# Circumnuclear Starburst Rings in Spiral Galaxies

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**Abstract** We advance a physical scenario for the origin of circumnuclear starburst rings on kiloparsec (kpc) scales in Seyfert galaxies that involve gravitationally excited spiral fast magnetohydrodynamic (MHD) density waves at the modified inner Lindblad resonance (mILR) in a central magnetized gas disk. Within corotation, an effective damping of these sustained fast MHD density waves will continuously reduce the disk angular momentum and thus lead to a ringlike accumulation of gas materials and magnetic flux inside the mILR which, during a critical stage, would be vulnerable to massive star formation at smaller scales. Depending on the effectiveness of MHD density wave damping, several qualitatively different outcomes for central activities in Seyfert galaxies may develop.

## 1 A Brief Overview

We mainly focus on circumnuclear starburst activities on kiloparsec (kpc) scales in Seyfert galaxies. We shall use multiwavelength observations of the starburst ring in the nearby barred spiral galaxy NGC1097 as an example to illustrate the basic idea. We emphasize that magnetohydrodynamic (MHD) density waves should play an important role and therefore radio-continuum observations in the circumnuclear region with high resolution and sensitivity are extremely valuable in understanding the formation and dynamics of circumnuclear starburst rings. Here, we offer several important clues that lead to our scenario on circumnuclear starburst rings in spiral galaxies.

The density wave theory initiated by Lin & Shu (1964) has stimulated fruitful research on various aspects of large-scale structures and dynamics of spiral galaxies. There is now a growing appreciation for the density wave theory in understanding the disk stability, the angular momentum transport and the mass transfer in a differentially rotating disk. In essence, if one treats a stellar disk as a fluid, a spiral density wave involves epicyclic oscillations, self-gravity, and stellar velocity dispersion mimicked as an effective sound speed in a differentially rotating disk. The dispersion relation can be readily derived in the WKBJ or tight-winding approximation. A density wave carries a negative or positive angular momentum inside or outside the corotation radius, respectively.

In a series of papers by Goldreich & Tremaine (1979, 1982), the galactic density wave theory was adapted to the Keplerian dust disk around the Saturn. Specifically, the gravitational potential perturbation of the Mimas satellite excites outgoing long trailing density waves at the inner Lindblad resonance (ILR). Without dissipations, such waves would be reflected at the so-called $Q-$barrier in the form of incoming short trailing density waves. By inevitable viscous damping in the dust disk of Saturn, these density waves, carrying negative angular momentum within corotation, effectively remove angular momentum from the disk. During the lifetime of the solar system, dust materials in the disk have been gradually cleared up to form the widest Cassini division. Likewise, other satellites of Saturn give rise to corresponding gaps at appropriate resonance locations to form the Saturn ring system we observe today.

Synchrotron radio emissions reveal magnetic fields and relativistic cosmic-ray electrons in spiral galaxies. For nearby spiral galaxies, which can be mapped in details, total radio-continuum emissions show large-scale spiral structures that largely follow optical spiral arms. Likewise, polarized radio-continuum emissions also show large-scale spiral structures in associations with optical spiral arms, yet with two distinct possibilities. In the case of M51 (e.g, Neininger 1992; Berkhuijsen et al. 1997), polarized radio emissions are strongest along the dust lanes at the inner edges of optical arms. In contrast, for NGC 6946 (e.g., Beck & Hoernes 1996; Frick et al. 2000), polarized spiral arms are interlaced with the optical spiral arms. With these facts in mind, we proposed (Fan & Lou 1996; Lou & Fan 1998) the scenario of fast and slow MHD density waves (FMDWs and SMDWs) that can exist in the magnetized disk of interstellar medium (ISM). Recently, we have further shown that SMDWs can also persist extensively in a disk with a flat rotation curve in the form of stationary logarithmic spirals with displaced optical and magnetic arms (Lou & Fan 2002; Shen & Lou 2003).

As a thin circumnuclear disk involves magnetic field and differential rotation, it is natural to study the roles of circumnuclear MHD density waves, their excitation at the ILR, and their effective damping to form circumnuclear starburst rings on kpc scales and central AGNs (Lou et al. 2001).

