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Preliminary Exploration of Areal Density of Angular Momentum for Spiral Galaxies

Lan Zhang[1], Feilu Wang[1,2], Xiangxiang Xue[1,3], David Salzmann[1], Baifei Shen[4], Zehao Zhong[1], and Gang Zhao[1,2]
[1] CAS Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; wfl@bao.ac.cn
[2] School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 101408, China
[3] Institute for Frontiers in Astronomy and Astrophysics, Beijing Normal University, Beijing 102206, China
[4] Department of Physics, Shanghai Normal University, Shanghai 200234, China
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Abstract

The specific angular momenta (j_t) of stars, baryons as a whole and dark matter halos contain clues of vital importance about how galaxies form and evolve. Using a sample of 70 spiral galaxies, we perform a preliminary analysis of j_t, and introduce a new quantity, e.g., areal density of angular momentum (ADAM) ($j_t\, M_\star/(2R_d)^2$) as an indication for the existence of jet(s) in spiral galaxies. The percentage of spiral galaxies having jet(s) shows a strong correlation with ADAM, although the present sample is incomplete.

Key words: galaxies: jets – galaxies: spiral – galaxies: statistics

1. Introduction

The first evidence of jet-like features emanating from the nuclei of galaxies goes back to the discovery by Curtis (1918) of the optical jet from the elliptical galaxy NGC 4486 (M87) in the Virgo cluster. According to the definition of Bridle & Perley (1984) for extragalactic jets, the term "jets" is used to designate collimated ejecta that have opening angles $\leqslant 15°$.

Jets of matter occur in many astrophysical situations, but can broadly be classified into two types: stellar jets and galactic jets. Stellar jets are generated by a number of different sources, such as T Tauri stars, planetary nebulae, neutron stars and stellar black holes (BHs). Galactic jets, however, are believed to have only a single source, namely, a supermassive black hole (SMBH) at the center of the galaxy.

Many attempts have been made to understand the formation of galactic jets by testing various relations among the physical and observational properties of the host galaxy and its central SMBH. Several options for such relations have been suggested in the literature,

1. correlation between jet properties and central BH mass/spin/accretion rate, e.g., Laor (2000), Dotti et al. (2013), Narayan & Yi (1995);
2. correlation between jet properties and accretion disk spin, e.g., Natarajan & Pringle (1998), Ho & Peng (2001), King et al. (2013a);
3. correlation between jet formation and magnetic fields, e.g., Asada et al. (2002), Takabe et al. (2008).

Fully evolved relativistic jets have traditionally been associated with high-mass elliptical galaxies hosting the most massive BHs, but Vietri et al. (2022) confirmed that also less massive BHs in spiral galaxies could launch and sustain powerful jets, implying that the launching of the jets is governed by factors other than those mentioned previously.

The role that angular momentum in galaxies plays in the jet properties is little understood, although it is believed to control the kinematics of their stars, which on the other hand drives observable quantities such as the apparent radius, the bulge fraction and the alignment with other nearby structures (Cimatti et al. 2020). The galactic angular momentum originates from the initial spin, and is lost during mergers. It plays a major role in galaxy formation and evolution and is closely related to the coupling between dark and visible matter (Li et al. 2022). The primary goal of this paper is to study the correlation between the presence of jet(s) and various physical quantities.

2. $j_t - M_\star$ Diagram for Spiral Galaxies

Our sample consists of 67 spiral galaxies in Table 4 of Romanowsky & Fall (2012), whose bulge-to-total mass ratios B/T range from 0.0 to 0.6, that correspond to Sc (pure disks) to S0, and three spiral galaxies, in order to extend the stellar mass range of samples in this study. These are the Milky Way, 2MASX J23453268-0449256 (hereafter J2345-0449) with large stellar mass and NGC 4395 with small stellar mass, which were added to construct our sample.

