A PAIR OF LEADING SPIRAL ARMS IN A LUMINOUS INFRARED GALAXY?1

PETRI VÄISÄNEN, STUART RYDER, SEppo MATTILA, and JARI KOTILAINEN

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ABSTRACT

Leading spiral arms are a rare phenomenon. We present here one of the very few convincing candidates of spiral arms opening counterintuitively in the same direction as the galaxy disk is rotating. This detection in the luminous IR galaxy (LIRG) IRAS 18293−3413 is based on near-infrared (NIR) adaptive optics imaging with the Very Large Telescope and long-slit NIR spectroscopy with the Anglo-Australian Telescope. We discuss the orientation of the galaxy based on imaging and derive rotation curves from both emission and absorption features in the spectrum. The galaxy is strongly star-forming and has a minor companion in a high-velocity encounter. The fact that the arms of IRAS 18293−3413 are not easily traceable from optical images suggests that larger samples of high-quality NIR imaging of interacting systems and LIRGs might uncover further cases of leading arms, placing constraints on spiral arm theories and retrograde encounters, and especially on the relationship between disk masses and dark matter halo masses.

Subject headings: galaxies: individual (IRAS 18293−3413) — galaxies: interactions — galaxies: kinematics and dynamics — galaxies: spiral — galaxies: structure — infrared: galaxies

Online material: color figures

1. INTRODUCTION

Although once a subject of active discussion, the sense of rotation of spiral arms in galaxies has generally been considered as resolved for half a century. In a thorough discussion de Vaucouleurs (1958) showed that all galaxies in his sample had trailing arms, in agreement with the early position of Slipher and Hubble, and in contrast to the leading arm camp of Lindblad.

Afterward, the only systematic study of the subject with large samples of spirals is work done in the early 1980s by Pasha & Smirnov (1982) and Pasha (1985). The crucial question for them was not whether spirals are trailing or leading, but rather whether all spirals are trailing, or whether some leading arm cases could be found. In the end, they came up with a sample of four leading arm galaxy candidates from a sample of close to 200. However, one of them (NGC 5395) was later shown not to be leading (Sharp & Keel 1985), another (NGC 4490) is a highly dubious case regarding its orientation and existence of arms, and even the remaining two (NGC 3786 and NGC 5426) are not clear-cut cases regarding their tilt, which determines the sense of rotation. More recently, NGC 4622 has attracted attention (Buta et al. 1992, 2003; Byrd et al. 2008). The authors conclude that regardless of its orientation, the galaxy must have leading arms since the two pairs of detected arms wind in opposite directions. Another example of a similar “counterwinding” spiral structure in ESO 297−27 was recently published by Grouchy et al. (2008).

If leading arms are convincingly detected, it naturally places constraints on any theory of the origin and structure of spirals in galaxies. In the favored density wave models (see, e.g., Binney & Tremaine 1987), leading arms are allowed in principle; the density waves themselves can be trailing or leading, although trailing waves are expected to be more robust (Toomre 1981). However, many theoretical studies suggest that retrograde encounters with companion galaxies should generate a robust single leading arm (Athanassoula 1978; Thomasson et al. 1989; Byrd et al. 1993). It is very interesting that indeed every case of a suspected leading arm galaxy has a companion or a suspected companion. This then raises an interesting problem: since encounter directions are random, it is not easy to understand why there are so very few observed candidates of leading arms (single or otherwise) in the multitude of observed interacting galaxies. Thomasson et al. (1989) find that if the disk mass is similar to, or larger than, the surrounding halo mass, the formation of a leading arm is suppressed in the interaction. The question to answer thus becomes (1) whether the spiral galaxy dark matter (DM) halos really are so small, (2) whether leading arms are extremely short-lived (the modeling cited argues against this), or (3) are leading arms perhaps hidden from typical searches thus far?

With the link to interactions and tidal disturbances and a way to probe the DM halo, leading arms are cousins of other intriguing and rare effects in disk galaxies, such as counterrotating disks and (polar) rings (Tremaine & Yu 2000; Vergani et al. 2007; Brosch et al. 2007). To understand spiral galaxy evolution, and to answer the questions above, more modeling and more and new kinds of observations are needed. In this Letter we present a strong candidate for the most clear-cut leading arm case to date, detected using a mode of observation not attempted before in the case of leading arms: a galaxy with an obvious classical two-arm spiral pattern as seen in adaptive optics (AO) imaging in the near-infrared (NIR).