## 2 Theoretical Formulation and Main Results

With a high stellar velocity dispersion ( $\gtrsim 100\,\mathrm{km\,s^{-1}}$) in the central bulge and a low gas temperature, the circumnuclear region of a spiral galaxy contains a thin gas disk within a few kpcs. The gas rotation curve in an extended radial range is determined by the total mass distribution in the galaxy (Meaburn et al. 1981; Blackman 1981; Gerin et al. 1988; Ondrechen et al. 1989) and the *background* magnetic field in the circumnuclear disk plane of a strength $\gtrsim$ several tens of $\mu$G (Beck et al. 1999) is presumed to be axisymmetric and azimuthal to avoid the magnetic-field winding dilemma. This circumnuclear magnetized gas disk is embedded with molecular clouds (Gerin et al. 1988) with a mean-free path $l_c$ and a velocity dispersion $v_c$. Spiral FMDWs involve collectively the magnetized gas disk embedded with clouds. For NGC 1097, the large-scale *barred spiral structure outside* the central gas disk rotates at a pattern speed $\Omega_p$ and gives rise to an *external* periodic gravitational potential $\phi^E$ as felt by the magnetized central disk. In cylindrical coordinates $(r, \theta, z)$, our model is developed using the standard two-dimensional equations for coplanar MHD density waves in the central magnetized gas sheet (Lou & Fan 1998) at $z = 0$ with $\phi^E$ varying slowly in $r$ as the inhomogeneous driving term.

Without $\phi^E$ driving and away from the resonances, the dispersion relation for free FMDWs in the WKBJ or tight-winding regime is

$$(\omega - m\Omega)^2 \approx \kappa^2 + k^2(C_A^2 + C_S^2 + v_c^2 - 2\pi G\mu_0/|k|) \ , \tag{1}$$

where $v_c^2$ mimics an “effective pressure” due to random cloud velocities $v_c$, $\omega$ is the angular frequency in an inertial frame of reference, $m \geq 0$ is an integer for the number of spiral arms, $\Omega$ is the disk angular speed, $\kappa \equiv [(2\Omega/r)d(r^2\Omega)/dr]^{1/2}$ is the epicyclic frequency, $G$ is the gravitational constant, $\mu_0$ is the background surface mass density, $k$ is the radial wavenumber, $C_S$ is the sound speed, and $C_A$ is the Alfvén speed (Lou & Fan 1998). The relevant FMDW amplitude equation (Fan & Lou 1999) is

$$\frac{d}{dr}\left[\frac{r\mu_0 k}{(\omega-m\Omega)^2}\left(C_S^2+v_c^2+C_A^2-\frac{\pi G\mu_0}{|k|}\right)|\tilde{v}_r|^2\right]=0\ , \tag{2}$$

where $\tilde{v}_r(r)$ is the magnitude of the radial velocity $v_r$. Equation (1) contains the familiar short- and long-branches of FMDWs (Lou & Fan 1998). For FMDWs, one has $B_\theta\mu\cong\mu_0 b_\theta$, where $\mu$ is the surface mass density perturbation, and $b_\theta$ and $B_\theta$ are the perturbation and background azimuthal magnetic fields, respectively.

The MHD stability against axisymmetric ring fragmentation requires $Q_M\equiv\kappa(C_A^2+C_S^2+v_c^2)^{1/2}/(\pi G\mu_0)>1$ in a magnetized self-gravitating gas disk (Lou & Fan 1998, 2002; Shen & Lou 2003). The radial group velocity of FMDWs becomes

$$F_G=-\frac{\partial\omega}{\partial k}\cong-\frac{\mathrm{sgn}(k)[(C_A^2+C_S^2+v_c^2)|k|-\pi G\mu_0]}{(\omega-m\Omega)}\ , \tag{3}$$

with $F_G>0$ and $F_G<0$ for outgoing and incoming waves. Here, $k>0$ and $k<0$ represent leading and trailing spirals. Inside corotation of FMDWs, wave energy travels away from the disk center for long-trailing and short-leading FMDWs; wave energy travels toward the disk center for long-leading and short-trailing FMDWs. Outside corotation of FMDWs, the directions of energy flow reverse for all these FMDW types.