Following Romanowsky & Fall (2012), the total specific stellar angular momenta (j_t, in the unit of km s^{-1} kpc) of all the samples are calculated by

$$j_t = f_b j_b + (1 - f_b) j_d, \qquad (1)$$

where f_b is the bulge stellar mass fraction and j_b and j_d are intrinsic values of specific stellar angular momentum of bulge

Table 1
Observations used in j_t Calculation

Name	R_d (kpc)	f_b	$a_{e,b}$ (kpc)	i (deg)	$v_{s,b}$ (km s^{-1})	$v_{c,d}$ (km s^{-1})	j_t (km s^{-1} kpc)	$\log(M_\star/M_\odot)$	$\log(M_{\rm BH}/M_\odot)$
Milky Way	3.00[a]	0.00	0.00	...	...	218[a]	1308	10.70	6.63[b]
NGC 4395	3.93[c]	0.00	0.00	46.9[c]	...	18[c,d] 83[c,e] 85[c,f]	141[d] 644[e] 660[f]	8.58[c,d] 9.32[c,e] 9.40[c,f]	5.64[g]
J2345-0449	7.51[h]	0.15[h]	1.18[h]	59.7[h]	266[h,i]	371[h]	5625	11.66[h]	⩾8.30[j]

Notes. References are:
[a] Bovy et al. (2012);
[b] Marasco et al. (2021);
[c] Repetto et al. (2017);
[d] gas only;
[e] star only;
[f] total baryonic matters;
[g] Davis et al. (2018);
[h] Bagchi et al. (2014);
[i] calculated by Equation (8) of Bagchi et al. (2014);
[j] Mirakhor et al. (2021);

and disk components, respectively. Both j_b and j_d are calculated from the values along the projected semimajor axis of galaxies ($j_{p,b}$ and $j_{p,d}$). For the bulge part,

$$j_{p,b} = k_n v_{s,b} a_{e,b}, \qquad (2)$$

where $v_{s,b}$ is the observed rotation velocity of the bulge, $k_n \sim 1$–5 is a numerical coefficient that depends on the Sérsic index n of the galaxy (Equation (A31) in Romanowsky & Fall 2012) and $a_{e,b}$ is the effective radius along the semimajor axis. While for the disk component,

$$j_{p,d} = 2 v_c \sin i R_d, \qquad (3)$$

where R_d is the intrinsic exponential-disk scale length, v_c is the intrinsic circular rotation velocity of the disk, based on the rotation curves over the range (2–3)R_d, and i is the inclination. Then the intrinsic values of j are converted by the deprojection factor C_i which are correlated with i,

$$j = j_p C_i. \qquad (4)$$

For the bulge component,

$$C_i \simeq \frac{0.99 + 0.14 i}{\sin i}, \qquad (5)$$

and for the disk component,

$$C_i = \frac{1}{\sin i}. \qquad (6)$$

For the Milky Way, NGC 4395 and the giant radio source J2345-0449, their j_t are calculated by using Equation (1) and observable data from literature studies, which are listed in Table 1.

The stellar specific angular momentum-mass relation was first studied by Fall (1983). Follow-up studies confirmed the relation with more and better data (e.g., Romanowsky & Fall 2012; Posti et al. 2018; Fall & Romanowsky 2018). However, no previous literature studies explore whether the jets can effect the relation or not. For better understanding the role of jets in the stellar specific angular momentum-mass relation, especially for spiral galaxies with jets, we modeled j_t ($j_{t,\rm mod}$) as a function of $M_\star$ in log – log space for samples both with and without jets

$$\log j_{t,\rm mod} = \beta + \alpha \times \log\left(\frac{M_\star}{M_\odot}\right). \qquad (7)$$

We carried out a Markov chain Monte Carlo (MCMC) calculation to explore the relation and the uncertainties of the fitted parameters α and β, for three groups of our sample, that is, (a) all the sample galaxies; (b) all possible jetted galaxies; (c) all possible jetted galaxies excluding NGC 3898, NGC 4258, NGC 4736 and NGC 5033, because the jets of these four galaxies are still in doubt (Baldi et al. 2021).

The fitting also does not include NGC 4395 since its mass is much lower than the others and is an irregular galaxy whose gas component seems to dominate (Repetto et al. 2017). Our fitting results for three groups are shown in Figure 1 and Table 2.

Here the fitting parameters for the whole sample are $\alpha = 0.529^{+0.073}_{-0.073}$ and $\beta = -2.638^{+0.790}_{-0.790}$, which show good agreement with the study of Romanowsky & Fall (2012), where $\alpha = 0.52 \pm 0.04$ and $\beta = -2.54 \pm 0.05$ for all spirals in their work. While for the group with jets, $\alpha = 0.607^{+0.235}_{-0.235}$ and $\beta = -3.575^{+2.394}_{-2.394}$, which display large fitting uncertainties.

