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Fast magnetohydrodynamic density waves in spiral galaxies

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ABSTRACT

The newly observed large-scale structures of a southern grand-design spiral galaxy NGC 2997 in total and polarized radio-continuum emission together with their overall correlations with the known optical spiral structure are physically interpreted in terms of *fast* magnetohydrodynamic (MHD) density waves in contrast to *slow* MHD density waves in NGC 6946. The global spiral pattern of such fast MHD density waves extends from the very centre, where the disc rotates almost rigidly within ~0.5 arcmin, all the way to the outer disc with a more or less flat rotation curve. To strengthen the case, several known features of spiral galaxies M51 and IC 342 are referred to and their pattern identifications discussed. It is emphasized that the nature of a magnetized spiral galaxy would be much better appreciated by examining large-scale structures in optical, atomic hydrogen H I, total and polarized radio-continuum and infrared emission *together.* As various star-formation processes occur concurrently and/or sequentially in spiral arms of high gas concentration, relatively broad and fuzzy H I arms, roughly coincident with optical arms in the inner disc, are expected to extend from the extremities of fading optical arms further into the outer gas disc. We predict that the south-east 'magnetic arm', apparently isolated from any optical features, in total and polarized radio-continuum intensity maps of NGC 2997 should be associated with an H I gas arm yet to be detected in 21-cm line emission.

Key words: MHD – polarization – galaxies: individual: NGC 2997 – galaxies: individual: M51 – galaxies: individual: IC 342 – galaxies: individual: NGC 6946.

1 INTRODUCTION

For nearby spiral galaxies within tens of Mpc, it has been quite successful over the decades to map out in some detail total and polarized continuum emissions at radio wavelengths with ever-improving sensitivity and angular resolution (e.g. Mathewson, van der Kruit & Brouw 1972; Sofue, Fujimoto & Wielebinski 1986; Kronberg 1994; Beck et al. 1996 and references therein). Non-thermal radio-continuum emissions result from interactions between relativistic cosmic-ray electrons and galactic magnetic fields of several to a few tens μG in strength. The overall pattern correlation among large-scale galactic structures in optical, neutral hydrogen H I, total and polarized radio-continuum, CO, infrared, as well as other electromagnetic wavelengths clearly indicates that a *global* mechanism plus various subprocesses in a magnetized interstellar medium (ISM) should be mainly responsible for what have been observed.

It has been widely accepted that the density-wave scenario (Lin & Shu 1964; Toomre 1977; Binney & Tremaine 1987; Lin 1987; Bertin & Lin 1996) forms the physical basis for understanding various *large-scale* structural phenomena in spiral galaxies. In response to density waves in a more massive *stellar* disc, a thin *magnetized gas* disc in rotation can give rise to large-scale fast and slow magnetohydrodynamic (MHD) density waves (Fan & Lou 1996, 1997, 1999; Lou & Fan 1998a) through the mutual gravitational coupling within a composite disc system (Lou & Fan 1997, 1998b, 1999, in preparation). It is of vital importance to establish the sensible physical connection between MHD density waves in a magnetized gas disc and hydrodynamic density waves in a stellar disc, as most large-scale structures of a spiral galaxy are manifest of various subprocesses occurring in the magnetized ISM. In order to verify the MHD-density-wave scenario, it is essential to examine and compare at least optical and radio observations of *specific* spiral galaxies. As a real galactic system is never ideal, with various peculiar factors involved, we mainly aim at identifying the overall scenario; such kind of galactic applications is obviously important and worthwhile.

