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Large misalignment between stellar bar and dust pattern in NGC 3488 revealed by *Spitzer* and SDSS

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Abstract

A large position angle misalignment between the stellar bar and the distribution of dust in the late-type barred spiral NGC 3488 was discovered, using mid-infrared images from the *Spitzer Space Telescope* and optical images from the sloan digital sky survey (SDSS). The angle between the bar and dust patterns was measured to be 25° ± 2°, larger than most of the misalignments found previously in barred systems based on Hα or H I/CO observations. The stellar bar is bright at optical and 3.6 μm, while the dust pattern is more prominent in the 8 μm band but also shows up in the SDSS *u* and *g*-band images, suggesting a rich interstellar medium environment harboring ongoing star formation. This angular misalignment is unlikely to have been caused by spontaneous bar formation. We suggest that the stellar bar and the dust pattern may have different formation histories, and that the large misalignment was triggered by a tidal interaction with a small companion. A statistical analysis of a large sample of nearby galaxies with archival *Spitzer* data indicates that bar structure such as that seen in NGC 3488 is quite rare in the local Universe.

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1. Introduction

Bar structure as a major non-axisymmetric feature on all scales is important in studying the morphology, mass and light distributions (e.g. Freeman, 1996; Elmegreen and Elmegreen, 1985; Elmegreen, 1996; Elmegreen et al., 1996; Eskridge et al., 2000; Menéndez-Delmestre et al., 2007), star formation (e.g., Zurita et al., 2004; Knapen, 2005; Ondrechen and van der Hulst, 1983; Regan et al., 1996; Sheth et al., 2000), gas dynamics (e.g., Kormendy, 1983; Bettoni and Galletta, 1988; Sancisi et al., 1979; Benedict et al., 1996; Downes et al., 1996; Regan et al., 1999) and central activities (e.g., Ho et al., 1997b; Hawarden et al., 1986; Knapen et al., 2002; Sakamoto et al., 1999; Martini et al., 2003; Sheth et al., 2005) of disk galaxies. Theoretical models, including N-body and hydrodynamic simulations, generally confirm that bar formation is spontaneous and ubiquitous in disk evolution (e.g., Athanassoula, 1992; Sellwood and Wilkinson, 1993; Friedli and Benz, 1993, 1995; Athanassoula and Bureau, 1999). Because of the dissipative nature of the interstellar medium (ISM), the streaming motions of the molecular gas in and

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around bar regions can be different from the stellar orbits (Athanassoula, 1992; Regan et al., 1999; Sheth et al., 2002). Due to the delayed star formation after the clouds have been triggered (∼30 Myr; Vogel et al., 1988), the locations of gas/dust in galaxies can often be offset from that of young stars (e.g., Sheth et al., 2002; Phillips, 1996; Martin and Friedli, 1997). The molecular gas can be transported from galactic disk toward central region by the gravitational torques from bars (e.g., Sakamoto et al., 1999; Sheth et al., 2002, 2005), and the condensation of gas leads to subsequent circumnuclear star formation (e.g., Ho et al., 1997b; Knapen et al., 2002; Martini et al., 2003; Jogee et al., 2005; Fisher, 2006).

Observationally, the gas/dust patterns can often be seen as dust lanes, atomic and molecular gas concentrations, or isophotes of H II regions with active star formation (Martin and Friedli, 1997; Sakamoto et al., 1999; Regan et al., 1999; Rand et al., 1999; Crosthwaite et al., 2000; Sheth et al., 2002, 2005). As predicted by theoretical models (Athanassoula, 1992; Friedli and Benz, 1993, 1995), there is a small position angle misalignment between the gas/dust distribution and the stellar bar, usually of a few (and up to 10) degrees, in the sense that the former is *leading*. Kenney et al. (1991) found the gaseous pattern is offset from the major axis of the stellar distribution by 24° ± 6° in M 101. Crosthwaite et al. (2000) found that the central gas distribution as indicated by H I map leads the stellar bar by almost 10° in the late-type galaxy IC 342. Similarly, Rozas et al. (2000) identified a large sample of H II regions in barred galaxy NGC 3359 and showed a position angle misalignment of a few degrees exists in Hα and I-band images. They also pointed out that the *u*-band image of this galaxy shows a bar pattern more aligned with Hα, further suggesting massive star formation “at the leading edge of the bar”. Sheth et al. (2002) found offsets between molecular gas (CO) and star formation (traced by Hα) in bars of six nearby spirals, which were caused by the gas flow dependent star formation. Understanding the misalignment between stellar and gas/dust patterns and their formation scenarios is crucial for studying the ISM properties and star formation processes taking place in environments where gas dynamics are strongly perturbed (e.g., Regan et al., 1996; Martin and Friedli, 1997; Sheth et al., 2000; Zurita et al., 2004), and also offers a good opportunity to study dynamical properties and secular evolution of barred galaxies (e.g., Kormendy, 1983; Benedict et al., 1996; Regan et al., 1999; Kormendy and Kennicutt, 2004; Sheth et al., 2005; Kormendy and Fisher, 2005; Fisher, 2006; Regan et al., 2006).