The angular momentum flux carried by a FMDW now becomes

$$\mathcal{F}_J=-\frac{\pi mkr\mu_0}{(\omega-m\Omega)^2}\left(C_S^2+v_c^2+C_A^2-\frac{\pi G\mu_0}{|k|}\right)|\tilde{v}_r|^2\ , \tag{4}$$

with the surface densities of angular momentum $\mathcal{J}^F\equiv m\mu_0|\tilde{v}_r|^2/[2(\omega-m\Omega)]$, of energy $\mathcal{E}^F=\omega\mathcal{J}^F/m$ and of wave action $\mathcal{N}^F=\mathcal{J}^F/m$. Inside and outside corotation, $\mathcal{J}^F$ is negative and positive, respectively. By eqns (2) and (4), the angular momentum flux of free FMDWs is conserved. The corotation at $\omega-m\Omega(r_c)=0$ is forbidden to wave access by the $Q_M$-barrier when $Q_M\gtrsim 1$, and in the WKBJ regime, the slightly modified Lindblad resonances occur at $\Gamma\equiv\kappa^2-(\omega-m\Omega)^2+m^2C_A^2f(r)/r^2=0$ with $f(r)\sim\mathcal{O}(1)$ being a dimensionless factor. Outside the $Q_M$-barrier, long-FMDWs exist only within the two modified Lindblad resonances, while short-FMDWs propagate within and outside the two modified Lindblad resonances as in the hydrodynamic case.

By a massive bar, a satellite, or a large-scale spiral structure, an external gravitational potential $\phi^E(r,\theta,t)$ felt at the central gas disk induces FMDWs at the modified Lindblad resonances $r_M$. Around $r_M$, one writes $x\equiv(r-r_M)/r_M$ and $\Gamma\equiv\mathcal{G}_M x$ with sgn $\mathcal{G}_M=\pm1$ for *modified inner and outer Lindblad resonances* (mILR and mOLR). In the WKBJ limit, the set of inhomogeneous FMDW equations for small $x$ may be reduced to the familiar form in terms of the disk self-gravity potential $\phi$ as

$$\frac{d^2\phi}{dx^2}-i\alpha_M\frac{d\phi}{dx}-\beta_M x\phi=i\alpha_M\Psi\ , \tag{5}$$

where $\alpha_M\equiv-[2\pi G\mu_0 r/(C_S^2+v_c^2+C_A^2)]_{r_M}\mathrm{sgn}(k)$, $\beta_M\equiv[r^2\mathcal{G}_M/(C_S^2+v_c^2+C_A^2)]_{r_M}$, and $\Psi\equiv d\phi^E/dx+2m\Omega\,\phi^E/(m\Omega-\omega)$. The solutions of eq (5) involving Airy functions with proper energy flow directions are known; the physics of these solutions studied previously (without magnetic field and clouds) in contexts of large-scale galactic density waves (Goldreich & Tremaine 1979) and of planetary rings (Goldreich & Tremaine 1982) can now be extended and applied to a circumnuclear magnetized gas disk of a spiral galaxy.

By solutions of eq (5), long-trailing FMDWs are dominantly excited by $\phi^E$ at mILR and mOLR; these waves exist between the two resonances and propagate toward corotation after their generations at mILR and mOLR. Reflections at the $Q_M$-barrier transform these long-trailing FMDWs to short-trailing FMDWs that travel away from corotation and continue across the mILR and mOLR. In the case of mILR, long-trailing FMDWs sustained by $\phi^E$ carries a *negative* angular momentum toward corotation; a subsequent reflection at the $Q_M$-barrier gives rise to short-trailing FMDWs again carrying a *negative* angular momentum that may reach the disk center until being disrupted by small-scale ($\lesssim$ a few pc) nuclear processes.