Recent observations of a southern grand-design spiral galaxy NGC 2997 in total and polarized radio continuum at 6.0, 3.5 and 13-cm wavelengths (Han et al. 1999) together with previously known optical observations provide an interesting case to confront the MHD-density-wave scenario. Except for the absence of a conspicuous companion, NGC 2997 bears a strong resemblance to

M51 (NGC 5194) in many respects. The main thrust of this letter is to interpret large-scale optical and radio-continuum spiral structures of NGC 2997 in terms of fast MHD density waves (Fan & Lou 1996; Lou & Fan 1998a). To make the case for NGC 2997 and to clarify the basic concepts, we also refer to relevant observations and pattern identifications of M51 and IC 342.We advance the point of view that large-scale structures of a spiral galaxy reveal coherent MHD density waves that should be comprehensively probed by optical, H I, total and polarized radio-continuum as well as other wavelength observations. We thus emphasize the necessity of juxtaposing images of a magnetized spiral galaxy at all these wavelengths in order to better appreciate its physical nature. In particular, H I spiral structures (usually extended to a much larger spatial extent) are an inseparable component in the overall MHD-density-wave scenario.

2 MHD-DENSITY-WAVE FEATURES IN MAGNETIZED SPIRAL GALAXIES

It should be made clear at the outset that MHD density waves discussed here require a background mean magnetic field, the origin of which still remains an important open question (Parker 1979; Ruzmaikin, Sokoloff & Shukurov 1988; Kronberg 1994; Beck et al. 1996; Zweibel & Heiles 1997; Shukurov 1998). In theoretical models (Lynden-Bell 1966; Roberts & Yuan 1970), it was presumed that such a background field is tangential to disc rotation or ring-like to avoid the known winding dilemma in a disc with a strong differential rotation. We have shown the existence and properties of fast and slow MHD density waves given such a field configuration (Fan & Lou 1996, 1999; Lou & Fan 1998a, in preparation). Note that fast and slow MHD density waves can also exist in other large-scale magnetic field configurations (e.g. a bisymmetric spiral case) on physical grounds, despite the increasing complexity of theoretical analysis.

The overall scenario is as follows. A typical system hosting a spiral galaxy consists of a massive spherical halo (dark matter included), a stellar disc, a magnetized gas disc, and perhaps, an oblate spheroid of cosmic-ray gas. The massive halo with high internal velocity dispersions plays crucial roles in sustaining the observed disc rotation curve and in stabilizing the disc (Ostriker & Peebles 1973). For large-scale structures in spiral galaxies, it turns out that one can yield most information by analysing compressible perturbations of a magnetized gas disc in rotation and by incorporating empirical insights on how these structures may be seen at various electromagnetic wavelengths. As in hydrodynamic density waves, self-gravity plays the key role of exerting a long-range influence over the entire magnetized gas disc. As the thermal, magnetic and cosmic-ray energy densities are comparable in magnitudes, both fast and slow MHD density waves can exist in such a disc system (Fan & Lou 1996; Lou & Fan 1998a) and can be identified from optical and radio (as well as other wavelengths) observations.

In the well-known Wentzel–Kramers–Brillouin (WKB) or tight-winding approximation, the dispersion relation of fast MHD density waves is

$$(\omega - m\Omega)^2 \cong \kappa^2 + k^2(C_{\mathrm{A}}^2 + C_{\mathrm{S}}^2 - 2\pi G\mu_\circ/|k|) \tag{1}$$

and the dispersion relation of slow MHD density waves is

$$(\omega - m\Omega)^2 \cong \frac{k^2 C_{\mathrm{A}}^2 (C_{\mathrm{S}}^2 - 2\pi G\mu_\circ/|k|) m^2/r^2}{\kappa^2 + k^2(C_{\mathrm{A}}^2 + C_{\mathrm{S}}^2 - 2\pi G\mu_\circ/|k|)} \tag{2}$$

(cf. Lou & Fan 1998a for specific definitions of notations and detailed discussions on properties of fast and slow MHD density waves). The most important feature of fast MHD density waves is that the enhancements of gas density and parallel magnetic fields are more or less in phase, while the most distinguished property of slow MHD density waves is that the enhancements of gas density and parallel magnetic fields are significantly phase-shifted ($\gtrsim \pi/2$). According to Lou & Fan (1997, 1998b, 1999), density arms in stellar and magnetized gas discs should overlap on large scales *within* the corotation radius where the local speeds of wave pattern and disc rotation are equal. Similar to galactic applications of hydrodynamic density waves by comparing theoretical and observational distributions of H I gas density and velocity fields along the line of sight (Lin, Yuan & Shu 1969; Visser 1980a,b), a comparison of observed line-of-sight H I velocity fields, H I gas density distribution and magnetic field perturbations with theoretical calculations serves as an important test of MHD-density-wave theory.

