以 X 射線連續光譜限制在 GX 339-4 中黑洞的自旋

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摘要

我們利用擬合X射線連續光譜方法去限制X射線雙星GX 339-4中的恆星級黑洞的自旋。Reis et al. (2008)利用鐵Kα線模型測定出它的自旋爲a_*=0.935±0.01。然而，Kolehmainen & Done (2010)從X射線連續光譜中得到它的自旋不會超過0.9的結果。爲了解決這兩個不一致的結果並計算其自旋，我們先採用兩個相對論性吸積薄盤模型，並且結合簡單的康普吞化模型，用以擬合RXTE/PCA對於GX 339-4自2002年至2010年的爆發觀測的X射線連續光譜。我們依循McClintock et al. (2006)和Steiner et al. (2009a & 2010)的建議，爲了利於進一步分析而設立了限制條件以挑選符合吸積薄盤模型的資料。我們更進一步地利用新建立的修正模型(McClintock et al. 2006)去限制這黑洞的自旋。我們的結果顯示這個黑洞的自旋不會小於a_*=0.94，這似乎支持了Reis et al. (2008)的結果。

Constraint on the Spin of the Black Hole in GX 339-4 from X-ray Continuum

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Abstract

We present our analysis result for constraining the spin of the stellar-mass black hole (BH) in the X-ray binary GX 339-4 by fitting its X-ray continuum spectra. Reis et al. (2008) determined its spin to be a_*=0.935±0.01 by modeling the profile of Fe Kα line. However, Kolehmainen & Done (2010) concluded that its spin is no more than 0.9 from X-ray continuum fitting method. To resolve these contradictive results and estimate its spin, we first adopted two fully relativistic, thin accretion disk models combined with a simple comptonization model to fit X-ray continuum spectra of GX 339-4 observed by the Proportional Counter Array (PCA) on Rossi X-Ray Timing Explorer(RXTE) during its 2002-2010 outbursts. We set up constraints suggested by McClintock et al. (2006) and Steiner et al. (2009a & 2010) to select the data suitable for thin accretion disk model to further analyze. Using the same constraints described by McClintock et al. (2006) and Steiner et al. (2009a & 2010) to select the data, we employed a newly developed fully relativistic accretion disk model (McClintock et al. 2006) to further constrain the black hole spin. Our result indicates that the BH spin is no less than a_*=0.94, which is likely favorable to the results from Reis et al. (2008) and Miller et al. (2009).

關鍵字 (Keywords)：X 射線雙星(X-rays: binaries)、黑洞物理(black hole physics)、吸積盤(accretion disks)

Received : 2011.10.24; Accepted: 2011.12.12

1. Introduction

There are only two physical quantities that are measurable for a BH: mass and spin. Spin of a BH is described by a dimensionless parameter, $a_*\equiv cJ/GM^2$, where M and J are its mass and angular momentum, respectively. The spin of a non-rotating Schwarzschild BH is zero, whereas the spin of a maximally rotating Kerr BH is one. Presently a BH spin can be measured by two methods: modeling the profile of a relativistically broadened Fe Kα line and fitting the X-ray continuum from emissions of accretion disk. In fact, both methods estimate BH spin by evaluating the radius of innermost stable circular orbit (ISCO), which is identified with the inner radius accretion disk of a BH binary in thermal radiation dominated state, decreasing from $6GM/c^2$ to GM/c^2 as a_* increases from 0 to 1.

The spin of BH X-ray binary GX 339-4 has been measured by both methods with inconsistent results. Kolehmainen & Done (2010) (hereafter KD10) suggested a_* is no more than 0.9 using continuum fitting but Reis et al. (2008) (hereafter R08) proposed a_*=0.935±0.01 by modeling the profile of Fe Kα line. In this study, we adopt an up dated model and algorithm to fit the X-ray continuum to resolve the contradiction.

2. Observation and data reduction

A total of 813 RXTE/PCA observations of GX339-4 were collected during several outbursts between 2002 and 2010. Because only one of the five Proportional Counter Units, PCU-2, was always on during the observations, only the Standard-2 mode data from all Xe gas layers of this PCU were analyzed. All the selected data were reduced by the tools of HEAsoft. Bright source background model was used to estimate the background spectra of the observations and they would be subtracted from the observed spectra to yield background subtracted source spectra.