## 3 Circumnuclear Spiral Arms and Starburst "Ring" of NGC 1097

NGC 1097 is a nearby barred spiral galaxy with a declination of $\sim -30°$ and an inclination estimated to range from $\sim 37°$ to $57°$. It is of Seyfert type with an AGN known as a LINER (Barth et al. 1995) and might host a supermassive black hole (SMBH) of $\sim 2 \times 10^{10} M_\odot$ (Rickard 1975). Estimates of its distance range from $11.6 - 17$ Mpc. It has a bright circumnulear starburst "ring" with a diameter of $\sim 18''$ and a far infrared (FIR) luminosity of $\sim 3 \times 10^{10} L_\odot$ (Telesco 1988; Gerin et al. 1988), forming stars at a rate of $\sim 5\, M_\odot\, \mathrm{yr}^{-1}$ (Hummel et al. 1987). The rotation curves were determined for $r \sim$ 4"—20", using $H_\alpha$ 6563Å and [N II] 6584Å (Meaburn et al. 1981; Blackman 1981) as well as CO (J=$1-0$) (Gerin et al. 1988), and for $r \sim$20"—6', using H I 21 cm despite a strong depletion in the bar region (Ondrechen et al. 1989). For 10"$\lesssim r \lesssim 20''$, the inferred rotation speed $V_\theta \sim 300\, \mathrm{kms}^{-1}$ remains roughly constant. The two dark dust lanes originating at $\sim 4'' - 5''$ follow along the inner edges of the two spiral arms and extend continuously out to the bar (Rickard 1975) with large arm pitch angles of $\sim 50°$ there. Shown in Fig. 1 is our wavelet analysis (Lou et al. 2001) on an *HST* image of central NGC 1097 (Barth et al. 1995) that reveals two distinct circumnuclear spiral arms extended inward to $\lesssim 1.5''$.

Synchrotron emissions (Ondrechen & van der Hulst 1983) at 20 cm reveal that the intensity contour closely follows the dust lanes along the bar and merges into the central region of $r \sim 30''$ to $35''$. The total radio intensity "ring" overlaps with the circumnuclear optical/infrared "ring" (Hummel et al. 1987; Telesco 1988), implying intense magnetic fields and profuse cosmic-ray electrons. Polarized radio emission at 22, 18, 6.2 and 3.5 cm (Beck et al. 1999) indicates that regular magnetic fields are parallel to the two dust lanes along the bar and gradually swirl into a trailing pattern. Relative to the circumnuclear "ring", magnetic fields are inclined by $\sim 50°$. Despite the limited resolution, it is indicative that a trailing spiral magnetic-field pattern inside the "ring" continues toward the nucleus. By this evidence and our Fig. 1, it is clear that spiral FMDWs (Fan & Lou 1996; Lou & Fan 1998, 2002) play a significant dynamic role in the circumnuclear region of a barred spiral galaxy, and magnetic fields provide an important radio diagnostics. For orientations along magnetic spiral arms, the tendency that magnetic field of central NGC 1097 seems to be axisymmetric instead of bisymmetric within the circumnuclear "ring" region may be understood from the intuitive picture of distorted unaligned magnetic-field rings for FMDWs (Lou & Fan 1998, 2002) analogous to that of distorted stellar orbits for density waves (Kalnajs 1973).

For NGC 1097, the mean magnetic field $B_\theta$ threads through the central thin HI gas disk embedded with $H_2$ molecular clouds. Spiral FMDWs interact with the magnetized HI gas and $H_2$ clouds together. Random motions of $H_2$ clouds provide an "effective pressure" and a damping mechanism for FMDWs. The mILR is identified at $r \sim 10''$, the outer rim of the circumnuclear "ring". For $m = 2$, $\Omega$ at mILR is $2 + \sqrt{2}$ times $\Omega_p$ in a flat rotation curve, the corotation is located around 30"$\lesssim r \lesssim$ 35", and the mOLR would be around 50"$\lesssim r \lesssim$60".