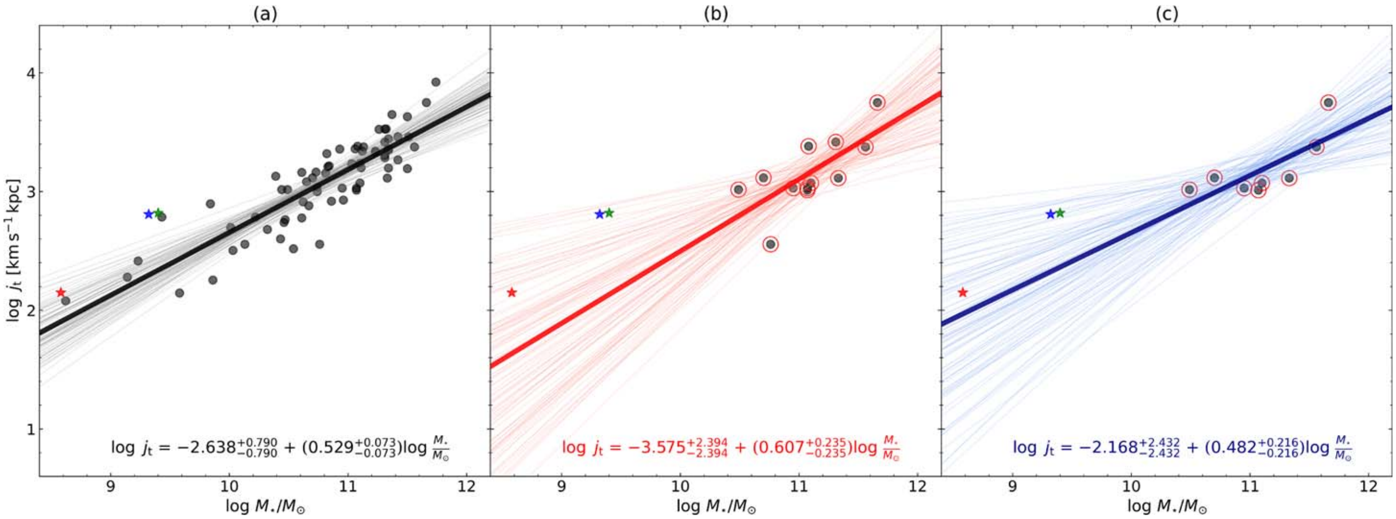

Figure 1. The total angular momenta of our sample vs. their stellar mass. For all plots, black dots are observation data, while galaxies with jets are marked with red circles. Thick lines are best fits of $\log j_t - \log\frac{M_\star}{M_\odot}$ relations. Star symbols indicate NGC 4395, which was excluded during the fittings. Red, blue and green represent that its j_t is calculated with stellar mass and velocity, gas mass and velocity, and total baryonic mass and velocity, respectively. The shaded area of each line indicates 1σ fitting error range. (a) features the fitting results of all spiral galaxies in the present study; (b) displays the fittings for all possible spiral galaxies with jets; (c) is similar to (b), but with the assumption that NGC 3898, NGC 4358, NGC 4736 and NGC 5033 are spiral galaxies without jets.

Table 2
Fits to Stellar Mass and Specific Angular Momenta

Sample	α	β
All spiral galaxies	$0.529^{+0.073}_{-0.073}$	$-2.638^{+0.790}_{-0.790}$
Spiral galaxies with jets	$0.607^{+0.235}_{-0.235}$	$-3.575^{+2.394}_{-2.394}$
Spiral galaxies without uncertain jets	$0.482^{+0.216}_{-0.216}$	$-2.168^{+2.432}_{-2.432}$

The reason is that this group is concentrated in the large stellar mass range. For NGC 4395, if its j_t is calculated with the stellar mass and stellar velocity, it shows good agreement with the fitted relation. If all baryonic matters are included, the j_t deviates from the best fitting, although it is still covered by 1σ fitting uncertainty. Unlike stellar composition, the gas component is not in an equilibrium state, and its high velocity may be sped up by the jet, which results in a large j_t value.