3. Data Analysis

3.1 The Spectral models for Constraining the Black Hole Spin

We used XSPEC in HEAsoft to analyze the X-ray spectra. To estimate the black hole spin by fitting the X-ray continuum, we considered two fully relativistic thin accretion disk models implemented in XSPEC: KERBB (Li et al. 2005, hereafter L05) and BHSPEC (Davis et al. 2005, hereafter D05). Because of the Compton scattering in the disk, the emissions from disk are not a true blackbody. Therefore, KERRBB uses the spectral hardening factor $f_{col} = T_{col}/T_{eff}$, where T_{col} is the color temperature and T_{eff} is the effective temperature, respectively, to modify the thermal spectra. Besides, D05 used a different approach to model the thin accretion disk of a Kerr black hole though the non-local thermal equilibrium atmosphere and the viscosity parameter α of thin accretion disk (Shakura & Sunyaev 1973). The viscosity parameter is defined by the midplane accretion stress $\tau_{r\varphi}=\alpha\times P$, where P is the total pressure at the disk midplane. BHSPEC is tabulated for only two values of α: 0.1 and 0.01. Because BHSPEC considers the opacity of metal ions in disk, the theoretical spectra of BHSPEC already contain the information of f_{col}. However, BHSPEC does not include the self-irradiation effect (i.e., returning radiation, a part of photon from disk would return to the disk due to the gravity of the black hole). For comparison, we fitted data with the two fully relativistic, thin accretion disk models above individually.

In addition, we fitted the same photon energy range (i.e., from 3 to 20 keV) as KD10 for comparison and combined three additional components with each thin disk model to consider the following spectral features of the accretion disk in a black hole X-ray binary:

(1) To model the non-thermal (power-law) spectral feature, we applied the Comptonization of a seed spectrum model, SIMPL (Steiner et al. 2009b). It has two parameters: a fraction of the photons in an input seed spectrum which is scattered into a power-law f_{SC} (This fraction indicates how many thermal photons are scatted by hot electrons in the corona.) and the photon power-law index Γ. Besides, the model includes two scattering types: only up-scattering (i.e., inverse Compton scattering) and both up- and down-scattering. We adopted both types for comparison.

(2) We used the photoelectric absorption model PHABS to include the interstellar absorption. We adopted two values of neutral hydrogen column density N_H, which were fixed at 0.5×10^{22} cm^{-2} (R08) and 0.6×10^{22} cm^{-2} (KD10), for comparing the two values which were measured by others before.

(3) We added gravitational broadening, smeared Fe edge (SMEDGE) and Gaussian emission-line (GAUSSIAN) to model the effect of disk reflection generated through the photoabsorption and fluorescence of iron atoms on thin disk by the hard X-rays from corona. Because the center of the Fe Kα line is at 6.4 keV, we followed the approach of KD10, which they restricted the central energy of the Gaussian emission-line to the range 6-7 keV and constrained the smeared edge energy from 7-9 keV.

Furthermore, we set up the following criteria which are suggested by (McClintock et al. 2006) and Steiner et al. (2009a & 2010) to select data:

(1) Steiner et al. (2009a) found that when the scattered fraction f_{SC} is less than 0.25, the radius of inner disk will remain constant within a few percent. To ensure this radius is the same as the radius of innermost stable circular orbit, we used

$f_{SC} < 0.25$ as the criterion to select the suitable spectra.

(2) The Eddington-scaled disk luminosity $l_D \equiv L_D/L_{Edd}$ is between $0.05 < l_D < 0.3$, where L_D is the disk luminosity and L_{Edd} is the Eddington luminosity. The upper threshold is required to ensure one can employ the thin-disk models (McClintock et al. 2006), such as KERRBB and BHSPEC, and the lower threshold is chosen to remove hard-state spectra in which the disk may be truncated before it reaches the radius of innermost stable circular orbit so that we cannot determine the spin (Esin et al. 1997).

(3) The reduced χ^2 is less than 2 to ensure the quality of fitting is good.

(4) All the spin values in our results are obtained from taking the weighted average for spin values of all selecting spectra.

