A New Set of Parameters of High-Mass X-ray Binaries Found with their Cyclotron Lines

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Received date ; accepted date

ABSTRACT

We have derived new physical quantities for several High-Mass X-ray Binaries (HMXBs) with supergiant (SG) companions through their cyclotron lines. The parameters are: the terminal velocity of the wind, the mass loss rate of the donor, the effective temperature and the magnetic fields. These parameters influence significantly the improvement of the model of accretion. In spite of the variety of their observational properties, the corresponding magnetic field is around \( B \sim 10^{12} \) G. This result can be constrained by the effects on stellar evolution. In addition, we have performed a segmentation in the parameter space of donors intended for several SG-HMXB listed in our sample set. The parameter space can be categorized into five regimes depending on the possibility of disk formation associated with accretion from the stellar wind. This can give a quantitative clarification of the observed variability and the properties of these objects. We show that, when these systems come into the direct accretion region, systems with corresponding parameters can emit X-rays.

Key words: Binaries: X-rays: binaries; accretion discs; formation: magnetic fields.

1 INTRODUCTION

The detection of Cyclotron Resonance Scattering Features (CRSFs) in spectra of many accreting neutron stars (NSs) with high magnetic field (\( B \geq 10^{12} \) G) provides valuable insights into the physics of emitting regions and the evolution of these systems. They form due resonant scattering processes with electrons, protons, and other ions in the plane and perpendicular to the magnetic field (Voges et al. 1982; Wilson et al. 2008). As a result, the cyclotron line features provide the only direct estimate of the magnetic field strength of NSs in X-ray binary systems. In High-Mass X-ray Binaries (HMXBs), an NS accretes matter from a companion star via stellar wind. The accreted matter is channeled along field lines of the strong magnetic field of the NS onto the magnetic poles. X-ray emission from the NS is produced in regions around the magnetic poles. It is noteworthy to mention here that most observed cyclotron lines have been detected above 10 keV and are interpreted as electron features, with inferred magnetic fields \( B \sim 10^{12} \) G (Heindl et al. 2001). The combined effects of poor statistics, photoelectric absorption and the lack of evidence for a remnant accretion disk have made these energy sources elusive.

According to recent studies, several pulsars show changes in luminosity dependence in the cyclotron resonance energy. The first aim of this paper is to derive magnetic field strengths, which is crucial for these systems, and obtain clues about the evolution of HMXBs, which can be understood in terms of the conservative evolution of normal massive binary systems.
The second aim of this study is to derive unknown parameters of HMXBs without uncertainty in the strength of the NS magnetic field. With robust data on the NS magnetic field, combined with spin period \( P_{\text{spin}} \) and orbital period \( P_{\text{orb}} \), we can fix several hitherto-unknown parameters, such as wind velocity and wind mass loss rate. These parameters influence significantly the model of wind-fed binary systems and can constrain the effects of binary evolution (Taani et al. 2012a; b; Taani & Khasawneh 2017; Dai et al. 2017; Taani et al. 2019; Karino et al. 2019). From this standpoint, with observations of NS magnetic fields, we could constrain the end products of HMXBs, such as an NS-NS merger, which is considered to be one of the most powerful gravitational wave sources and also the most probable site for heavy element creation (Postnov & Yungelson 2001; Taani 2015).

In the next section, we introduce the recent results of NS magnetic field given by CRSF observations. In Section 3, we discuss the method to obtain hitherto-unknown binary parameters from robust data on the NS magnetic field in SG-HMXBs. In Section 4, we discuss our findings. The last section is devoted to conclusions.

2 CYCLOTRON LINES

Since the physical conditions are expected to vary over the emission region, the X-ray spectrum is expected to change with the viewing angle and therefore with pulse phase. This variation can be because during one rotation phase different parts of the surface are exposed and also due to change in local field structure due to accretion dynamics, e.g. change in accretion rate, as is seen for sources like Her X-1 and V0332+53. The difference in time scales of variation for \( E_{\text{cyc}} \) and luminosity will allow researchers to distinguish between these two distinct cases. (Nagase et al. 1991; Wilson et al. 2008). In this work, we have selected 11 persistent sources with SG companions known to have at least one cyclotron line (see table 1). Here, our analysis of all pointing observations provides an opportunity to infer the values of magnetic field strength according to their spectra. However, the gravitational redshift \( z \) that at the NS surface is approximately