3. Percentage of Galaxies with Observed Jet(s)

After cross-matching the samples with recent radio- and X-ray observation studies (e.g., King et al. 2013b; Baldi et al. 2021), 13 galaxies are labeled as ones with jets. Among them, there are nine galaxies with the presence of a jet or jets in the observations, i.e., NGC 2639 (Sebastian et al. 2019), NGC 3031 (M81) (Baek et al. 2019), NGC 4395 (King et al. 2013b), NGC 4594 (M104) (Hada et al. 2013), NGC 2841 (Baldi et al. 2018), NGC 3198 (Baldi et al. 2018), NGC 7217 (Baldi et al. 2018), J2345-0449 (Bagchi et al. 2014) and the Milky Way (Cecil et al. 2021). For the other four galaxies, NGC 4258 (M106) was identified as a galaxy with jet in Cecil et al. (2000), however, in the recent study of Baldi et al. (2021), the jet morphology of NGC 4258 (M106), as well as those of NGC 3898, NGC 4736 and NGC 5033, were uncertain. Therefore, NGC 3898, NGC 4258, NGC 4736 and NGC 5033 may not be galaxies with jets (Baldi et al. 2021).

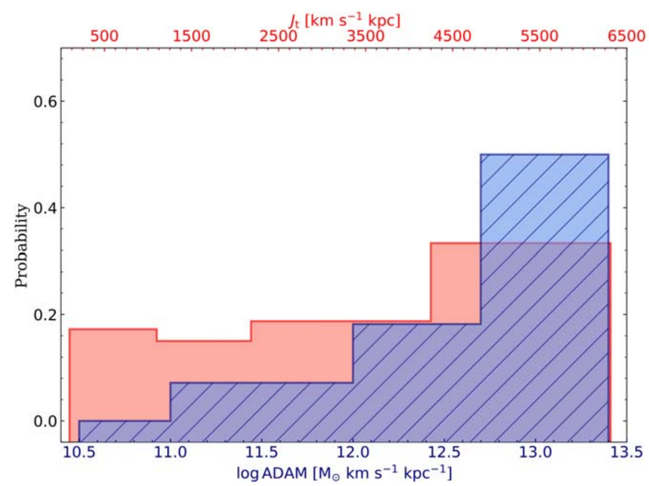

Figure 2. The percentage of galaxies having jet(s) in the sample as a function of the specific angular momenta j_t (in red, upper scale) and those having ADAM (in blue, lower scale).

Figure 2 gives the percentage of galaxies with jet(s) in our sample to find a better indication for the existence of a jet in spiral galaxies. Here we introduce a new quantity, e.g., the areal density of angular momentum (ADAM), which is defined by $j_t\ M_\star/(R_{\rm eff})^2$, where $R_{\rm eff}$ is the effective radius of the stellar mass. For the present samples, we take $2R_d$ as the effective radius. Therefore, the ADAM adopted in this work is $j_t\ M_\star/(2R_d)^2$. In order to ensure the percentage is statistically significant, the number of samples in each j_t or ADAM bin is more than or equal to 3. Comparing j_t with ADAM, the latter seems to be a better indicator of the presence of a jet, since the percentage is lower than 20% when ADAM is less than $10^{12}\,{\rm km\,s^{-1}}\,M_\odot$ kpc. What makes j_t a quantity of great astrophysical importance is not only its relation to the baryonic matter content of galaxies, but also its connection with galactic jet(s).

The present results are preliminary. First, our samples are limited to spiral galaxies. As far as we know, more jets are launched in elliptical galaxies. However, spiral galaxies have, on average, higher angular momentum than elliptical ones for a given stellar mass (Fall 1983; Cadiou et al. 2022). Second, our galaxy sample is neither statistically complete nor the average distribution of the parameters, e.g., stellar mass, BH mass and j_t. In addition, the scale of jets is not taken into account, which is from several pc to 10^2–10^3 kpc. It may matter, since the relation of accretion mass with the jet luminosity seems to be valid for kpc-scale jets, but not for pc-scale cases (Panessa & Giroletti 2013).