3.2 The Parameter Sets to Constrain the Black Hole Spin

KD10 concluded that the spin of the black hole in GX 339-4 is no more than 0.9 by fitting with BHSPEC. In order to compare our results with them, we chose the same parameters, that is, the mass of black hole $M_{BH}=15M_{\odot}$, the inclination angle of inner disk $i_{disk}=45^{\circ}$ and the source distance D=6kpc. We found that the spins are likely above 0.9, which contradict the claim of KD10. In addition, the results from Fe line (Miller et al. 2004) and radio jets (Gallo et al. 2004) claimed that the inclination angle of inner accretion disk of GX 339-4 is less the 30˚. Their results are inconsistent with the assumption of KD10, that is, the lower limit of orbital inclination i_{orb} is 45˚ and the orbital inclination is the same as the inclination of the inner accretion disk. Therefore, we have to find more reasonable parameter sets to constrain the black hole spin.

Because the radius of innermost stable circular orbit R_{ISCO} is decreasing from $6GM_{BH}/c^2$ to GM_{BH}/c^2 as spin a_* increases from 0 to 1, we used a function $f(a_*)$ to relate R_{ISCO} and spin:

$$R_{ISCO} = f(a_*) \times \frac{GM_{BH}}{c^2} \qquad (1)$$

, where $f(a_*)=6$ for $a_*=0$ and $f(a_*)=1$ for $a_*=1$.

In addition, we assumed a parameter to consider the disk flux that we received:

$$flux \propto par. = \left(\frac{R_{ISCO}}{D}\right)^2 \times \cos i_{disk} \qquad (2)$$

Thus, we can obtain the formula below by putting R_{ISCO} from equation (1) into equation (2):

$$f(a_*) = \left(\frac{par.}{\cos i_{disk}}\right)^{\frac{1}{2}} \times \frac{c^2 D}{GM_{BH}} \qquad (3)$$

According to the formula, to find the lower limit of the black hole spin, smallest black hole mass M_{BH}, largest inner disk inclination angle i_{disk} and longest source distance D have to be applied for spectral fitting, and vice versa.

To find a more reasonable parameter set, we summarized the dynamical parameters of this system. The mass function of GX 339-4 is $5.8 \pm 0.5 M_{\odot}$ (Hynes et al. 2003). Muñoz-Darias et al. (2008) suggested that the mass of the donor star must between $0.166\ M_{\odot}$ and $1.1\ M_{\odot}$. Though Hynes et al. (2004) claimed that the distance of GX 339-4 may be great than 15kpc, we adopted D=8kpc, which assumed that the source is a galactic bulge source as proposed by Zdziarski et al. (2004).

As mentioned in the beginning of this section, Gallo et al. (2004) and Miller et al. (2004) suggested that the inclination angle of inner disk i_{disk} < 30°. If the inclination angle of inner disk were the same as the one of the binary orbit, 30°, according to the mass function and the mass of the donor star, the mass of black hole would have been greater than $40M_{\odot}$, which is highly unlikely.

On the other hand, Fragos et al. (2010) pointed out the orbital plane and the inner disk could be misaligned no more than 20° at 95.4% confidence level. Thus, we assumed the spin- orbit misalignment is less than 20° (i.e., the orbital inclination is less than 50°). According to the mass function and the mass of the donor star, we found the lower limit of the black hole mass is 12.12 $M_{\odot}$. Therefore, we adopted M_{BH}=12.12$M_{\odot}$, i_{disk}=30°, D=8kpc for estimating the lower limit of spin.

To find the upper limit of spin, we chose the largest black hole mass in the low-mass X-ray binary GRS 1915+105 (14.0±4.4$M_{\odot}$, Harlaftis & Greiner 2004) as the upper limit of the black hole mass. According to this value of mass and the mass function, we found the lower limit of orbital inclination is 46.81°. Therefore, we adopted M_{BH}=14$M_{\odot}$, i_{disk}=26.81°, D=8kpc to account for the upper limit of spin.

3.3 Constrain on the Spin by the Modified Spectral Model: KERRBB2

In section 3.2, we fixed the spectral hardening factor f_{col} at 1.7 and fitted for spin and accretion rate with KERRBB. However, the spin could be sensitive to f_{col}. Thus, we fixed f_{col} =1.5, 1.6, 1.8 and 1.9, which are the range of reasonable values for accretion disks around stellar-mass black holes, and fitted data with KERRBB. We found the selected data were not sensitive to spectral hardening factor but the spins were indeed sensitive to it. Therefore we do not know the correct spin value. Besides, BHSPEC does not include the self-irradiation effect.