\[
z \simeq \frac{1}{\sqrt{1 - \frac{2GM_{\text{NS}}}{R_{\text{NS}} c^2}}} - 1 \simeq 0.3 \tag{1}
\]

where \( M_{\text{NS}}, R_{\text{NS}} \) and \( c \) are the NS mass, radius and speed of light, respectively. Assuming canonical values for \( M_{\text{NS}} \) and \( R_{\text{NS}} \) of 1.4 \( M_{\odot} \) and 10 km, thus \( z = 0.3 \). As such, the line energy of the fundamental cyclotron line is related to the magnetic field strength by the equation

\[
E_{\text{cyc}} = 11.6 B_{12} (1 + z)^{-1}. \tag{2}
\]

Here \( B_{12} \) is the magnetic field strength in units of \( 10^{12} \) G, and the higher harmonics have an energy \( n \) times the fundamental energy \( E_{\text{cyc}} \).

In general, the magnetic field of NSs spans a range from \( 10^8 \) G or less (LMXBs) to \( 10^{15} \) G (magnetars); this concentration seems rather odd. Additionally, the magnetic field shows no correlation with the spin period of NSs and orbital period of the binary systems (see Fig. 1). This result disagrees with the dependence of B-field on the spin period in Be-systems shown by previous studies (Corbet 1986, 2004; van den Heuvel 2009; Taani et al. 2012a). Though, of course, we need to consider some observational biases: too strong of a magnetic field prevents accretion onto the NS and we could not observe such systems as bright X-ray sources (Taani 2016). Besides such possibility of biases, this concentration around \( B \approx 10^{12} \) G will draw a lot of interest and promote further studies on the NS magnetic field (Taani et al. 2018). The fundamental energy covers a wide range, starting at 10 keV for Swift J1626.6-5156 (DeCesar et al. 2009) to 100 keV for LMC X-4 (La Barbera et al. 2001).

The strong energy variation of the cyclotron lines (for example, in V0332+53, GRO J1008-57 and GX301-2) can be used to argue that during different phases of the X-ray pulses, regions with different magnetic fields are observed.

It is noteworthy to mention here that 4U 0115+634 is one of the pulsars whose CRSFs have been studied in great detail (see, e.g., Wheaton et al. 1979; Nagase et al. 1991; Nishimura 2005). In previous outbursts, CRSFs have been detected up to the fifth harmonic (Heindl et al. 2016). This high number of detected CRSFs in 4U 0115+634 makes this system an outstanding laboratory to study the physics of cyclotron lines in X-ray pulsars.

3 INVESTIGATING WIND PARAMETERS IN SG HMXB SYSTEMS

Under the assumption that the spin period of an NS is nearly in equilibrium, the magnetic field strength of an NS can be estimated by

\[
B_{\text{NS}} = 2.184 \times 10^{12} G \times c^{1/2} \left( \frac{\dot{M}}{10^{18} \text{g s}^{-1}} \right)^{1/2} \left( \frac{P_{\text{orb}}}{1 \text{s}} \right)^{7/6}, \tag{3}
\]

assuming that the mass of the NS is 1.4 \( M_{\odot} \) and its radius is 10 km (Ghosh & Lamb 1979; Campana et al. 2002; Tsyganov et al. 2016; Karino & Miller 2016). The parameter \( \zeta \) is the ratio of accretion velocity to the free-fall velocity, and hereafter we fix this value as 0.5.

The mass accretion rate \( \dot{M} \) can be obtained as the following, if we assume the Hoyle-Lyttleton accretion scenario

\[
\dot{M} = \frac{4 \pi G M_{\text{NS}}}{c^2} B_{\text{NS}}^2 \tag{4}
\]
Table 1. List of some observational parameters of all known persistent sources with supergiant companions through the cyclotron resonant scattering features