It is indeed a complex procedure to compare in detail structures and their inter-relations observed at various wavelengths and to pinpoint the specific underlying mechanisms. Even within a single galaxy, variance of a certain structural feature exists (e.g. Casoli 1991; Viallefond 1991). As much has been said about density waves in a stellar disc, the focus here is on more systematic structural correlation features in association with magnetic fields and cosmic rays over large scales in spiral galaxies. To do this, one needs to take into account relevant ISM subprocesses and a few realistic aspects of an actual galactic system, as described below.

First, red-light and near-infrared emissions reveal large-scale density-wave structures of moderate strengths in a stellar disc that contains relatively old stars. These spiral structures usually appear broad and smooth. Young massive OB stars and other Population I signatures generally associate with high-density gas arms in magnetized ISM. Spiral structures in blue light often appear more prominent and sharp. In these and other optical bands, narrow dense dust lanes, presumably ISM shocks along inner edges of optical arms, can usually be identified because dusts obscure light passage. This slight systematic shift of dust lanes from optical arm ridges is attributed to the delay in star formation.

Secondly, cosmic rays are confined by galactic magnetic fields and their distribution should be fairly smooth over large-scale structures within a disc (or an oblate spheroid) owing to MHD wave–particle interactions. In the central bulge and along spiral arms of star-forming regions, cosmic-ray concentrations are expected to be higher with broad profiles across spiral arms as a result of diffusion. Given such broad cosmic-ray distributions, synchrotron emissions are stronger at locations where magnetic fields are strong. In the presence of incessant turbulent processes in ISM, large-scale *ordered* magnetic fields tend to be disrupted (not necessarily completely) while small-scale *random* magnetic fields tend to be much more enhanced such that *total* non-thermal radio-continuum emissions are typically strong along dust lanes where shocks occur in the magnetized ISM.

Thirdly, in addition to the important discovery of a tight *global* correlation between the far-infrared and radio-continuum luminosities of galaxies, recent progress of instrumental and observational development in infrared and submillimetre bands offers an important means to examine large-scale structures within individual spiral galaxies. Large-scale enhancements of dust-grain concentrations would be expected to roughly overlap with gas arms resulting from entrainments by gravitational potential wells, by sufficiently frequent gas–dust collisions, and by magnetic field/dust coupling. Mid- and far-infrared emissions produced by the interaction of copious UV photons from young OB stars with dusts should outline broad large-scale spiral structures. Meanwhile, more cosmic rays associated with young OB stars can interact with enhanced random magnetic fields and thus give rise to strong *total* radio-continuum emissions. An overall correlation of mid- and far-infrared emissions with radio continuum in large-scale spiral structures is expected on this ground (cf. Hoernes, Berkhuijsen & Xu 1998 for the case of M31).

Fourthly, for fast MHD density waves in ISM, it is expected that ridges of total and polarized radio continuum follow narrow dust lanes and shift slightly relative to ridges of both optical arms in blue light and H I gas arms. As the typical lifetime of a star is $\lesssim 10^7$ yr, the magnitude of this slight systematic shift depends on the pattern speed of fast MHD density waves. *Theoretically, fast MHD density waves given by (1) can exist in a disc with a fairly general rotation curve, including both almost rigidly and differentially rotating disc portions* (Fan & Lou 1996; Lou & Fan 1998a).