As to the possible relation between the ADAM and the jet, it is well known that a tornado can suck matter on Earth and a solar storm is related to magnetic helicity. We carried out a numerical simulation by putting plasma in an axial magnetic field and a radial electrical field which could be formed by a quick shrink. In the real case the electric field could be replaced with the gravitational force. In simulation, we find the particles rotate around the axis and jets are emitted along the axis (Qiu et al. 2018). The rotation of the particles can also be driven by a twist in a laser pulse. In that case, jets are also observed in simulation (Wang et al. 2019).

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References

Asada, K., Inoue, M., Uchida, Y., et al. 2002, PASP, 54, L39
Baek, J., Chung, A., Schawinski, K., et al. 2019, MNRAS, 488, 4317
Bagchi, J., Vivek, M., Vikram, V., et al. 2014, ApJ, 788, 174
Baldi, R. D., Williams, D. R. A., McHardy, I. M., et al. 2018, MNRAS, 476, 3478
Baldi, R. D., Williams, D. R. A., McHardy, I. M., et al. 2021, MNRAS, 500, 4749
Bovy, J., Rix, H.-W., & Hogg, D. W. 2012, ApJ, 751, 131
Bridle, A. H., & Perley, R. A. 1984, ARA&A, 22, 319
Cadiou, C., Pontzen, A., & Peiris, H. V. 2022, arXiv:2206.11913
Cecil, G., Greenhill, L. J., DePree, C. G., et al. 2000, ApJ, 536, 675
Cecil, G., Wagner, A. Y., Bland-Hawthorn, J., Bicknell, G. V., & Mukherjee, D. 2021, ApJ, 922, 254
Cimatti, A., Fraternali, F., & Nipoti, C. 2020, Introduction to Galaxy Formation and Evolution: from Primordial Gas to Present-day Galaxies (Cambridge: Cambridge Univ. Press)
Curtis, H. D. 1918, Publications of Lick Observatory, 13, 9
Davis, B. L., Graham, A. W., & Cameron, E. 2018, ApJ, 869, 113
Dotti, M., Colpi, M., Pallini, S., Perego, A., & Volonteri, M. 2013, ApJ, 762, 68
Fall, S. M. 1983, in Internal Kinematics and Dynamics of Galaxies, ed. E. Athanassoula, ed. E. Athanassoula, 100 (Berlin: Springer), 391
Fall, S. M., & Romanowsky, A. J. 2018, ApJ, 868, 133
Hada, K., Doi, A., Nagai, H., et al. 2013, ApJ, 779, 6
Ho, L. C., & Peng, C. Y. 2001, ApJ, 555, 650
King, A. L., Miller, J. M., Raymond, J., et al. 2013a, ApJ, 762, 103
King, A. L., Miller, J. M., Reynolds, M. T., et al. 2013b, ApJ, 774, L25
Laor, A. 2000, ApJL, 543, L111
Li, J., Obreschkow, D., Power, C., & Lagos, C. d. P. 2022, MNRAS, 515, 437
Marasco, A., Cresci, G., Posti, L., et al. 2021, MNRAS, 507, 4274
Mirakhor, M. S., Walker, S. A., Bagchi, J., et al. 2021, MNRAS, 500, 2503
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Natarajan, P., & Pringle, J. E. 1998, ApJL, 506, L97
Panessa, F., & Giroletti, M. 2013, MNRAS, 432, 1138
Posti, L., Fraternali, F., Di Teodoro, E. M., & Pezzulli, G. 2018, A&A, 612, L6
Qiu, J., Shen, B., Zhang, L., et al. 2018, LPB, 36, 384
Repetto, P., Martínez-García, E. E., Rosado, M., & Gabbasov, R. 2017, MNRAS, 468, 180
Romanowsky, A. J., & Fall, S. M. 2012, ApJS, 203, 17
Sebastian, B., Kharb, P., O'Dea, C. P., Gallimore, J. F., & Baum, S. A. 2019, MNRAS, 490, L26
Takabe, H., Kato, T. N., Sakawa, Y., et al. 2008, PPCF, 50, 124057
Vietri, A., Järvelä, E., Berton, M., et al. 2022, arXiv:2204.00020
Wang, W. P., Jiang, C., Shen, B. F., et al. 2019, PhRvL, 122, 024801