Because of these drawbacks of KERRBB and BHSPEC, McClintock et al. (2006) modified the code of KERRBB, which is so-called KEEBB2. Although one cannot obtain the spectral hardening factor from BHSPEC explicitly, the theoretical spectra of BHSPEC already contain the information of f_{col}. According to McClintock et al. (2006), they first used BHSPEC and KERRBB to calculate the spectral hardening factor and generate a table of f_{col}. Furthermore, they modified the code of KERRBB so that it (i.e., KERRBB2) can read into the table before fitting. Thus, they can just fit for spin and accretion rate with KERRBB2.

However, KERRBB2 is still proprietary so that it cannot be applied by XSPEC's users presently. Therefore, we could only use KERRBB and BHSPEC to constrain the black hole spin in our early work. Fortunately, the owners of KERRBB2 recently agreed to share with us the private source code KERRBB2. Thus, we could use KREEBB2 to further analyze.

To use KERRBB2, we must generate the f-table first. According to the methodology of McClintock et al. (2006), we chose a set of reasonable values of the spin a_* and the logarithm of the Eddington-scaled disk luminosity $\log(l_d)$ for calculating spectral hardening factors. In our previously analysis, we found that the spin is about 0.86< a_* <0.97. Thus, we chose spin values from this range. In addition, we adopted $\log(l_d)$ from -1.3 to -0.5, which are consistent with the limits in the criterion for selecting data as mentioned previously.

Because BHSPEC includes the information of f_{col} in theoretical spectra and KERRBB can fit for f_{col}, we use the two models to generate a f-table. For each given a_*, $\log(l_d)$ and parameter set (i.e., M_{BH}, i and D), we used the command "**fakeit**" in XSPEC and the model PHABS×BHSPEC to generate faked spectrum. Because the response files are almost same in all the observations, we adopted the same response file for all the faked spectra when we used **fakeit**.

Furthermore, we loaded the faked spectra and fixed a_* and $\dot{M}$ at the values same as them to fit with the model PHABS*KERRBB for the f_{col}.

After finishing last step, we got a table for spectral hardening factor. Finally, we used the model PHABS×SMEDGE×(SIMPL×KERRBB2 +GAUSSIAN) to read the so-called f-table and fitted for spin and accretion rate. As in the section 3.2, we adopted M_{BH}=12.12$M_{\odot}$, i_{disk}=30°, D=8kpc and M_{BH}=14$M_{\odot}$, i_{disk}=26.81°, D=8kpc to estimate the lower and upper limit of spin, respectively. We found that the spin is about 0.96< a_* <0.99 and 0.94< a_* <0.99 for the viscosity parameters α=0.01 and 0.1, respectively. Figure 1 and 2 show the data with the folded model and unfolded spectra for M_{BH}=12.12$M_{\odot}$, i_{disk}=30°, D=8kpc, respectively. The histogram shows the summed of models fitted to the data with the individual component shown as point line. Table 1 summarized one of our spectral fitting results for M_{BH}=12.12$M_{\odot}$, i=30°, D=8kpc and α=0.1. The confidence level of errors is 1 σ.

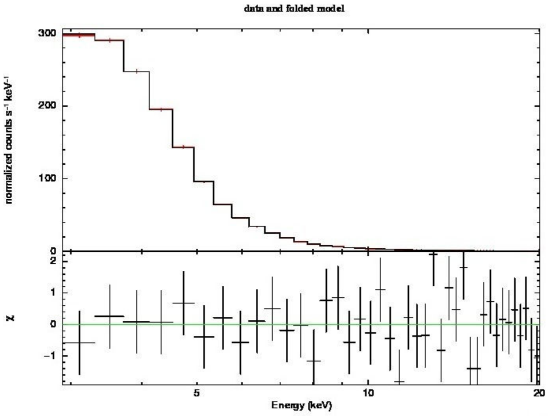

Fig. 1: The data with the folded model for M_{BH}=12.12$M_{\odot}$, i=30°, D=8kpc. The bottom shows the residuals in terms of sigmas with error bars of size one.