2. OBSERVATIONS AND DATA REDUCTION

IRAS 18293−3413, a gas-rich spiral with an IR luminosity of $L_{\text{IR}} = 10^{11.7} L_\odot$ (Sanders et al. 2003), was observed with the NAOS-CONICA (NACO) AO instrument on the VLT UT4 as part of our program to find dust-obscured core-collapse supernovae in the inner regions of LIRGs and to study star formation.
and its triggering in LIRGs (Mattila et al. 2007; Vääsnän et al. 2008). The K-band data set used here was taken on 2004 September 14 with the S27 camera, giving a pixel size of 0.027”, and using the visual wave-front sensor. These observations and data reduction are described in more detail in Mattila et al. (2007), where we presented the discovery of the highly obscured core collapse (see Pérez-Torres et al. 2007) supernova 2004ip detected within the nuclear regions of this galaxy. The final combined K-band image (Fig. 1, left) has an on-source integration time of 1230 s. Two spiral arms are seen to open clockwise around a single nucleus. We also extracted HST ACS images from the archive (PI: A. Evans), which show the chaotic optical appearance of IRAS 18293–3413, although the arms can be traced in the J-band image aids by the NIR view.

Spectroscopic observations were obtained with the IRIS2 instrument at the Anglo-Australian Telescope (AAT) on the nights of 2007 September 27 and 28, using a 1” wide slit, at a resolution $R \sim 2400$. The position angle (P.A. = 128°) is close to the major axis of the galaxy and was such that the suspected companion galaxy to the northwest also fell on the slit. Three sets of data were taken of the target, in the $J$, $H$, and $K$ bands, in 300 s nodded exposures. Total integration time was 2700 s in the $K$ band and 3600 s in the $J$ and $H$ bands. An A0 V–type standard star was observed in each band, as well as arc and flat lamps.

The AAT data were reduced with IRAF$^5$ and IDL. All science frames were flat-fielded by a normalized, smoothed ON-OFF flat, cosmic-ray–corrected, and then subtracted pairwise from each other. Xe arcs were used to fit the wavelength solution and also correct for the 2D shape distortion of the frames. A final background subtraction along columns was done to remove some sky-line residuals remaining after the pairwise subtraction. Frames were then shifted, co-added, and traced to produce a clean, integrated, straightened 2D spectrum in each band. The standard star data were reduced in exactly the same way, except that the prominent hydrogen absorption features were fitted and removed. The 1D extracted standard star spectrum was then divided into the target and the result multiplied by a smooth blackbody model of the star, thereby removing telluric features from the target spectrum while also performing a relative flux calibration.

3. ANALYSIS

3.1. Rotation Curve

To determine the sense of rotation of the galaxy we first analyzed the spectra and derived rotation curves using five of the brightest emission lines in the whole $JHK$ region. As an example, Figure 2 shows the extracted spectrum in $K$ band over a central 4” wide aperture. Single component Gaussians were fitted line by line in the 2D spectra around the regions of interest, providing the wavelengths of the peaks. The resulting heliocentric radial velocities as a function of spatial position over the slit are plotted in Figure 3. The radial velocities calculated from all the lines are very consistent. The rotation of IRAS 18293–3413 on the sky is such that the northwest side facing the companion is approaching us.

We also examined the $^{12}$CO $J = 2 \rightarrow 1$ absorption feature at 2.2935 μm in order to measure the velocity of the stellar population in addition to the warm emitting gas producing the emission lines. For this purpose we fitted stellar templates of giant and supergiant stars (C. Winge et al., in preparation)$^6$ to the relevant $K$-band region (per five binned pixel rows) by redshifting the templates and convolving them with a range of internal velocity dispersions. The exact choice of the stellar template had no relevance for the resulting radial velocity and only a small effect on the fitted velocity dispersion. The overlay in Figure 2 shows the best-fit K7 III type template (HD 63425B). The re-

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$^5$ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

$^6$ See http://www.gemini.edu/sciops/instruments/nir/spectemp/.
The resulting velocity curve is overplotted with black circles over the emission-line derived curves in Figure 3. It is seen that the stellar rotation closely follows that of the warm gas.