| Object      | $P_{\text{spin}}$ (s) | $P_{\text{orbit}}$ (d) | $E_{\text{cyc}}$ (keV) | Ref. |
|-------------|------------------------|-------------------------|------------------------|------|
| 4U 1907+09  | 439                    | 8.37                    | 18.8±0.4               | 1, 2, 3 |
| 4U 1538–52  | 529                    | 3.73                    | 21.4±0.9               | 6, 9, 10 |
| Vela X-1    | 283                    | 8.96                    | 27±1.3                | 5, 6, 7 |
| Cen X-3     | 4.8                    | 2.09                    | 30.4±0.3              | 2, 3, 11 |
| LMC X-4     | 13.5                   | 1.4                    | 100±2.1               | 4, 12 |
| OAO1657–115 | 37.7                   | 10.4                    | 36                   | 15, 16, 17 |
| J16493–4348 | 1069                   | 6.78                    | 33±4                  | 18, 19 |
| 4U 1700–377 | 53.4                   | 37                     | 18                   | 15, 16 |
| 2S 0114+65  | 9700                   | 11.6                    | 22                   | 15, 20 |
| J16393–6433 | 904                    | 4.2                     | 29.3±1.3              | 21 |
| IGR J18027–201 | 140, 4.6              | 23                     | 27 |

References.—These references are to period measurements in the literature. Some have errors originating from applied analysis, designated with a dagger, or from the supplied data, designated with an asterisk. (1) Cusumano et al. 1998; (2) Coburn et al. 2002; (3) Rivers et al. 2010; (4) Clark et al. 1990; (5) Rodes-Roca et al 2009; (6) Robba et al. 2001; (7) Kreutzschmar et al. 2005; (8) Makishima et al. 1999; (9) Kreykenbohm et al. 2002 (10) Schanne et al. 2007 (11) Santangelo et al. 2008; (12) Barbera et al. 2001; (13) Orlandini et al. 1999; (14) Denis et al. 2010; (15) Pottschmidt, S et al. 2011 (16) Nespoli et al. 2010 (17) D’Al et al. 2011 (18) Reynolds et al. 1999 (19) Bonning et al. 2005 (20) den Hartog et al. 2006 (21) Bodaghee et al. 2016. (22) Lutovinov et al. 2017.

\[ \dot{M} = \frac{G^2 M_*^2}{a^2 v_{\infty} v_{\text{rel}}^3} \tag{4} \]

where $\dot{m}_w$ is the wind mass loss rate from the donor. Here, orbital radius $a$ can be obtained from the orbital period of the system. The X-ray luminosity is related to the mass accretion rate as follows

\[ L_X \approx \frac{G M_* M}{R_{\text{NS}}} \tag{5} \]

Thanks to this relation, we can deduce the mass accretion rate from the observed X-ray luminosity. The relative velocity of the wind to the NS is

\[ v_{\text{rel}} = \left( v_{\text{orb}}^2 + v_{\infty}^2 \right)^{1/2} \tag{6} \]

and the velocity of the line-driven wind is usually prescribed in the model by so-called $\beta$-law (Castor, Abbott & Klein 1975).

\[ v_{\infty} = v_{\infty} \left( 1 - \frac{R_d}{a} \right)^{\beta} \tag{7} \]

In this study, we assume $\beta$, which is a free input parameter, to be $\beta = 1$ (Puls et al. 2008). $v_{\infty}$ denotes the terminal velocity of the wind.

The wind parameters such as $\dot{m}_w$ and $v_{\infty}$ contain large uncertainties. Combining above equations with CRSF data introduced in the previous section, however, a single relationship between $\dot{m}_w$ and $v_{\infty}$ could be obtained for the canonical NS parameters. From Eqs. (4) to (7), we get

\[ v_{\text{rel}}^2 = -v_{\text{orb}}^2 \pm \sqrt{\frac{G M_*^2}{\pi a^2 M} \dot{m}_w}. \tag{8} \]

If the luminosity of the NS is known, the mass accretion rate $\dot{M}$ could be derived from Eq. (5). $a$ is the orbital semi-major axis and it is obtained from the orbital period if the mass of the donor is known. In Table 2, we show the values of donor mass and donor radius, which has appeared in Eq. (7).