Fifthly, for slow MHD density waves, it is expected that, as a result of small-scale turbulence, total non-thermal radio-continuum arms more or less follow H I gas arms and optical arms in blue light; the intensity peaks of *polarized* radio continuum (implying regular magnetic fields) are significantly phase shifted with respect to those of the *total* non-thermal radio continuum. Relative positions of Population I signatures may not differ much systematically as a result of a slower density-wave speed. *In contrast to fast MHD density waves, large-scale manifestation of slow MHD density waves is largely confined to a disc portion that rotates almost rigidly* (Fan & Lou 1996, 1997, 1999; Lou & Fan 1998a).

Sixthly, on theoretical grounds, fast and slow MHD density waves can coexist in a rotating galactic disc as a result of the transient Jeans instability, swing processes,[1] shear flows as well as non-linear couplings (Fan & Lou 1996, 1997; Lou & Fan 1998a; Rogava, Heirman & Poedts 1999). As slow MHD density waves tend to be confined to an almost rigidly rotating disc portion, there are several possibilities in the almost rigidly rotating disc portion of a spiral galaxy: (1) signatures of fast and slow MHD density waves are mixed with comparable strengths, (2) signatures of slow MHD density waves overwhelm, and (3) signatures of fast MHD density waves dominate. As for the galactic disc portion with a strong differential rotation, large-scale patterns of fast MHD density waves alone are most likely to appear.

Finally, as an integral part of global MHD density waves, spiral arms in H I gas, which coincide with optical arms at smaller radii, can persist to larger radii as optical features gradually fade. Small-scale activities keep going on along such H I arm extensions, but are not strong enough to produce a sufficient number of shining stars. At times, one can detect extensions of total and polarized radio-continuum arms corresponding to these H I arms but without apparent association of optical features. Note that along H I arms with an unusual conglomeration of clumps and clouds, local depolarization can also be effective.

3 COMPARISONS OF MULTIWAVELENGTH SPIRAL-GALAXY OBSERVATIONS

The size of radio emissions from a typical spiral galaxy is much larger than the size of the corresponding optical pattern. In fact, H I emission as well as total and polarized radio continuum usually show large-scale spiral structures (fuzzy and less perfect in some cases). From the perspective of MHD density waves, these radio and optical spiral patterns should be viewed together in a consistent manner because they are *concurrent* in the dynamical sense and involve various ISM subprocesses. We describe below three separate examples of magnetized spiral galaxies M51, IC 342 and NGC 2997.[2] For both spiral galaxies M51 and IC 342, there exist extensive publications of rotation curve, optical, non-thermal radio-continuum, and 21-cm H I observations. By these observations and direct pattern comparisons, we specifically emphasize that large-scale spiral structures in H I emissions are an integral part of the overall MHD-density-wave scenario. For NGC 2997, there are rotation curve and optical observations as well as the *currently ongoing* non-thermal radio-continuum observations (Han et al. 1999). So far, there is no published H I (21-cm) map of NGC 2997. Our main purpose is to make use of the available multiwavelength data of M51 and IC 342 as empirical support of our suggestion for NGC 2997. Meanwhile, we would emphasize the importance of forthcoming mid- and far-infrared observations of large-scale structures of these as well as other magnetized spiral galaxies (e.g. Hoernes et al. 1998 for M31) to complement the existing multiwavelength observations.

