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Cyclotron Radiation: a Jet-Driving Mechanism in Magnetized PN Nuclei

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Abstract. We claim that cyclotron radiation at the electron gyrofrequency ω_B is an efficient mechanism capable of driving highly collimated bipolar jets in magnetized nuclei of planetary nebulae.

Magnetic fields of white dwarfs (WDs) amount to $B_{\rm WD} \sim 10^6 - 10^9\,$G (see, e.g., Wickramasinghe & Ferrario 2000). Hence, planetary-nebula nuclei (PNNi), the WD progenitors, can also have magnetized degenerate cores with radii similar to the WD radius $R_{\rm WD} \sim 10^9\,$cm and magnetic fields about $B_{\rm WD}$. A magnetic field gives rise to the strong cyclotron resonance between plasma and radiation at the electron gyrofrequency $\omega_B = eB/(mc)$, where e and m are the electron charge and mass, and c is the speed of light. Cyclotron interaction of radiation with electrons in a magnetized plasma leads to the radiation pressure force per unit volume (cf. Zheleznyakov 1996)

$$\boldsymbol{f}_B = \frac{2\pi^2 e^2 N}{mc^2} \int_{-\infty}^{+\infty} \phi(\xi)\,\mathrm{d}\xi \oint_{4\pi} (1+\cos^2\alpha)\, I_{\omega 1}(\omega_B/[1-\sqrt{2}\beta_{T\parallel}\xi\cos\alpha],\alpha)\,\boldsymbol{n}\,\mathrm{d}\Omega\,,$$

where N is the electron number density, α is the angle between $\boldsymbol{B}$ and the photon wave vector $\boldsymbol{n}$, Ω is the solid angle, $\beta_{T_\parallel} = (\kappa T_\parallel/mc^2)^{1/2}$, $T_\parallel$ is the longitudinal plasma temperature with respect to $\boldsymbol{B}$, $\phi(\xi) = \pi^{-1/2}e^{-\xi^2}$ describes the Doppler profile of the cyclotron line, and $I_{\omega 1}(\omega,\alpha)$ is the specific intensity of the elliptically polarized extraordinary mode whose polarization ellipse in the plane perpendicular to $\boldsymbol{n}$ is similar to the projection of the electron Larmor circle onto this plane. The electric-field vector of this mode rotates in the same direction as an electron in a magnetic field. The force f_B is a factor of about $(fX)^{-1} \gg 1$ greater than the radiation pressure from ion resonance lines in atmospheres of luminous early-type stars (f and X are the oscillator strength and abundance of the corresponding ion transition). Thus, the cyclotron radiation pressure can be an efficient mass-loss mechanism in strongly magnetized stars.

Let the magnetized core of a PNN have surface gravity $g_* \simeq g_{\rm WD}$, radius $R_* \simeq R_{\rm WD}$, dipole magnetic field $B = (B_*/2\rho^3)\sqrt{1+\cos^2\Theta}$ (here $\rho = r/R_*$, Θ is the angle between the radius-vector $\boldsymbol{r}$ from the core center and the magnetic axis, and $B_* \sim B_{\rm WD}$ is the magnetic-pole field), and temperature $T_* \sim 10^5 - 10^6\,$K, and emit the blackbody radiation with the intensity $B^*_\omega(\omega) = \omega^2\kappa T_*/(8\pi^3 c^2)$ per one mode (we assume that the Rayleigh–Jeans limit holds for $\omega \simeq \omega_B$). According to Zheleznyakov, Serber, & Kuijpers (1996), the radiation-driven acceleration of optically thin hydrogen plasma along the magnetic axis is given by

$$a_B(\rho) = f_B(\rho)/m_{\rm p} = \Gamma^*_B g_*[\rho^{-8} - \rho^{-10}/4],$$

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where $\Gamma_B^* = (4\pi^3 e^2/mc^2) B_\omega^*(\omega_{B*})/(m_\mathrm{p} g_*) \simeq 400\, B_8^2 T_6 g_8^{-1}$ is the ratio of the cyclotron radiation pressure force to the gravitational force, $g_8 = g_*/10^8 \mathrm{cm\,s^{-2}}$, $B_8 = B_*/10^8$G, and $T_6 = T_*/10^6$K. The integral

$$v_\infty^2 = \int_1^\infty 2R_* a_B(\rho)\,\mathrm{d}\rho = v_\mathrm{esc}^2 \Gamma_B^* (1/9 - 1/44)\,,$$

shows that the terminal velocity $v_\infty \simeq 2.66 \times 10^9\, B_8 T_6^{1/2} R_9^{1/2}$ cm/s of the plasma accelerated by the cyclotron radiation along the magnetic axis exceeds the escape velocity of the core, $v_\mathrm{esc} = \sqrt{2g_* R_*} \simeq 4.5 \times 10^8\, g_8^{1/2} R_9^{1/2}$ cm/s, if $g_8^{1/2} \lesssim 6 B_8 T_6^{1/2}$, where $R_9 = R_*/10^9$ cm. Thus, cyclotron radiation can drive bipolar plasma jets along the open field lines close to the magnetic axis of the PNN core.

The plasma density N along a dipolar field line $\rho(\Theta) = (\sin\Theta/\sin\Theta_*)^2$ can be found from the condition of mass conservation: $N(\Theta)v(\Theta) \sim (J_*/2)\sin^6\Theta_*$, where Θ_* is the angle at which the field line crosses the PNN core. The particle flux J_* injected per unit surface area at the foots of the field line, where $\Theta = \Theta_*$, can be estimated from the maximum amount of momentum available in the form of cyclotron radiation to drive an opaque flow (Zheleznyakov et al. 1996; cf. also Lamers & Cassinelli 1999):

$$J_* \simeq \pi B_\omega^*(\omega_{B*})\omega_{B*}/(m_p c^2) \sim 7 \times 10^{15}\, B_8^3 T_6 \ \mathrm{cm^{-2} s^{-1}}.$$

The opening angle Θ_*^jet of the polar jet can be determined from the condition that the dynamic pressure $2m_\mathrm{p} N v^2$ of the bipolar plasma flow is equal to the magnetic-field pressure $B^2/(8\pi)$ at the top of the field line corresponding to $\Theta_* = \Theta_*^\mathrm{jet}$. Estimating $v(\Theta = \pi/2) \simeq v_\infty$ and $B(\Theta = \pi/2) \simeq (B_*/2)\sin^6\Theta_*$ for a narrow jet ($\Theta_*^\mathrm{jet} \ll 1$) at the top of a dipolar field, we obtain

$$\Theta_*^\mathrm{jet} \sim \left[32\pi J_* v_\infty B_*^{-2}\right]^{1/6} \simeq 0^\circ\!.5\, B_8^{1/3} T_6^{1/4} R_9^{1/12}.$$

Thus, cyclotron-radiation-driven acceleration of plasma near a strongly magnetized ($B_* \sim 10^8$ G), hot ($T_* \sim 10^5 - 10^6$ K) PN core, whose free-fall acceleration $g_* \sim 10^8$ cm/s^2 and the radius $R_* \sim 10^9$ cm are similar to those of a typical white dwarf, can form bipolar, highly-collimated jets oriented along the dipole magnetic axis, which have high terminal velocities $v_\infty/c \sim 0.01 - 0.1$ and opening angles of about a fraction of degree.

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