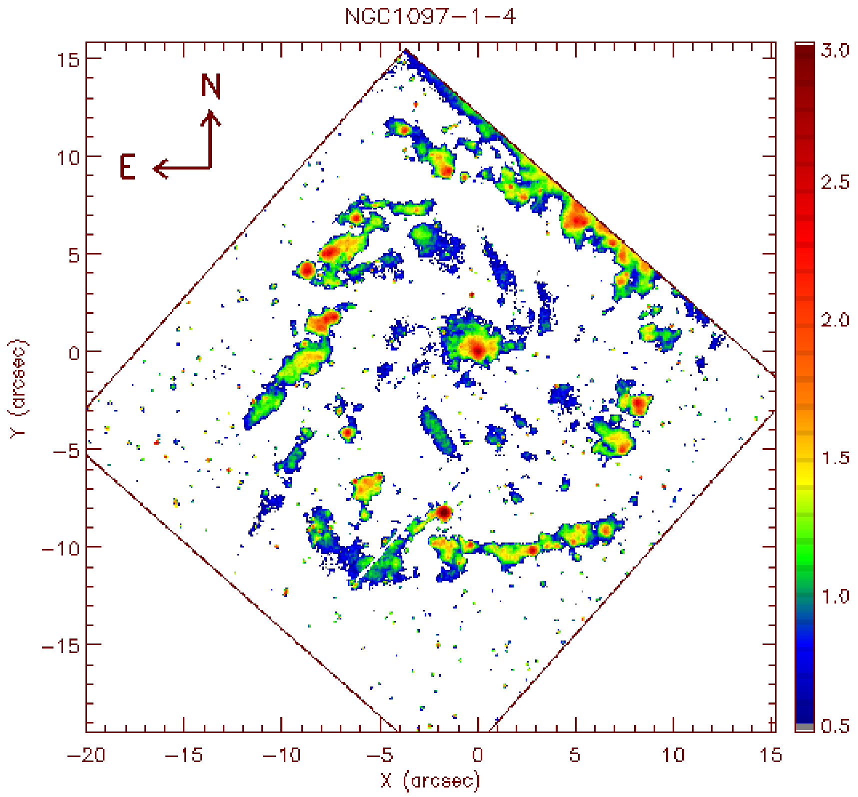


Fig. 1 A wavelet transformed and reconstructed WFPC2/HST (F555W filter) image in false color for the central spiral arms around and within the circumnuclear starburst "ring" of NGC 1097 showing a less than 2" angular scale.

Our emphasis is on wave processes around the mILR. Long-trailing FMDWs are excited and sustained at the mILR by $\phi^E$ and propagate toward corotation. They are reflected by the $Q_M$-barrier around corotation and travel backward to the mILR as short-trailing FMDWs. Inside corotation, both long- and short-trailing FMDWs carry *negative* angular momenta (Fan & Lou 1999). By dissipations, these FMDWs damp and deposit in the disk their negative angular momentum. As the disk angular momentum is reduced continuously, disk material outside the mILR gradually spirals inward, bringing along magnetic flux meanwhile. By this process, disk materials (HI and $H_2$ etc) and magnetic flux would accumulate inside the mILR. Regions of high gas density and enhanced magnetic flux naturally favor births of bright young massive stars as well as star clusters (Elmegreen 1994); this gives rise to a circumnuclear starburst "ring" inside the mILR. Outside the mILR, the strength of a long-trailing FMDW is stronger than that of a returning short-trailing FMDW by wave damping.