The spectra also yield a redshift, for the first time, of the smaller elliptical galaxy to the northwest, based on the K-band CO-feature and Fe ii emission in J band; we derived 5960 ± 80 km s⁻¹, while the main galaxy systemic velocity is 5450 ± 20 km s⁻¹.

3.2. Orientation of the Galaxy

As thoroughly discussed in the literature (e.g., de Vaucouleurs 1958; Pasha 1985; Sharp & Keel 1985), a key issue in determining the sense of rotation of a moderately inclined spiral galaxy is the difficulty in deciding its orientation in space (i.e., which side is nearer). Two methods discussed in the literature are appropriate here: detection of dust lanes obscuring some of the brighter and smoother central regions of a galaxy often reveal the side of the disk nearer to the observer, and essentially for the same reason the surface brightness profile along the minor axis of the nearer side of the disk falls more abruptly than the profile along the far side.

First, looking at the images in Figure 1, the significantly more drastic dust obscuration in the ACS B- and I-band images on the southwest side of the system, and extending to the south and southeast, as well as the more pronounced dust filaments against the brighter regions on the same southwest side, give a visual impression of that being the near side of the galaxy. More quantitatively, Figure 4 shows the surface brightness profiles along the minor axis of the galaxy in all three images. Since the exact P.A. depends somewhat on the isophote used, the plotted curves are averages from cuts ranging from 20° to 30°. While the chaotic appearance and numerous star-forming regions make the profiles ragged, it nevertheless is clear that the brightness on average falls more rapidly on the southwest side in all bands, suggesting that this is the side nearer to us.

4. DISCUSSION AND CONCLUSIONS

Figure 3 illustrates that the side of the galaxy closest to the companion galaxy is the approaching side. If we now accept, on the basis of imaging and surface brightness profiles, that the southwest side of IRAS 18293–3413 is the one nearer to us, we have to conclude that the galaxy is turning clockwise in the image, i.e., in the same direction that the spiral arms open. It is a leading arm spiral.

Is there any ambiguity in the result leading to the classification of a leading arm spiral? Since spectroscopy can be interpreted in only one way, the tilt of the galaxy opens the only possibility of misinterpretation. It could be that while the southwest side of the disk with the obscuring dust is the near one, the stellar disk and arm structure as seen in the NIR has the opposite tilt. Although possible in principle, this is extremely unlikely; it would require that the rotational velocities and angles of the decoupled stellar and gas disks are exactly fine-tuned to produce the identical line-of-sight rotation curves measured (Fig. 3). Decoupling in itself is not far-fetched at all as evidenced by counterrotating disks. On the other hand, and more seriously, perhaps the significant amount of extinction on the southwest side of the galaxy (Fig. 4) is not related to the main galaxy and its orientation at all, but is rather foreground material, for example, stripped off of a companion galaxy. Given the chaotic nature of LIRGs and the assumed interaction here, this is quite plausible; indeed, it may not be trivial to apply “normal” tilt-determining criteria to LIRGs. If this were the case, the tilt of the galaxy would be more difficult to judge and would have to be based essentially only on NIR imaging. However, since our slit in the spectral observations does overlap the dust structure on the southeast and northwest sides of the galaxy, we would expect some signal of decoupled and/or complex velocity fields (cf., e.g., Väisänen et al. 2008). We see no such structures. Moreover, the visual impression of the J-band image does suggest the intertwining of the dust structures and the stellar light clearly associated with the spiral arms especially on the east and southeast sides of the galaxy. Nevertheless, with the present data we cannot resolve this ambiguity and rather stress that we have detected a very strong candidate for a leading arm spiral. Future integral field unit spectroscopy, or long-slit observations at other orientations, could put the issue to rest.