M51: Systematic multiwavelength observations of this magnificent 'whirlpool' galaxy have been extensively documented (cf. Rand 1993 and references therein). The ridge lines of total radio continuum track the dark dust lanes, which are slightly offset from the optical spiral pattern in blue light as a result of time delay in star formation (Mathewson et al. 1972). The large-scale H I structure also reveals extended fuzzy spiral arms in contrast to sharp optical arms (cf. figs 2 and 3 of Rots et al. 1990; Tilanus & Allen 1989, 1991). Similar to total radio-continuum emission, ridge lines of polarized radio-continuum arms (Neininger 1992; Berkhuijsen et al. 1997) also indicate slight systematic offsets with respect to optical spiral arms. For example, the polarized emission at 6 cm seems to be concentrated near the spiral arms. More specifically, the higher resolution (12 arcsec) 6-cm map shows that the magnetic field indeed closely follows the dust lanes (see figs 1 and 2a of Neininger & Horellou 1996). Most of the multiwavelength spiral structures occupy the disc region with a more or less flat rotation curve (Mathewson et al. 1972), while in radio continuum, CO, and near-infrared emissions (Lo et al. 1987; Zaritsky, Rix & Rieke 1993), spirals continue in the radial range between $r \sim 30$ arcsec and $r \sim 10$ arcsec within which the disc rotates almost rigidly. M51 has been identified as a clear case of fast MHD density waves (Fan & Lou 1996, 1997, 1999; Lou & Fan 1998a, in preparation) based on its tight correlation between optical and radio structures. We also see a close correlation of H I and optical arms in M51 as well as longer extensions of H I arms (Rots et al. 1990). As fast MHD density waves are fairly strong in M51, the size of the H I spiral pattern is only moderately larger

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[1] For the original hydrodynamic theory of swing amplification in spiral galaxies, the reader is referred to Goldreich & Lynden-Bell (1965) and Toomre (1981). In fact, this is related to a classical fluid problem which can be traced back to Lord Kelvin (1887).

[2] A vast amount of literature of observations for each of these spiral galaxies exists. Only limited references are cited for direct relevance and convenience of further search.

than the optical one. The reason is that star formation and the level of H I gas concentration are intimately connected.

IC 342: The optical spiral pattern of IC 342 is largely confined to the inner disc portion ($\lesssim$10 arcmin) with a nearly rigid rotation [see both figs 7 of Newton (1980a,b)]. The size of the radio-continuum emission region is, however, considerably larger than the optical one, with a spiral pattern of the ordered magnetic field extending from the centre outwards (fig. 9 of Gräve & Beck 1988). Krause (1993) presented evidence that ridges of polarized emission in the inner disc are located in the interarm regions of the optical spiral arms and the regular magnetic field is oriented along the ridges. In the outer disc, Krause, Hummel & Beck (1989) found large-scale isolated, somewhat asymmetric 'magnetic arms' in polarized emission extending far outside the optical spiral pattern (see their figs 2, 4 and 8). Note that the H I distribution is also asymmetric on large scales in the outer disc, which seems to imply a causal relationship. Furthermore, H I images of IC 342 show a much larger ($\lesssim$35 arcmin) spiral pattern with several broad fuzzy arms (plate 1 of Newton 1980b) that persist in the disc portion with a largely flat rotation curve (Newton 1980a,b). As expected, H I structure correlates well with Population I signatures in the inner disc and clear H I spiral arms are visible beyond the optical spiral pattern. Adjusting to the same spatial scale, we directly compared the H I pattern of fig. 1 from Newton (1980b) with the radio-continuum pattern of fig. 2 from Krause et al. (1989) and found that the overall correspondence of large-scale spiral structures in H I and radio continuum was apparent with slight offsets between emission ridges. From this perspective, we suggest that IC 342 may involve slow MHD density waves in the inner region and fast MHD density waves in the outer region. With increasing radius, the strength of fast MHD density waves becomes relatively weak in the outer H I gas disc, but they are sufficiently strong to correlate large-scale magnetic field and H I spiral structures there.