For estimates, we take $v_c \sim 35\,\mathrm{km\,s^{-1}}$ (Gerin et al. 1988) and $l_c \sim 100$ pc. The gross turbulent dissipation coefficient $\nu_c$ is $\nu_c \sim v_c l_c/3 \cong 3\times10^{26}\,\mathrm{cm^2\ s^{-1}}$. For a $B \sim 40\mu$G (Beck et al. 1999), a HI gas column density of $\lesssim 10^{21}\,\mathrm{cm^{-2}}$ (Ondrechen et al. 1989), a $H_2$ gas column density $\sigma_0 \sim 6\times10^{22}\,\mathrm{cm^{-2}}$ (Gerin et al. 1988) and a disk thickness $h \lesssim 100$ pc, the Alfvén speed is $C_A \sim 4\times10^5\,\mathrm{cms^{-1}}$. For a gas temperature $T \lesssim 100$ K°, the sound speed is $C_S \lesssim 10^5\,\mathrm{cms^{-1}}$. The $Q_M$ estimate is uncertain, as the corotation region 30"$\lesssim r \lesssim 35''$ for twoarmed spiral FMDWs may involve both stellar and magnetized gas disks; we take $Q_M \gtrsim 1$. Right at the mILR ($r \sim 10''$), the short wavelength is $\lambda_S = (C_A^2 + C_S^2 + v_c^2)/(G\mu_0) \sim 300$ pc, while the long wavelength $\lambda_L$ is infinite; at the reflection point of the $Q_M$-barrier ($r \sim 30''$), they become equal $\lambda_S = \lambda_L = 2(C_A^2 + C_S^2 + v_c^2)/(G\mu_0) \sim 600$ pc. For a mean radial wave lengthscale of $\bar{\lambda} \sim 450$ pc, the damping timescale is $\tau_c \sim \bar{\lambda}^2/\nu_c \cong 6 \times 10^{15}$ s. The wave timescale $\tau_w$ for a FMDW to go from the mILR to $Q_M$-barrier and back to the mILR is estimated to be $\tau_w \sim 3 \times 10^{15}$ s. Thus, a sizable fraction of negative angular momentum carried by long-trailing FMDWs sustained at the mILR would have been deposited in the disk as a remnant short-trailing FMDW returns to the mILR. As the disk angular momentum is reduced, gas materials with frozen-in magnetic flux from outside tend to accumulate inside the mILR to form a circumnuclear starburst "ring". An estimate of net mass inflow rate $\dot{M}$ involves several uncertain aspects because the magnitude of excited FMDWs relates to the strength of $\phi^E$ and the wave damping distribution depends on the effective viscosity as well as nonlinear effects. By taking a $|v_r| \sim 10\,\mathrm{kms}^{-1}$ and a $|\omega - m\Omega|r \sim 30\,\mathrm{kms}^{-1}$ in eq (4), an upper limit of $\dot{M}$ may be estimated by $\dot{M} \lesssim 10 M_\odot\,\mathrm{yr}^{-1}$. For a stronger $\phi^E$, nonlinear wave and damping effects may become important and this upper limit may be raised. The large pitch angle of $\sim 50°$ of optical arms (Rickard 1975) and magnetic field (Beck et al. 1999) outside the "ring" is interpreted in terms of long-trailing FMDWs sustained by $\phi^E$ at the mILR. As a test, it may be possible to detect a weaker short-trailing FMDW outside the "ring" superposed with the stronger long-trailing FMDW.

## 4 Discussion

In our scenario, the effectiveness of MHD density wave damping can give rise to qualitatively different outcomes for nuclear and circumnuclear activities around the centers of magnetized spiral galaxies. For a very weak damping, FMDWs excited at the mILR and reflected by the $Q_M-$barrier would travel to the nucleus; and disk processes on sub-kpc scales in the vicinity of the central SMBH would destroy these FMDWs that carry negative angular momentum. In this case, central accretions onto the SMBH should lead to an AGN with much less circumnuclear activities on kpc scales. For a very strong wave damping, FMDWs excited at the mILR are largely damped without even reaching the $Q_M-$barrier and therefore disk angular momentum is incessantly reduced *outside* the mILR. In this situation, circumnuclear accretion of gas and magnetic flux occurs somewhere inside the mILR. One thus expects a prominent circumnuclear starburst ring without necessarily involving an AGN. For an intermediate wave damping, a significant fraction of FMDWs excited at the mILR can be damped outside the mILR with remnant FMDWs coming towards the galactic neucleus. Thus, in addition to a circumnuclear "ring" of starbursts inside the mILR, remnant short-trailing FMDWs travel across the mILR and be partially enhanced by the $r^{-1}$ geometric converging effect. Damping of these remnant short-trailing FMDWs on sub-kpc scales around the nucleus would then induce a net accretion of gas and magnetic flux to fuel galactic nuclear activities.

For NGC 1097, in addition to the starburst "ring", circumnuclear tight-winding trailing spiral arms of FMDWs are detected (Fig. 1) down to the immediate environs of the nucleus ($r \lesssim 1.5''$). We identify this spiral structure inside the "ring" (Fig. 1) as remnant short-trailing FMDWs and suspect that the damping of these FMDWs plays a key role in fueling the central SMBH on sub-kpc scales. For future observational campaigns, it is crucial that coordinated and dedicated multiwavelength observations of circumnuclear regions of spiral galaxies would provide more detailed information. While already indicative, it is anticipated that refined maps of polarized radio-continuum emissions would eventually establish specific correspondences of spiral structures of gas density and magnetic field around and within the circumnuclear starburst "ring", analogous to those of galactic spiral structures on much larger scales. In particular, we expect the total and polarized radio-continuum spiral arms to closely follow the inner edges of circumnuclear optical spiral arms of NGC 1097 shown in Fig. 1.

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