting the shock wave, it is useful to define the parameter (CL)

\[
\sigma = \frac{B^2}{4\pi \rho v_w^2} = \frac{B^2 r^2}{M v_w^3} \left( v_{rot} \right)^2,
\]

where \( \dot{M} \) is the mass-loss rate to the fast wind and \( \rho = M (4\pi r^2 v_w)^{-1} \) is the density in the wind; \( \sigma \) is the ratio of field
energy density to kinetic energy density in the wind. CL find
that the magnetic field shapes the nebula for \( \sigma \approx 10^{-8} \). From
equation (2), we can write the magnetic field in the equatorial
plane in the free wind as

\[
B = 3.5 \times 10^{-7} \left( \frac{\sigma}{10^{-8}} \right)^{1/2} \left( \frac{M}{5 \times 10^{-8} M_\odot \, \text{yr}^{-1}} \right)^{1/2}
\times \left( \frac{v_w}{4000 \, \text{km s}^{-1}} \right)^{1/2} \left( \frac{r}{10^{16} \, \text{cm}} \right)^{-1} \text{G}.
\] (3)

The mass-loss rate is scaled according to the value Borkowski
et al. (1995) used for A30.

Let us consider first a single globule with radius \( R_g \). A super-
sonic flow incident on it will form a bow shock at its nose, a
turbulent shear layer around its sides, and a turbulent wake
behind it. The magnetic field is expected to be enhanced in
these regions because of line stretching (e.g., Jones et al. 1994,
1996). As shown in the extensive numerical simulations of
Jones et al. (1996), when the magnetic field lines are transverse
to the flow, the magnetic pressure on the nose of the clump
reaches equipartition with the ram pressure, even if the initial
magnetic field is quite weak. Using their analysis for the nu-
cerical results, we can estimate the growth rate of the magnetic
field by the following considerations (their eqs. [8]–[10]).

Jones et al. (1996, eq. [8]) start with the ideal MHD magnetic
induction equation

\[
\frac{d \ln (B/\rho)}{dt} = \frac{B \cdot (\nabla \times u)}{B^2},
\] (4)

where \( u, \rho, \) and \( B \) are the velocity, the density, and the magnetic
field in the flow, respectively. Taking \( (B \cdot \nabla) u \sim \Delta u R_{cl} \), equa-
tion (4) becomes

\[
\frac{d \ln (B/\rho)}{dt} = \frac{u}{R_{cl}}.
\] (5)

The last equation gives exponential growth to the magnetic
field as long as the magnetic field lines stay near the stagnation
point. Jones et al. (1996) estimate that at the stagnation point,
the magnetic pressure will rise exponentially until the bullet is
crushed or until the magnetic pressure equals the ram pressure.
However, since they performed two-dimensional calculations,
they neglected the sliding of the magnetic field line around the
bullet. Although they claim that irregularities in the three-
dimensional spherical bullet will capture the field lines and
prevent sliding, we believe that for a flow with very large
\( \beta = P_\rho/P_B \), the field lines will be carried around the globule in
a time \( \approx R_p/u \), much shorter than the bullet’s crushing time.
Here \( P_\rho \) and \( P_B \) are thermal and magnetic pressures, respectively.

Other sites of magnetic field enhancement are the turbulent
mixing layer at the sides of the globule and its turbulent wake.
These are more promising sites, mainly because the clumps
(globules) appear in groups and turbulent flows dominate the
region.

In here, we consider the flow around and inside an ensemble
of clumps, occupying a region of size \( R_{ens} \). The typical distance
between the clumps is on the order of their size \( R_g \). This case
has not been studied numerically, but we can apply an analytical
approach to estimate the magnetic field enhancement. A tur-
bulent flow will form between the globules, where the magnetic
field can be amplified. There, the change of the wind velocity
\( u \) along a field line depends on the size of the mixing layer
\( l \sim R_g \). That is, \( (B \cdot \nabla) u \sim \Delta u R_{cl} \). The time a field line spends
in the turbulent region is the time it takes the flow to pass the
group: \( R_{ens}/u \). Substituting these values in the induction equa-
tion (4) and integrating over the time the field lines spend inside
the group of globules give the relative amplification

\[
B/\rho \sim \exp \left( \frac{R_{ens}}{R_g} \right).
\] (6)