Based on our knowledge of peculiarities in spiral galaxies, the origin of the leading arms is likely due to an encounter with another galaxy. The smaller elliptical (it is well fit by a de Vaucouleurs profile) companion is the obvious candidate, which makes IRAS 18293–3413 a “mixed” interacting/merging pair (e.g., Johansson et al. 2008), rather than a typical LIRG case of a pair of gas-rich spirals (unless the companion is the
remaining bulge of a long-lived larger spiral). The radial velocity offset of 500 km s$^{-1}$ is surprisingly large, and typical only right at first close passages of merging galaxies (Murphy et al. 2001; Väisänen et al. 2008). However, given the disturbed morphology of the main galaxy, an ongoing LIRG-scale star formation burst, and that there are no other 2MASS galaxies seen within 7′ (~160 kpc distance at z = 0.0185), it is very unlikely that the companion would be unrelated. Of course, we do not know the transverse motion of the companion, but with the measured rotation of the main galaxy, the positive radial velocity offset of the companion is retrograde with respect to the rotation of the spiral disk. This fits well the general picture that it is retrograde encounters that might trigger leading arms (e.g., Thomasson et al. 1989).

The leading arm simulations of Byrd et al. (1993) concerning NGC 4622 favor a small companion of 1 : 100 mass ratio passing close to a disk galaxy center, while Thomasson et al. (1989) show how a more distant and massive retrograde companion produces a leading arm. Our system clearly resembles more the small perturber case. We can estimate the galaxy masses from their NIR light and velocity dispersion. We measure $M_k \approx -21.4$ for the companion, while the main galaxy has $M_k \approx -25.0$. Assuming that both have the same mass-to-light ratio, their mass ratio would thus be close to 1 : 30. The companion does, however, have a fairly significant mass of $\sim 7 \times 10^9 M_\odot$, based on the $K$-band mass-to-light ratio of Thronson & Greenhouse (1988). The CO bands are detected in the companion, although with low signal-to-noise ratio (Fig. 2). By directly fitting a Gaussian to the feature, and correcting for instrumental effects, we arrive at $v_p = 90$ km s$^{-1}$. Using an effective radius of $r_e = 0.62$ kpc determined by surface brightness profile fitting with GALFIT (Peng et al. 2002), we calculate a dynamical mass estimate (e.g., Väisänen et al. 2008) of $\sim 7 \times 10^9 M_\odot$, while an equivalent mass estimate for the main galaxy results in $\sim 1 \times 10^{11} M_\odot$ (adopting $50^\circ$ inclination, observed $v_p = 140$ km s$^{-1}$, $r_e = 1.0$ kpc, $\sigma = 260$). The ratio is 1 : 16; however, given the uncertainties of the $\sigma$ determination of the companion, the result is consistent with the 1 : 30 ratio from NIR light.

Perhaps the most far-reaching aspect of leading arms is their connection to cosmology via DM halos; these halos are generally thought to dominate the dynamics of galaxies, but their nature and structure are still uncertain and actively debated (e.g., Ostriker et al. 1974; Olling & Merrifield 2000; Sofue & Rubin 2001; Salucci et al. 2007). Thomasson et al. (1989) found that leading arms form only when the surrounding DM halos dominate the disk mass. The nonexistence of leading arms could thus be seen as support for maximum-disk and small DM halo models, while more evidence, such as our result, for leading arms would support massive DM halos.

There are not many candidate leading arm spirals in the literature. Of the handful, the case of IRAS 18293−3413 is unique: the interpretation is significantly less ambiguous than any of the Pasha (1985) candidates, and ours is less complex compared to the better known case of NGC 4622 and the recent ESO 297−27. The latter two are “counterwinding spirals” with sets of arms opening in opposing directions, while our case appears to be a classical two-arm spiral (in the NIR). Notably, this is the type of leading spiral that has not been theoretically studied in the literature to the degree that single leading arms have. In particular, whether a 1 : 30 mass-ratio companion in the high-velocity encounter described above actually can produce a pair of leading arms, and what the arms would suggest about the DM halo properties, obviously needs to be followed up by modeling.

Typical of many LIRGs, but in contrast to the previous leading-arm candidates, IRAS 18293−3413 has a large dust and gas mass and is very strongly star-forming, and its appearance in the optical is chaotic. We argue that this last aspect may in fact prove significant: there appear to be no published systematic studies of spiral arm characterization and rotation determinations in the infrared. Once larger interacting IR-galaxy samples are followed up with high spatial resolution imaging in the NIR together with high-quality spectroscopy, we speculate that more leading arms may well be found. These cases must be searched for, and if more are identified, they should be studied and modeled dynamically. This will be crucial to fully understand the dynamics and evolution of disk galaxies.

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