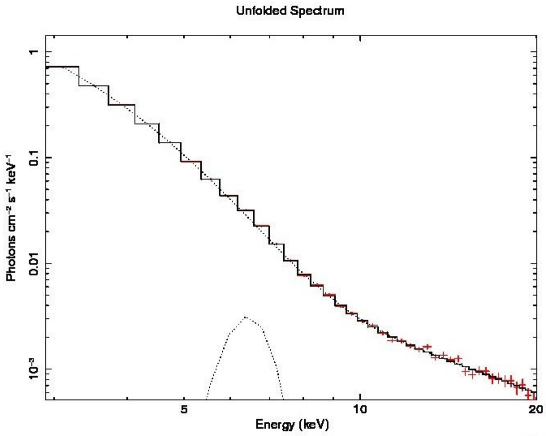

Fig. 2: The unfolded spectra for M_{BH}=12.12$M_{\odot}$, i=30°, D=8kpc. The dotted lines are indicate the individual component (low energy for thermal component, high energy for power low component and Fe line is around 6~7kev) of model the histogram shows the summed of models fitted to the data.

4. Discussion and Conclusion

4.1 The Comparisons of Our Results with Previous Study

We adopted the same parameter set as KD10 but fitted with different model and obtained inconsistent results (see section 3.2). In this section, we discuss the inconsistence by comparing our model and the criteria of selecting disk-dominated spectra, listed in Table 2.

Table 1. One of our spectral fitting results for M_{BH}=12.12$M_{\odot}$, i=30°, D=8kpc and α=0.1 model: PHABS×SMEDGE(SIMPL×KERRBB2+GAUSSIAN)

Parameters	Fitting results
Neutral hydrogen column density N_H (PHABS)	Fixed at $0.6\times10^{22}cm^{-2}$
Smeared edge energy (SMEDGE)	7.76 ± 0.48 (keV)
Photon power-law index Γ (SIMPL)	2.44 ± 0.13
Scattered fraction f_{SC} (SIMPL)	0.074 ± 0.014
Black hole spin a_* (KERRBB2)	0.9389 ± 0.0240
Mass accretion rate of the disk (KERRBB2)	1.62± 0.15 ($10^{-8}gs^{-1}$)
Spectral hardening factor f_{col} (KERRBB2)	Fixed at 1.6036
Gaussian emission line energy (GAUSSIAN)	6.39 ± 0.18 (keV)
χ^2/d.o.f.	33.41/33

Note: the confidence level of errors is 1 σ.

Table 2. The differences between KD10 (second row) and our work (third row)

Model	Criteria for selecting disk-dominated spectra
TBABS×SMEDGE×(BHSPEC+THCOMP+GAUSSIAN)	Hardness Ratio: HR≤0.2
PHABS×SMEDGE×(SIMPL*BHSPEC+GAUSSIAN)	f_{SC} <0.25 ; $0.05 < l_D < 0.3$

First, KD10 used the Tuebingen-Boulder interstellar medium absorption model (TBABS) and the thermal Comptonization model (THCOMP) for the effects of interstellar absorption and Comptonization, respectively. Second, KD10 chose hardness ratio, i.e., the ratio of flux in soft and hard X-ray energy band, HR≤0.2 as the criterion to select disk-dominated spectra.

Although THCOMP considers the temperature of seed photons and hot electrons, it does not combine thermal and power-law components together. Therefore, we used the Comptonization of a seed spectrum model (SIMPL) to account for Comptonization, couples the thermal and power-law components together, whereas THCOMP only considers the power-law component. In other words, SIMPL uses the photons emitted from accretion disk as input seed photons and scattered into power-law component of spectra. Because it is believed that the power-law component is generated by up-scattering the seed photons from accretion disk by the coronal electrons, SIMPL is better than THCOMP to approach the power-law component. In addition, our criteria for selecting disk-dominated spectra, suggested by Steiner et al. (2009a & 2010), were set up to select not only the thermal spectra but also rule out the spectra that are inconsistent with thin disk model (McClintock et al. 2006). It is unlike the ardness ratio criterion that only considers the flux ratio between the thermal and power-law components to select disk-dominated spectra. Therefore, when we used the same parameter set as KD10 to evaluate the upper limit of the black hole spin, we conclude it is larger than 0.9.