For \( R_g \sim 0.1 R_{ens} \), for example, there is a large amplification
factor of \( \sim 10^4 \). Therefore, the magnetic field will reach equi-
partition even if its initial value is \( \sim 10^{-4} \) that of equipartition,
i.e., \( \sigma \sim 10^{-8} \) (eq. [2]). In the model of CL and Garcia-Segura
(1997), the postshock magnetic field grows as \( B \sim r \), which
gives a factor of \( \sim 10-100 \) for the magnetic field and \( \sim 100-10^4 \)
for the magnetic pressure. Since CL assume that the magnetic
field shapes the PN globally, they have to assume that the initial
magnetic pressure is \( \sim 10^{-12} \rho^2 v^2 \), where \( \rho v^2 \) is the fast wind’s
ram pressure. This means \( \sigma > 10^{-4} \). In the flow pattern assumed
here, the localized turbulence results in a much larger increase
in the magnetic field. Therefore, to achieve equipartition be-
tween the magnetic pressure and the postshock thermal
pressure, a value of \( \sigma \approx 10^{-8} \) is sufficient.

3. NONTHERMAL RADIO EMISSION

The upper limit for the enhanced magnetic field is the equi-
partition value, found from the relation \( P_\rho = \rho v^2 \),

\[
B_{\max} = 5 \times 10^{-3} \left( \frac{M}{5 \times 10^{-8} M_\odot \, \text{yr}^{-1}} \right)^{1/2}
\times \left( \frac{v_w}{4000 \, \text{km s}^{-1}} \right)^{1/2} \left( \frac{d}{10^{16} \, \text{cm}} \right)^{-1} \text{G},
\] (7)

where \( d \) is the distance between the central star and the group
of globules. If the relativistic electrons are produced in the bow
shock and then carried downstream to the magnetized region,
they can emit synchrotron radiation. We assume equipartition
between the magnetic field and relativistic particles (electrons
and nuclei). The radio luminosity between \( \nu_1 \) and \( \nu_2 \) can then be
estimated if the spectral index \( \alpha \) (i.e., the flux \( F_\nu \propto \nu^{-\alpha} \))
of the radiation is known (cf. Pacholczyk 1970, p. 171, eq. [7.14]).
The radio luminosity is given by

\[
L = \frac{B^{7/2} \Phi R_{ens}^3}{4.5 (1 + k) c_{12} (\alpha, \nu_1, \nu_2)},
\] (8)

where \( \Phi \) is the fraction of the ensemble volume occupied by
magnetic field and relativistic particles, \( k \) is the ratio of the
heavy particle energy to the electron energy, and \( c_{12} (\alpha, \nu_1, \nu_2) \) is tabulated in Appendix 2 of Pacholczyk.

Taking \( \nu_1 = 10^7 \) Hz and \( \nu_2 = 10^{11} \) Hz, \( \alpha = 0.75 \), for which
\( c_{12} = 5 \times 10^7 \) and \( k = 100 \) (Chevalier 1977, 1995), we obtain

\[
L = 4.9 \times 10^{28} \phi \left( \frac{R_{\text{eas}}}{5 \times 10^{13} \text{ cm}} \right)^3 \times \left( \frac{B}{5 \times 10^{-3} \text{ G}} \right)^{7/2} \frac{\text{erg s}^{-1}}{7/2} \text{ mJy}.
\]

(9)

The radio flux at 1 GHz can now be estimated:

\[
F_{\nu} \approx 3.5\phi \left( \frac{R_{\text{eas}}}{5 \times 10^{15} \text{ cm}} \right)^3 \times \left( \frac{B}{5 \times 10^{-3} \text{ G}} \right)^{7/2} \left( \frac{D}{10 \text{ kpc}} \right)^{-2} \text{ mJy},
\]

(10)

where \( D \) is the distance to the source, and 1 mJy = \( 10^{-29} \) W m\(^{-2}\) Hz\(^{-1}\). This is at the lower end of the range of thermal radio fluxes observed from PN shells, which is less than a few millijanskys (Zijlstra, Pottasch, & Bignell 1989). However, the emission we predict is far from the PN shell, near the central star, and will not be overwhelmed by thermal emission. Chevalier (1995) discussed the case in which nonthermal electrons are produced in the fast wind termination shock and then carried downstream to the magnetized region near the shell. In this case, the nonthermal emission region neighbors the thermal emission region and cannot be separated observationally. Therefore, Chevalier concluded that a search for radio synchrotron emission from planetary nebulae would involve a frequency lower than 1 GHz.