If we choose the mass loss rate from the donor $\dot{m}_w$ as a fundamental variable, then Eq. (5) becomes a biquadratic equation and has four solutions. Two of them are physically nonsense, so we consider the other two solutions since they have a clear correlation between wind velocity and the mass loss rate of donors in SG-HMXBs. These solutions of the wind velocity are shown in Figs. 2 - 4 by solid curves, as functions of mass loss rate in SG-HMXBs. In these figures, the wind parameter given by the frequently used wind model by (Vink, de Koter & Lamers(2001)) are also shown at the same time. In these figures, the approximated wind mass loss rates from SG stars are given as the complex functions of mass, radius (escape velocity), luminosity (effective temperature) of SG stars. To derive the mass loss rate of the HMXB donors, we use the mass and radius data introduced in previous papers (Falanga et al.(2015) Reggi, Nersesian & Zzasas(2016) Chatty et al.(2005) Rawls, Orosz & McClintock(2011) Cusumano et al.(2010) Mason et al.(2012)). From these data, we derive the effective temperature and corresponding luminosity using approximated stellar evolution scheme. We compile Eqs. (1) to (30) in Hurley et al.(2000) and find the evolution stage of each donors in SG-HMXBs listed in Table 2. Then, we derive the effective temperature at this evolutionary stage.

The obtained wind parameters ($v_{\infty}$ and $\dot{m}_w$) are also shown in Table 2. From these results, we could confirm that the terminal velocities of the wind from donors in SG HMXBs are rather slow. In seven systems, the terminal velocities of donors dip from the typical wind velocity of galactic single SG stars (1,000 – 2,000 km s$^{-1}$). This result is consistent with recent result given by Giménez-García et al. (2016) who argued that the stellar wind of donors in persistent HMXBs is systematically slow. For instance, from recent observations, it is suggested that the wind velocity in persistent SG HMXBs, Vela X-1, is relatively slow ($v_{\text{w}} = 700$ km s$^{-1}$). In our samples, even for systems with higher $v_{\infty}$, the wind velocities at the NS positions are typically $v_{\text{w}} \approx 500$ km s$^{-1}$, and still show very slow wind.

It is broadly considered that in wind-fed HMXBs, the wind matter is captured by the NS magnetic field at a certain point, designated with a dagger, or from the supplied data, designated with an asterisk. (1) Cusumano et al. 1998; (2) Coburn et al. 2002; (3) Rivers et al. 2010; (4) Clark et al. 1990; (5) Rodes-Roca et al 2009; (6) Robba et al. 2001; (7) Kreutzschmar et al. 2005; (8) Makishima et al. 1999; (9) Kreykenbohm et al. 2002 (10) Schanne et al. 2007 (11) Santangelo et al. 2008; (12) Barbera et al. 2001; (13) Orlandini et al. 1999; (14) Denis et al. 2010; (15) Pottschmidt, S et al. 2011 (16) Nespoli et al. 2010 (17) D’Al et al. 2011 (18) Reynolds et al. 1999 (19) Bonning et al. 2005 (20) den Hartog et al. 2006 (21) Bodaghee et al. 2016. (22) Lutovinov et al. 2017.
radius, and transported onto the polar regions of the NS. In this process, around the polar region, the accretion column is formed and the potential energy of the accretion matter is converted into strong X-ray radiation.

However, it is believed that, when the NS (and consequently NS magnetic field lines) rotates rapidly, the accretion matter cannot fall onto the NS surface and in some conditions it could be expelled out (Pfahl et al. 2002; Podsiadlowski et al. 2004). This rotational inhibition of the accretion matter is called the propeller effect (see Reig & Zazas 2018). The propeller / accretion limit could be defined by three typical radii (accretion radius \( r_a \), magnetic radius \( r_m \) and corotation radius \( r_{\text{co}} \)). The propeller regime is defined when the accretion radius of the disk is larger than the magnetic radius. In contrast, in the supersonic inhibition regime, the magnetic radius is larger than the accretion radius and corotation radius, thus it rotates more slowly than inner regions of the disk.

The parameter space could divided into five accretion regimes based on their magnitude relation as follows: supersonic inhibition (\( r_m > r_a, r_{\text{co}} \)), subsonic inhibition (\( r_{\text{co}} > r_m > r_a \)), supersonic propeller (\( r_a > r_m > r_{\text{co}} \)), subsonic propeller (\( r_{\text{co}}, r_a > r_m, \dot{M} < \dot{M}_c \)), and direct accretion regime.

Here, \( \dot{M}_c \) denotes the critical limit where radiative cooling starts working (see Bozzo et al. 2008).