4.2 The Spin Range of the Black Hole in GX 339-4

In the section 3.2, we adopted two parameter sets to constrain the black hole spin with two fully relativistic, thin accretion disk models individually. We found that the spin is about 0.86< a_* <0.97. Although the two models have their own drawbacks, the results imply that it is close to a Kerr black hole. In the section 3.3, we further used the modified model KERRBB2 and applied the same parameter sets to constrain the spin. We found that the spin is about 0.96< a_* <0.99 and 0.94< a_* <0.99 for the viscosity parameters α=0.01 and 0.1, respectively. In this section, we discuss the possible spin range of the black hole in GX 339-4.

The results are listed in Table 3. We can see that the two scattering types (i.e., only up-scattering and both up- and down-scattering) do not affect the spin value from spectral fitting too much. Because the upper limits of spin are very close to maximum spin value, it seems that the corresponding parameter set (i.e., M_{BH}=14$M_{\odot}$, i_{disk}=26.81°, D=8kpc) does not constrain the upper limit of spin very well. On the other hand, the lower limits of spin are slightly sensitive to the viscosity parameters; the larger the value of α, the lower the value of spin. Recently, the results from General Relativistic magnetohydrodynamics simulations favor the large viscosity parameter (Penna et al. 2010; King et al. 2007), so we adopt the spin results of α=0.1.

Table 3. The KERRBB2 fitting results (Lower limit: 12.12$M_{\odot}$ 30° 8kpc ; Upper limit: 14$M_{\odot}$ 26.81° 8kpc)

N_H=0.5 ($10^{22}cm^{-2}$); α=0.1, Up Only	0.9573(5)<a_*<0.9935(2)
N_H=0.5 ($10^{22}cm^{-2}$); α=0.1, Up & Down	0.9559(5)<a_*<0.9932(2)
N_H=0.5 ($10^{22}cm^{-2}$); α=0.01, Up Only	0.9712(4)<a_*<0.9949(4)
N_H=0.5 ($10^{22}cm^{-2}$); α=0.01, Up & Down	0.9714(4)<a_*<0.9949(4)
N_H=0.6 ($10^{22}cm^{-2}$); α=0.1, Up Only	0.9468(6)<a_*<0.9925(2)
N_H=0.6 ($10^{22}cm^{-2}$); α=0.1, Up & Down	0.9466(6)<a_*<0.9926(2)
N_H=0.6 ($10^{22}cm^{-2}$); α=0.01, Up Only	0.9642(5)<a_*<0.9951(3)
N_H=0.6 ($10^{22}cm^{-2}$); α=0.01, Up & Down	0.9643(5)<a_*<0.9954(4)

Note: the confidence level of errors is 1 σ.

In addition, Miller et al. 2009 constrained the black hole spin of GX 339-4 by Fe line and continuum modeling. They found the spin a_*=0.94(2), the inclination of inner disk i_{disk}=29(2)° and the neutral hydrogen column density N_H=5.7(1) ×10^{21} cm^{-2}. Table 4 shows the comparison of spin results from different groups. We believe that our parameter set of the lower limit (i.e., M_{BH}= 12.12$M_{\odot}$, i_{disk}=30°, 8kpc) may be very close to the real values of GX 339-4 and conclude our constrained spin is no less than 0.94, which are likely favorable to the values of spin from Miller et al. 2009 (a_*=0.94±0.02) and R08 (a_*=0.935±0.01).

Table 4. The comparison of spin results from different groups

Group	a_*	Method
KD10	<0.9	Continuum
R08	0.935±0.01	Fe line
Miller et al. (2009)	0.94±0.02	Fe line + Continuum
Our work	>0.94	Continuum

The mass of black hole, the inclination of inner disk and the distance of the source should be measured more accurately in order to further constrain the spin. Besides, spins should be determined and compared with different observable phenomena, such as the high-frequency X-ray quasi-periodic oscillations modeling and X-ray polarimetry (Remillard & McClintock 2006) in the future.

Acknowledgement

The RXTE/PCA data of this research were obtained from High Energy Astrophysics Science Archive Research Center (HEASARC) online service provided by NASA/Goddard Space Flight Center. This research was supported by National Science Council (NSC) grants NSC97-2112-M-008-012-MY3. The authors thank Dr. McClintock and Dr. Gou for their helpful discussions.

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