Dgani et al. (1998) show an 8 GHz radio map of the hydrogen-deficient PN A30. They present a source of \( \sim 0.1 \) mJy that extends to about 3\(^{\circ}\) west of the central star. A30 possesses a large shell (120\(^{\circ}\)), which is visible in both H\(\alpha\) and O III, and a hydrogen-deficient central region, which is visible in O III but not in H\(\alpha\) (Jacoby 1979). The radio emission emanates from the central region. The source extends to the vicinity of the main blobs of the HST image (Borkowski et al. 1995), but it cannot be identified with any of them. This is compatible with our model, where the radio emission results from magnetic amplification in the turbulent region formed by decelerating clumps.

A somewhat parallel situation occurs in young supernova remnants (SNRs). In the SNR Cassiopea A (Cas A), the radio knots as well as the optical knots appear to be connected to the clumpy component of the ejecta; however, they are not identical. Anderson et al. (1994) analyze the observations of optical and radio emission knots in the SNR Cas A. They claim that while the clumps are almost certainly sites of particle acceleration, when there is substantial magnetic field growth, it will enhance the synchrotron emission. Complex flow patterns bring in particles that were accelerated in different regions. In young SNRs, particles are produced in many acceleration sites: the blast-wave shock, the reverse shock, and many internal interaction shocks. Thus, the enhanced emission in the radio knots is probably a result of field amplification. The numerical simulations of Jun & Jones (1998) and of Jun, Jones, & Norman (1996) support this conclusion.

4. DISCUSSION AND SUMMARY

We studied the interaction of a weakly magnetized fast wind, of velocity \( v_w > 1000 \) km s\(^{-1}\), blown by the central stars of PNs with high-density condensations, and we propose that it leads to the amplification of the magnetic field. When this interaction is with a cluster of clumps, the magnetic field lines are trapped for a long time in the interaction region. This process is equivalent to the numerical simulations of Jones et al. (1996), in which the two-dimensional nature of the flow did not allow the magnetic field lines to slide around the condensation. Jones et al. (1996) found that the magnetic field can reach equipartition with the wind’s ram pressure.

The enhanced magnetic field will have several effects: (1) It will reduce the mixing (entrainment) of the clump material with the fast wind. (2) It will reduce the heat conduction between the cool clump and the hot, shocked fast wind material. (3) The magnetic field lines will reconnect among themselves. This process may lead to heating and further X-ray emission. (4) It may result in nonthermal radio emission. The first three processes will affect the X-ray emission from the hot material.

In the current study, we did not examine these processes. Here we explored and concluded that the expected nonthermal radio emission can be detected in PNs with fast winds and clumps close to the central star. Such a PN is A30 (Dgani et al. 1998), which is claimed also to have extended X-ray emission that partially overlaps with the location of the optical condensation (Chu, Chang, & Conway 1997).

The required initial magnetic field for detectable nonthermal radio emission is \( \sim 2 \) orders of magnitude lower than the field intensity required to influence the shape of PNs, according to the model of CL and Garcia-Segura (1997). The stronger magnetic field required by CL and Garcia-Segura (1997) requires much faster rotation, as shown by equation (2) with \( \sigma > 10^{-4} \). This is very problematic for their model, since the central stars of PNs are expected to rotate slowly because of mass loss. This is true even if their asymptotic giant branch (AGB) progenitors are spun up by companions on the AGB (Soker 1998). The field in the model of CL and Garcia-Segura (1997) is globally large. The amplification of the magnetic field through the interaction of the magnetized wind with a cluster of condensations, on the other hand, enhances the field locally, but not globally. Therefore, the detection of strong magnetic fields in specific locations in PNs does not necessarily mean that the magnetic field is globally strong.

The process proposed in this study predicts detectable radio synchrotron emission from PNs having fast winds and high mass-loss rates, both of which determine the magnetic field intensity (eq. [7]) and optical condensations. In order to detect this synchrotron emission, we need to resolve the central region of the nebula from the shell. This requires high spatial resolution observations.

To list several PNs, in addition to A30, for which we expect nonthermal radio emission, we select PNs having fast winds from Patriarchi & Perinotto (1991) and check their optical images for condensations in the inner region. We find that from the list of Patriarchi & Perinotto (1991), only NGC 2371 and NGC 7094 show no structure in the very inner regions. Therefore, in general, all PNs with fast winds blown by their central stars should be searched for nonthermal emission, in particular, those with strong condensations in their central regions: A78, NGC 5189, and NGC 6210.

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