In figures shown below (Figs. 2 - 4), the different accretion regimes (A) to (E) are divided by dashed lines. The shaded region denotes the direct accretion regime such that only systems in this region can be observed as a persistent HMXB. The efficiency of the propeller depends weakly on the magnetic moment of the star (Ustyugova et al. 2006). Since if the angular velocity of the star is larger, then the efficiency of the propeller becomes higher (Tsygankov et al. 2016). In contrast, in the inhibition regime the accreting matter will be prevented by the magnetic gate due to being gravitationally focused toward the NS and thus the centrifugal gate also propels away material along the magnetic boundary of the NS (Bozzo et al. 2016). In addition, the subsonic propeller regime becomes clearer as the strength of the propeller increases. As the strength increases there is a sharp decrease in the accretion rate to the star. In these figures, the solid curves represent the theoretical relations between \( \dot{m}_w \) and \( v_w \) given by Eq. (8) with the CRSF data. We show that when these curves come into the direct accretion region (shaded region) created in the figures, the systems with corresponding parameters can result in the emission of X-rays.

### 4 DISCUSSIONS

#### 4.1 wind parameters

In Figures 2-4, we show the direct accretion regime where the systems with corresponding parameters can emit strong X-rays. In the same figures, we plot the wind parameters given by the standard wind model combined with the stellar evolution track; furthermore we show the theoretical relations between \( \dot{m}_w \) and \( v_w \) given by Eq. (8) with the CRSF data. The position of each source is based on the results reported in Table 2. In systems shown in Figures 2 and 3, these plots show good consistency; the plots are located in the direct accretion region (shaded region) and roughly follow the theoretical curves (obtained with CRSF data). These result partly explain the slow wind tendencies in SG-HMXBs. Namely, when the wind velocity becomes too high, the wind plots might go outside of the accretion regime from the upper boundary of the shaded region. For typical mass loss rate in SG stars (say, \( 10^{-5} M_\odot \text{yr}^{-1} \)), the upper bound of the accretion regime is \( \approx 800 \text{km s}^{-1} \). Then, the systems with fast-wind donors cannot be observed as bright persistent X-ray sources.

On the other hand, our model cannot be applied for three binaries, such as LMC X-4, Cen X-3 and OAO1657 (see Fig. 4) although they share similar donor parameters. Since in systems with shortest orbital periods (LMC X-4 and Cen X-3) the Roche-lobe filling factors approach quite near to 1, their accretion mode may not be typical wind accretion any more. Their accretion mode could enter in the regime of RLOF, or quasi RLOF (Shakura et al. 2012; Shakura et al. 2013). In this case, it is little wonder that we cannot
obtain consistent wind parameters for these sources. Additionally, OAO1657 shows an inconsistent parameter set. As a result, the Roche lobe filling factor is much smaller and RLOF cannot be realized. On the other hand, it is suggested that the donor in this system is a Wolf-Rayet star (Mason et al. 2009; Mason et al. 2012). In this case, it might be ill-adopted to the standard wind model for typical SG stars. It is also argued that the system parameters of OAO1657 cannot be reproduced with standard binary evolution theory: a lot of mysteries remained in the understanding of this system (Jenke et al. 2012; Walter et al. 2015).

4.2 NS magnetic field

The question of where exactly the magnetic field is measured still remains unanswered. This depends on the accretion geometry and flow and other mechanisms (Wei et al. 2010; Coburn et al. 2002; Kreykenbohm et al. 2005). Hence, their line profiles reflect the geometrical and physical properties of the accretion column near the magnetic poles of the NS, and therefore constitute a diagnostic tool for accessing the physics of accretion.

It is noteworthy to mention here that the NS magnetic fields in Table 2 are surprisingly concentrated in a narrow range \( \sim 10^{12}\) G. Despite the fact that their physical properties, in particular their energy band (10 - 100 keV) which govern the evolution, are different, they strongly depend on the assumed parameters, and these parameters dominate their evolutionary stages. Thus, the magnetic field itself is of fundamental significance to having a thorough insight into the physics of the emitting region structure, and could also be imperative to assisting us in improving our understanding of binary evolution. Otherwise, the implementation of known stellar evolution and observational statistics in population synthesis codes will remain a major issue in our understanding of the processes occurring in compact binaries or in the treatment of selection effects (Postnov & Yungelson 2006). However, our results shown in Figs. 2 - 4 clearly demonstrate the variety of SG-HMXBs based on the different types of interactions between the wind mass loss rate and the three NS radii (accretion radius, magnetic radius and corotation radius). This diversity of X-ray binary systems is important in principle, and could be used to demonstrate the properties of wind-fed systems such as SG-HMXBs, and the parameters entirely control their evolution, since the binaries with compact remnants are primary potential GW sources.