The *Spitzer Space Telescope*’s (Werner et al., 2004) observations in the mid-infrared, with its higher sensitivity and better angular resolution than previous observations (e.g., ISO), provide a new opportunity to study both stellar and gas/dust structures in galaxies (e.g., Pahre et al., 2004; Wang et al., 2004; Cao and Wu, 2007). In particular, the four Infrared Array Camera (IRAC; Fazio et al., 2004) bands from 3.6 to 8.0 μm probe both stellar continuum and warm dust emissions (of the so-called polycyclic aromatic hydrocarbon, or PAH, and dust continuum emissions) with identical spatial sampling, thus enabling a powerful probe to compare non-axisymmetric features such as bar structures involving gas/dust and stellar mass. Recently, *Spitzer* observations of nearby galaxies have demonstrated the importance of using mid-infrared images for studying galaxy secular evolution driven by bar instabilities (e.g., Fisher, 2006; Regan et al., 2006).

In this paper, we present an analysis of data from *Spitzer* and SDSS of the late-type barred spiral galaxy NGC 3488. Previous studies show that, with an estimated distance of 39.9 Mpc (at this distance, 1″ corresponds to ∼193 parsecs) and a total infrared luminosity of $L_{\rm TIR} \approx 4.6 \times 10^9\ L_\odot$ (Bell, 2003), NGC 3488 [Hubble type SB(s)c] has a weak bar (∼1.5 kpc), with spiral arms beginning at the bar’s end but without an inner ring. This is consistent with the conventional view that bars in most late-type spirals are relatively weak (Erwin, 2005; Menéndez-Delmestre et al., 2007), and that weak bars tend to produce a SB(s) type response (in which the spiral arms begin at the ends of the bar; Kormendy and Kennicutt, 2004). The data reduction is presented in Section 2, and results on the bar structures in NGC 3488 with multi-wavelengths analysis are described in Section 3. Possible explanations of the large misalignment between the bar and dust patterns are discussed in Section 4.

2. Data Reduction

Broad-band infrared images of NGC 3488 were acquired with IRAC on board *Spitzer*. The Basic Calibrated Data (BCD) were part of the Lockman Hole field in the *Spitzer* Wide-field Infrared Extragalactic (SWIRE) Survey (Lonsdale et al., 2003). Following the preliminary data reduction by the *Spitzer* Science Center pipeline, images of each of the four IRAC bands (3.6, 4.5, 5.8 and 8 μm) were mosaicked, after pointing refinement, distortion correction and cosmic-ray removal (Fazio et al., 2004; Huang et al., 2004; Wu et al., 2005; Surace et al., 2005; Cao and Wu, 2007; Wen et al., 2007). The mosaicked images have pixel sizes of 0.6″ and angular resolutions (full width at half maximum, FWHM) of 1.9″, 2.0″, 1.9″ and 2.2″ for the four-bands, respectively. The angular resolution of IRAC 8 μm images (∼2.2″) is significantly improved over that of pre-*Spitzer* data at similar wavelengths (e.g., ∼10″ for ISOCAM LW2 at 7 μm; Roussel et al., 2001).

In order to derive the dust-only 8 μm component (PAH and dust continuum emissions), we remove the stellar continuum from the IRAC 8 μm image by subtracting a scaled IRAC 3.6 μm image (assuming that the 3.6 μm emission is entirely due to old stellar population):

$$f_\nu(8\ \mu\mathrm{m})_{\rm dust} = f_\nu(8\ \mu\mathrm{m}) - \eta_{8\ \mu\mathrm{m}} f_\nu(3.6\ \mu\mathrm{m}),$$

where the scaling factor $\eta_{8\ \mu\mathrm{m}} = 0.232$ was calculated based on *Starburst99* synthesis model (Leitherer et al., 1999), assuming solar metallicity and a Salpeter initial mass