NGC 2997: Except for optical bands, this spiral galaxy was less observed in other electromagnetic wavelengths. For example, H I results are not currently available.[3] Most of its spiral pattern occupies the disc portion with a more or less flat rotation curve (Milliard & Marcelin 1981) and its central region ($\lesssim$ 0.5 arcmin) is characterized by a nearly rigid rotation (Sperandio et al. 1995). Recent Very Large Arrary (VLA) and Australia Telescope Compact Array (ATCA) observations of NGC 2997 in total and polarized radio continuum at 6.0, 3.5 and 13 cm by Han et al. (1999) and the comparison with the optical spiral pattern reveal a striking resemblance to M51 (cf. Neininger & Horellou 1996) in that total and polarized intensity arms track the optical spiral arms well, with slight systematic offsets (i.e. along inner edges, see figures of Han et al. 1999). One important piece of evidence for fast MHD density waves is that total and polarized intensity peaks coincide closely with each other along several radial cuts (Beck, private communications). Furthermore, the spiral pattern of magnetic field swirls inwards near and around the centre where the disc rotates almost rigidly. According to the MHD-density-wave scenario, it is natural to identify the spiral pattern of NGC 2997 with fast MHD density waves in close analogy to M51. In the south-east quadrant, an isolated 'magnetic arm' stands out in total and polarized radio intensities without apparent optical features (figs 2a,b of Block et al. 1994a) or dust lanes (fig. 6 of Block et al. 1994b). As explained earlier, optical and H I spiral arms usually track each other very well; in particular, the latter can continue to reveal MHD density waves at larger radii in the magnetized gas disc as optical features gradually fade. The important inference here is that a moderate H I gas arm (as an extension of the relevant optical arm) yet to be discovered should be associated with the 'magnetic arm' in radio continuum. This would then be consistent with the fast MHD-density-wave scenario, and this prediction can be tested by forthcoming H I observations of NGC 2997. For subdued star-formation activities, it is further expected that mid- and far-infrared emissions should be weak along the isolated 'magnetic arm'.

4 CONCLUSIONS

Our main conclusion is that on the analogy of M51, large-scale optical, total and polarized radio-continuum spiral structures of NGC 2997 appear largely consistent with a global pattern of fast MHD density waves, extending from the very central region all the way to the outer disc. In addition, direct comparisons of optical, H I, total and polarized radio-continuum images of M51 (an example of global fast MHD density waves) indicate that large-scale broad (somewhat fuzzy) H I gas arms, coincident with optical arms at smaller radii, tend to extend further from fading optical spiral arms to larger radii and can continue to associate with polarized radio-continuum emission arms. Observations of IC 342 in the similar multiwavelength bands as those for M51 reveal slow MHD density waves in the almost rigidly rotating inner disc (as NGC 6946; Beck & Hoernes 1996; Fan & Lou 1996) and fast MHD density waves in the differentially rotating outer disc with a large-scale association of H I and radio-continuum spiral structures (as M51; Neininger & Horellou 1996; Lou & Fan 1998a). It thus seems to be a generic feature that H I and radio-continuum emission spiral arms are associated with each other, even in an outer disc portion where optical features gradually fade. This empirical fact appears to be consistent with the MHD-density-wave scenario in which enhancements of gas density and magnetic field strength are characterized by special structural inter-relations (Fan & Lou 1996; Lou & Fan 1998a).

We therefore predict that the isolated south-east 'magnetic arm' in total and polarized radio-continuum emissions of NGC 2997 should actually be accompanied by an H I gas arm yet to be detected. Such extended fuzzy H I spiral arms in the outer gas disc (cf. M51 and IC 342) should be viewed as an inseparable component of fast MHD density waves with somewhat weaker magnitudes and thus with less prominent star-formation activities; they can, on occasions, continue to associate with total and polarized radio-continuum arms which would otherwise appear quite isolated in the absence of optical arms. It is thus crucial to examine *together* optical, H I, total and polarized radio-continuum of a magnetized spiral galaxy in order to properly identify the presence of different types of large-scale MHD density waves. Observations at other wavelengths (e.g. CO and infrared bands) and of different features should offer further tests and constraints for the consistency of the MHD-density-wave scenario; here, we merely utilized the most commonly available information *necessary* for doing so.

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[3] With a declination of $\sim -30°$, it is somehow difficult to construct high-quality 21-cm images of NGC 2997 from synthesis radio observations. However, there were recent attempts with ATCA as well as forthcoming plans with a VLA BnC configuration.

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