Finally, 1A 0114+650 is a unique source with unusual properties (very slow rotation period, relatively low X-ray luminosity and a super-orbital periodicity of 30.7 days (see Farrell et al., 2006)), exhibiting properties consistent with both Be and SG X-ray binaries (Walter et al. 2015). This source suggests that it evolves on a time scale of several years (Wang 2010), or may be an accreting magnetar candidate (Sanjurjo-Ferrrin et al. 2017; Tong & Wang 2018). Possible signature of a transient disk was also found (Hu et al. 2017).
Figure 3. The same as previous, for the wind mass loss-rate, accretion mass-loss rate and accretion regimes. The position of each source is shown by a black filled circle.

Figure 4. The same initial conditions in terms of the stellar wind parameters as in Figs. 2-3, but these sources show different features and different distributions.
5 SUMMARY AND CONCLUSIONS

The following conclusions and implications are obtained:

We have derived new physical quantities for several HMXBs with supergiant companions through their cyclotron lines. These parameters are: the terminal velocity of the wind, mass loss rate of the donor, magnetic field, effective temperature and corresponding luminosity. Furthermore, for all systems, our analysis (direct accretion condition shown by shaded region, and the solution of wind equation shown by solid curves) suggests that the wind velocity should be systematically slow.

By adopting the accretion regime model by Bozzo et al. (2008), we have explored the parameter space in different regimes based on the intrinsic variabilities of mass accretion rate and wind velocity. This will allow us to describe an evolutionary path for several SG-HMXBs in these diagrams. Different regimes are sufficient to spatially separate bright X-ray sources, and can be probed through the magnetic field-wind velocity. As a result, persistent SG HMXBs within the shaded region can be observed through the direct accretion regime. This interpretation is based on its emission in high-energy X-rays.

It is seen that the wind velocity causes a significant effect on the results of their x-ray features and it can be used to determine the ejection mechanism. Consequently, when the wind velocity is slow, the accretion disk can be formed even in systems with large orbital period. This will allow to better characterize the HMXB of both types, SG and Be, hosting NS, by deriving accurate properties of these compact binaries.

From the updated measurement of HMXB cyclotron lines, the derived magnetic fields given by CRSF data are all concentrated around ~10^{15} G. However, the fundamental energy during X-ray observation, spin and other physical parameters property diverges and varies. The existence of a high magnetic field has the potential to control their formation and evolution.

Our model cannot constrain the accretion mechanism for fast-spinning NSs ($P_{\text{spin}} \lesssim 10$ s) with a short orbital period ($P_{\text{orb}} \lesssim 10$ d), like in LMC X-4, Cen X-3 and OAO1657 (see Fig. 4). In LMC X-4 and Cen X-3, these two binary systems are extremely tight systems. Thus, the accretion mechanism may not be approximated by spherical wind, because in such tight systems the concentrated asymmetric wind or RLOF accretion should be considered. While for OAO1657, the donor of this system is a further evolved star with a long orbit, and can be observed as a Wolf-Rayet star with stellar wind mass loss rate during its evolution.

Finally, however the currently available data for CRSFs are not sufficiently accurate or numerous to allow precise analysis. One would hope that the results of this work will be improved with data from Suzaku, INTEGRAL, eRosita and HXMT, which will provide significant increases in the observational sensitivity of some cyclotron sources.

ACKNOWLEDGEMENTS

We are grateful to A. D’Ai, E. Nespoli, O. Nishimura, M. Orlandini, K. Potschmidt, R. Rothschild, V. Sguera, Gaurav Jaiswal, and S. Tsygankov, for their comments and suggestions that allowed us to improve the clarity of the original version. Special thanks to Nicola Masetti for comparing our data with the data in his web page [http://www.iasfbo.inaf.it/~masetti/IGR/sources/17391.html](http://www.iasfbo.inaf.it/~masetti/IGR/sources/17391.html). This work has been supported by the Abdul Hameed Shoman Foundation (grant number 6/2017). A. Taani gratefully acknowledges support and hospitality from the Institute of High Energy Physics, Chinese Academy of Sciences through the CAS President’s International Fellowship Initiative (PIFI) 2018.

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